

# INFLUENCE OF SPAN TO DEPTH RATIO ON THE SHEAR STRENGTH OF REINFORCED CONCRETE DEEP BEAM

A Thesis

By

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Submitted to the Department of Civil Engineering of Bangladesh  
University of Engineering and Technology, Dhaka in partial  
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of

**MASTER OF SCIENCE IN CIVIL ENGINEERING**



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December, 1997.

# INFLUENCE OF SPAN TO DEPTH RATIO ON THE SHEAR STRENGTH OF REINFORCED CONCRETE DEEP BEAM

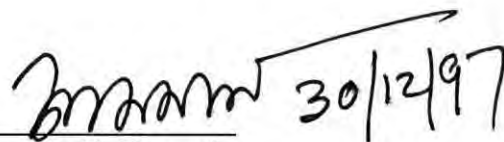
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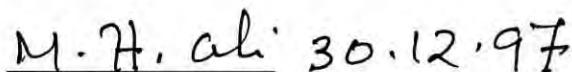
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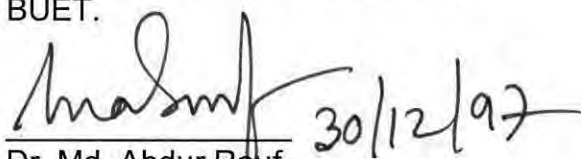
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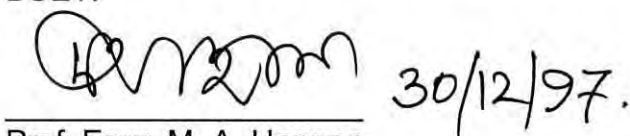
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## DECLARATION

I hereby certify that the research work reported in this thesis is the result of original research performed by me. Neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Further, to the best of my knowledge and belief, the thesis contains no material previously published or written by any other person, except when due reference is made in the text of the thesis.

December, 1997

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 (Md. Aminul Islam)

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## ABSTRACT

A total of twenty five brick aggregate reinforced concrete deep beams have been tested in this study in order to investigate the influence of span to depth ratio on the shear strength of reinforced concrete deep beam. The test beams were single span and simply supported type. The beams were divided into five series according to their span to depth ratio ( $L/D = 1$  to  $5$ ). The first beam of each series was designed and detailed as per the recommendations of ACI Building Code (ACI 318-89). In the other four beams of each series, the amount of either flexural or horizontal web reinforcement or both were changed in relation to those of first beam of the corresponding series.

All the beams were tested under single concentrated loading at mid span. The effects of different web steel arrangement and span/depth ratio on cracking load, ultimate load, crack patterns and modes of failure were investigated.

It was observed in the study that the amount of both flexural and horizontal web reinforcements influenced the diagonal cracking load and the ultimate load capacity of test beams to some extent. It was also found that the change in the amount of either the vertical or the horizontal web reinforcement alone could not bring a significant change in the load carrying capacity of test beams.

After comparing the observed initial cracking stress with that of by de Cossio<sup>(9)</sup>, Kabir<sup>(7)</sup> and Rashid<sup>(10)</sup>, it was found that the observed initial cracking stress was very close to the stress calculated by de Cossio<sup>(9)</sup>. It was also observed that the shear strength capacity of the deep beam having  $L/D$  ratio five was very close to the shear capacity of ordinary rectangular beam of similar size.

In general the ACI 318-89 recommendations regarding the ultimate strength of deep beams were observed to be conservative. Some available formulae (e.g. ACI 318-89, Ray & Reddy and Ramkrishnan & Ananthanarayana) were used to estimate the ultimate load in shear of deep reinforced concrete beams. It was shown that all the three formulae can be used efficiently to determine the ultimate shear strength of deep beams but these formulae need some modifications as proposed by Kabir<sup>(7)</sup> and Rashid<sup>(10)</sup>.

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## NOTATIONS

- $A_s$  = Cross sectional area of flexural steel  
 $A_y$  = Corss sectional area of individual vertical web steel  
 $A_{yh}$  = Cross sectional area of individual horizontal web steel  
 $A_v$  = Cross sectional area of individual horizontal web steel  
 $a_x$  = Clear shear span (unless otherwise specified)  
 $a'$  = Equivalent rectangular stress block  
 $\alpha$  = Inclination of the web steel with the horizontal (unless otherwise specified)  
 $b$  = Width of beam  
 $\beta$  = Angle of inclination of potential diagonal crack with the horizontal (unless otherwise stated)  
 $c$  = Cohesion of concrete  
 $C$  = Co-efficient of variation in percent  
 $D$  = Overall depth of beam  
 $d$  = Effective depth of beam  
 $E$  = Modulus of elasticity of steel  
 $E_c$  = Modulus of elasticity of concrete  
 $\sigma_x$  = Normal stress in the direction of length of beam  
 $\sigma_y$  = Stress in the direction perpendicular to the length of the beam  
 $f'_c$  = Compressive strength of standard cylinder specimen  
 $f'_{sp}$  = Split cylinder strenth of concrete  
 $f_t$  = Tensile stress in concrete  
 $f_y$  = Yield stress of flexural steel  
 $f_{hy}$  = Yield stress of horizontal web steel  
 $f_{vy}$  = Yield stress of horizontal web steel

## NOTATIONS

- $G$  = Shear modulus of concrete
- $I$  = Moment of inertia of concrete section
- $K$  = Splitting coefficient
- $L$  = Effective span of beam
- $M_{cr}$  = Moment developed at the critical section of the beam at the initiation of diagonal crack
- $M_u$  = Maximum moment developed in the beam at failure
- $M_{uf}$  = Flexural capacity of the beam
- $n$  = Modular ratio =  $E_s/E_c$
- $p_f$  = Flexural steel ratio
- $p_h$  = Horizontal web steel ratio
- $p_v$  = Vertical web steel ratio
- $p_a$  = Measured load at the initiation of arch-action
- $p_{cr}$  = Measured load corresponding to diagonal cracking
- $p_f$  = Measured load corresponding to flexural cracking
- $p_u$  = Measured ultimate load of beam
- $Q_u$  = Resisting shear force after Singh, Ray, and Reddy
- $s$  = Spacing of vertical web steel
- $s_2$  = Spacing of horizontal web steel
- $V_c$  = Contribution of concrete on ultimate shear
- $V_{cr}$  = Nominal shear force at the critical section at the initial diagonal cracking

## NOTATIONS

- $v_{cr}$  = Critical shear stress at the initial diagonal cracking
- $V_u$  = Ultimate shear force at the section of  $M_u$
- $v_u$  = Ultimate shear stress
- $\phi_h, \theta_h$  = Multiplying factor for contribution of total (flexural plus web) horizontal steel on ultimate load
- $\phi_y, \theta_y$  = Multiplying factor for contribution of vertical web steel on ultimate load
- $\tau_1, \mu_s, \mu$  = Empirical constants
- $w$  = Applied load per unit length upon the beam
- $\delta$  = Total deflection at mid-span of beam
- $\delta_m$  = Deflection of beam at mid-span due to bending only



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## CHAPTER 1

### INTRODUCTION

#### 1.1 GENERAL

The use of concrete as a construction material is increasing with the advancement of the modern civilization. Coarse aggregate and sand constitute the major bulk of concrete volume. And almost everywhere throughout the world, gravel and crushed stone are widely used as coarse aggregate in concrete construction. But in places where gravel and crushed stone aggregates are not abundant, some other substitutes have to be used as coarse aggregate. Besides, other considerations like those of reduced self weight or better insulation, damping characteristics etc. sometimes may encourage the use of artificial aggregates. In Bangladesh, the nonavailability of crushed stone aggregates is the prime cause for the use of crushed brick aggregates (locally known as *khoa*) in concrete construction.

A thorough understanding of the basic properties of brick aggregate concrete and the behaviour of brick aggregate reinforced concrete elements and structures are essential for a complete and judicious use of the existing building codes and design procedures commonly followed in Bangladesh. The inherent heterogeneity of concrete calls for an extensive research in this area to have an insight into the fundamentals of reinforced brick aggregate concrete members. But only a few studies on shear strength of brick aggregate concrete have so far been reported,<sup>(1,2)</sup> As such, the design and construction of structures made of brick aggregate concrete in Bangladesh are still carried out using foreign codes and specifications. These codes, however, are based on concrete made with gravel or structural light weight concrete.

It has already been established that the constituent materials of concrete have a significant influence on its basic properties. Indiscriminate use of such codes for brick aggregate concrete members is perhaps not justified. Therefore, it is absolutely necessary to have a systematic and well co-ordinated study on the various fundamental properties of structural concrete made with brick aggregates. The studies should aim at formulation of a code of practice for such concrete or to depict the deviations and similarity of such concrete structures with those made of crushed stone concrete.

Some concrete members have depth much greater than normal in relation to their span, while the thickness in the perpendicular direction is much smaller than either span or depth. The main loads and reactions act in the plane of the member, and a state of plane stress in the concrete is approximated. Members of this type are called deep beams. They can be defined as beams having a ratio of span to depth of about 5 or less, or having a shear span less than about twice the depth and which are loaded at the top or compression face only<sup>(3)</sup>.

According to CEB<sup>(4)</sup>, when span to depth ratio of simply supported beams is less than 2, or less than 2.5 for any span of a continuous beam, it is customary to define these beams as deep beams.



Deep beam structures are encountered in transfer girders, foundation walls, parapet walls, raft beams, walls of rectangular tanks and bins, hoppers, floor diaphragms and shear walls, as well as in folded plate roof structures. The behavior of a deep beam is significantly different from that of a beam of more normal proportions, requiring special consideration in analysis, design and detailing of reinforcements.

## **1.2 NEED FOR STUDY**

Cement concrete is one of the seemingly simple but actually complex material. Many of its complex behaviors are yet to be identified to employ this material advantageously and economically. ASCE-ACI shear committee report <sup>(5)</sup> gave a selective list of about 200 recent papers on shear which indicates clearly the intensive research effort in this regard during the last two decades. Yet, the progress in the understanding and quantitative assessment of the behavior of members subjected to flexure and shear has been less spectacular. This has been acknowledged by the ACI-ASCE Committee 426<sup>(6)</sup> in their concluding remarks as, "It has been emphasized that the design procedures proposed are empirical because the fundamental nature of shear and diagonal tension strength is not yet clearly understood. Further basic research should be encouraged to determine the mechanism which results in shear failures of reinforced concrete members."

There are quite a good number of research papers on the stresses and behaviors of stone aggregate reinforced concrete deep beams. On the other hand, only a limited study has been directed to understand the stresses and nature of such beams when made of brick aggregate concrete. Brick aggregate concrete is widely used in Bangladesh and it is generally felt that studies are needed to understand the behavior of structural members including deep beams made of such concrete both in working and ultimate load level. Attempts should be made to correlate their behavior with those made from stone aggregate concrete.

No accurate theory exists for predicting ultimate shear strength of deep reinforced concrete beams. The greater number of parameters affecting beam strength has led to a limited understanding of shear failure. These parameters include the proportions and shape of the beam, loading and support conditions, amount and arrangement of tensile, compressive and web reinforcements as well as the concrete and steel properties.

In Bangladesh, only a few series of test have been carried out so far to investigate the important properties of brick aggregate concrete deep beams. All the variables mentioned earlier can not be included in a single test program. Therefore it is instructive to study systematically the effect of a few variables at a time on the ultimate strength of deep reinforced concrete members made with brick aggregate concrete.

## **1.3 OBJECTIVE OF THE STUDY**

The basic objective of this research work is to investigate the shear strength and behavior of brick aggregate reinforced concrete deep beams by varying the span to depth ratio and the horizontal



and vertical web reinforcement. The results of this investigation may help to check the maximum limit of span to depth ratio over which a deep beam will act as a shallow one.

The main objectives of this research work on brick aggregate reinforced concrete deep beams subjected to single concentrated load are as follows:

To compare the shear strength capacity of a deep beam of L/D ratio 1 to 5.

To investigate the shear strength of deep beams by increasing both vertical and horizontal reinforcements more than that recommended by ACI Building Code (ACI 318-89).

To investigate the effect of L/D ratio on the vertical web reinforcement.

To investigate the influence of variation of web reinforcement spacing (both vertical and horizontal) on the shear strength of deep reinforced concrete beams.

To investigate the change point after which a deep beam will act as a shallow one.

To investigate the load deflection characteristics, initiation and subsequent propagation of crack patterns and the mode of failure of deep reinforced concrete beams.

#### **1.4 SCOPE AND LIMITATIONS OF THE STUDY**

In this study the amount of flexural & horizontal shear reinforcements, and the span to depth ratio (L/D) were varied and these are the two among the large number of variables affecting deep beam strength. The maximum span length (60") and maximum depth (21") of test beams were provided considering the dimension of the anvil and the vertical space for loading respectively of the universal testing machine used. To make the test beam simply supported, one of its end was rested upon roller support while the other end-support (considered as hinge) was a 3" wide, 1" thick steel plate covering the width of beam. This is not an ideal hinge mechanism. But considering practical situations, it is believed that the width of support would provide little resistance to resistance at this end.

## CHAPTER 2

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### REVIEW OF LITERATURE

#### 2.1 GENERAL

The literature review on deep beam analysis reveals that significant attempts have been made to investigate the behavior and strength of deep reinforced concrete beams in shear. Most of these efforts, however, concerns deep beams having stone as coarse aggregates and only a limited number of study were performed on deep beams having crushed brick as coarse aggregates. During these effort some followed uniform loading some concentrated loading and some with two point concentrated loading.

#### 2.2 DEEP BEAMS WITH BRICK AGGREGATE CONCRETE

Three studies concerning the behaviors of deep beams made of brick aggregate concrete were performed in Bangladesh. All of the beams of these researches were single span and simply supported. The study done by Kabir<sup>(7)</sup> was with the beams subjected to mid-span concentrated load, Ali<sup>(8)</sup> was related to the deep beams under uniformly distributed load and that of Rashid<sup>(10)</sup> with the beams subjected to uniformly distributed load. The aforesaid studies and the findings are described below.

##### 2.2.1 Brief Descriptions of Tests

In 1982, Kabir reported the results of investigations on the shear strength of deep reinforced concrete simply supported beams with crushed brick as coarse aggregate. This study consists of two sets of beams, five in each set were investigated. One set with span to depth ( $L/D$ ) ratio = 1 and the other was of ( $L/D$ ) ratio = 2. The applied load was a midpoint concentrated load in all the 10 cases. In each set of beams, only the amount and arrangement of web reinforcements (both vertical and horizontal) were varied.

In 1985, Ali reported the results of investigations on ten brick aggregate reinforced concrete deep beams having span to depth ratio of 1 and 2. The applied load was a uniformly distributed load for all the beams. In all of the beams flexural reinforcements were kept same but the amount of web reinforcements were varied.

In 1993 Rashid reported the results of investigation on fourteen brick aggregate reinforced concrete deep beams. In this study he investigated the effect of flexural and horizontal shear reinforcements on the strength of such beams. The test beams were single span and simply supported type. The beams were divided into two series according to their span to depth ratio ( $L/D = 1$  and  $2$ ). The first beam of each series was designed and detailed as per the recommendations of ACI Building Code (ACI 318-89). In the other six beams of each series, the amount of either the flexural or the horizontal web reinforcement or both were varied in relation to those of first beam of the corresponding series.

### **2.2.2 Findings of the studies**

From the test results all Kabir, Ali and Rashid made some remarks and then gave some suggestions on some specific properties of deep reinforced brick aggregate concrete beams. All these three investigations were carried out only for L/D ratio 1 to 2 and their findings and suggestions were not verified by further study till now. These findings are as follows:

#### **2.2.2.1 Cracking strength of deep beams**

In his study Kabir found that the different web reinforcement arrangements had no appreciable effect on the formation of initial diagonal crack in a deep beam under mid-span concentrated load. The observed diagonal cracks were usually the first cracks in the clear shear span of a deep beam, on some occasions they were simultaneously accompanied by flexural cracks. He also mentioned that the Diaz de Cossio <sup>(9)</sup> equation for predicting the nominal shear stress at initial diagonal cracking may be used fairly and reliably for deep beams under mid-span concentrated loading.

Ali reported that diagonal cracks develop first in relatively deeper beams (L/D=1) and flexural cracks develop first in the shallower deep beams (L/D=2) subjected to uniformly distributed load. He also commented that the ACI 318-89 Code <sup>(11)</sup> underestimated the diagonal cracking shear stress. However, the upper limit of shear stress causing diagonal crack set by ACI 318-89 Code was in conformity with his test results. He said that the Diaz de Cossio equation was unconservative for calculating diagonal shear stress for deep beams having lower span to depth ratio.

Rashid reported that the amount of both the flexural and the horizontal web reinforcements influenced to some extent the diagonal cracking load and the ultimate load capacity of test beams. It was also found that the change in the amount of either the flexural or the horizontal web reinforcement alone could not bring about a significant change in the load carrying capacity of test beams.

#### **2.2.2.2 Ultimate strength of deep beams:**

Kabir reported that the difference in web steel spacings and no significant influence over the ultimate shear strength of deep beams and percentage of flexural reinforcement had some positive bearing upon the nominal stress at failure. He presented that the ACI 318-77 Code provisions for determination of ultimate shear strength was conservative and he suggested that the limit of  $\sqrt{f'_c}$  for maximum shear stress as suggested in the Code might be raised to  $(10\sqrt{f'_c})$ . He also said that the Singh, Ray and Reddy <sup>(12)</sup> method of computing ultimate shear of deep beams could be used effectively providing the contribution of dowel force be limited to one-fourth of the total tension force developed in the flexural steel at yielding. He suggested to raise the splitting coefficient 'K' of Ramakrishnan and Ananthanarayana's <sup>(13)</sup> formula for a better prediction of ultimate load of deep R.C. brick aggregate concrete beams.

Ali published that the upper limit of  $8\sqrt{f'_c}$  for the ultimate shear stress suggested by ACI 318-77 Code was a fairly conservative estimate for brick aggregate concrete deep beams and the upper limit of  $6\sqrt{f'_c}$  for the contribution of concrete in ultimate shear stress was also conservative for deep beams subjected to uniformly distributed load.

Rashid published that the upper limit of the ultimate shear stress of simply supported brick aggregate RC deep beam subjected to uniformly distributed load may be taken as  $8.5\sqrt{f'_c}$  and  $11\sqrt{f'_c}$  for beams of span to depth ratio of 1 and 2 respectively.

### **2.2.2.3 Moment characteristics of beams**

In his report Kabir mentioned that the maximum moment at mid-span was about 50% of the ultimate flexural capacity of the test beams when the diagonal cracks first appeared.

### **2.2.2.4 Deflection of beams**

In his report Ali stated that the deflections of beams with span to depth ratio of 2 was fairly and accurately predicted by the ordinary shallow beam formula using uncracked section. For the lower values of span to depth ratio ( $L/D=1$ ) this formula grossly underestimated the actual deflections of beams. It was also mentioned that the ordinary shallow beam theory using cracked sections predicted the deflections of all the test beams fairly accurate.

### **2.2.2.5 Stresses in reinforcements**

Ali published that ordinary shallow beam theory as well as Holmes and Meson's<sup>(14)</sup> approach predicted the stresses in vertical and horizontal web reinforcements properly. Also steel stresses in flexural steel was predicted fairly accurate by the ordinary shallow beam theory using cracked section only when the load level is close to the ultimate load capacity of the deep beam.

### **2.2.2.6 Cracking pattern and mode of failure**

Rashid observed that the diagonal cracks develop first in relatively deeper beams ( $L/D = 1$ ) and flexural cracks develop first in the shallower beams ( $L/D=2$ ) provided the beams have sufficient reinforcements.

For deep beams under mid-span concentrated load Kabir stated that the principal mode of failure in the beams having adequate web steel was the diagonal tension cracking and the concrete 'strut' between two parallel diagonal cracks might sometime be formed but in general, the failure of a deep beam was not due to the compression failure by crushing of such a 'strut'.

But in Ali's study shear compression failure was found in relatively shallower deep beams ( $L/D=2$ ) whereas in the deeper beams ( $L/D=1$ ) diagonal tension failure was predominant.



## **2.3. STRENGTH AND BEHAVIOR OF STONE AGGREGATE R C DEEP BEAMS**

The behavior and strength of deep flexural members exhibit certain differences in failure mechanism and this has drawn attention of some researchers in this field. The length to total depth ratio ( $L/D$ ) of a member is used as an index of its deepness. Flexural members having  $L$  to  $D$  ratio below 2 are usually considered deep and  $L$  to  $D$  ratio between 2 and 8 are considered moderately deep members<sup>(2)</sup>. The behaviors of deep beams under different types of loading as were found by some researchers are stated below.

### **2.3.1 Study of De Paiva and Siess<sup>(15)</sup>**

In 1965, de Paiva and Siess reported the results of tests on 19 simply supported deep beams. They asserted that there is a gradual transition from shallow beam behavior to deep beam behavior. The transition range appears to be span-depth ratio between 2 to 6. The major variables involved in the study were the amount of tension reinforcement, the concrete strength, the amount of web reinforcement, and the span-depth ratio. In all the beams reported, well developed inclined cracks were observed at failure and the beams behaved essentially as tied arch. They have designated the failure of "tied arch" as a flexure failure either by crushing of concrete rib at the "crown" or by rupture of the tension bar. Such type of failure was usually accompanied by large inelastic deformation. For the beams that failed in shear, a second inclined crack was formed, which extended from the load point to the support outside the first inclined crack giving the beam a strut like appearance. The failure of this strut in compression was accompanied by the shearing of the unloaded part of the beam outside load block and unbonding of the tension steel over the support. Some of the test beams failed in a manner identical to that described for shear failure but had undergone extensive deformation like flexural failure before its final collapse. Such failures are described as flexure-shear by the authors.

During their investigation de Paiva and Siess observed that concrete strength had a negligible effect on the flexural capacity of the beams but can have significant influence on modes of failure of beams failing in shear. Some of their test beams changed from flexure-shear mode of failure to flexure as concrete strength was increased. Increasing the percentage of tension steel increased the moment capacity of beams and tended to change the mode of failure from flexure to shear. In their concluding remarks they have said "The addition of vertical and inclined stirrups have no effect on the formation of inclined cracks and seemed to have little effect on the ultimate strength of beams failing in either flexure or shear".

### **2.3.2 Study of Fritz Leonhardt<sup>(16)</sup>**

Fritz Leonhardt in the paper titled 'Strength and Behavior of Deep Beam in Shear' stated the followings:-

- (i) The principal stress trajectories of a deep beam with  $L/D=1$  indicate that a distribution of horizontal tie bars over approximately  $1/5$  to  $1/10$  of the depth will be helpful against the propagation of inclined cracks.
- (ii) For deep beams with  $L/D < 2$ , one should not speak of shear reinforcement. Such beam always fails because the concrete crushes near the bearing where the principal compression stress become critical and give the upper limit of carrying capacity, if the tie bars are well anchored and distributed.

### **2.3.3 Study of Ramakrishnan and Ananthanarayana<sup>(17)</sup>**

In 1968 Ramakrishnan and Anathanarayana reported the results of the investigations on 26 single span rectangular deep beams. Depth/span ratio and type of loading were the main variables considered. Effect of both single concentrated load and uniformly distributed load were investigated.

On the basis of the results of the investigation, they have put forward certain conclusions, some of which are given.

- (i) The mode of shear failure in deep beams are nearly the same as those in shallow beams under lower shear span/depth ratio ( $a/D < 2$ ).
- (ii) The shear failure in deep beam is always initiated by splitting action of concrete.
- (iii) The ultimate shear strength of deep beams failing by diagonal tension mode can be reasonably well predicted using split cylinder strength as an index.

### **2.3.4. Study of Kong et al<sup>(18)</sup>**

F.K. Kong et al investigated the effects of various types of web reinforcement on ultimate and cracking strengths, crack widths, crack spacing and deflections. 35 simply supported deep beams of span/depth ratio ranging from 1 to 3 clear shear span/depth ratio,  $x/D$  from 0.23 to 0.7 with seven different types of web reinforcement were tested. The loads applied were two point loading applied at top. Some of the conclusions in the study are:

- (i) For control of deflections and crack widths the preferred arrangement of web reinforcement depends very much on the  $L/D$  and  $x/D$  ratios, only horizontal web reinforcement placed near the bottom at a fairly close spacing is effective. Where  $L/D$  is higher than 1.5 and  $x/D$  higher than 0.35 vertical stirrups can be used and where  $L/D$  is 3 and  $x/D$  is 0.7, vertical stirrups are preferable to others.

- (ii) In general, the primary cause of failure was diagonal cracking. Crushing of concrete at the bearing blocks was usually only a secondary effect, and failure in compression of the concrete 'strut' between diagonal cracks occurred a few times only.

### **2.3.5 Study of Manual and Sutter<sup>(40)</sup>**

Manual and Sutter summarized the results of an investigation on 12 reinforced concrete deep beams in which the variables  $a/D$  (shear span/depth) and  $L/D$  (span/depth) were systematically varied and other major variables were kept constant. The effects of changes in  $a/D$  and  $L/D$  on failure, diagonal cracking, maximum crack width and midspan deflections were summarized. The following conclusions were drawn:

- (i) The ultimate strength of reinforced concrete deep beams appears to be influenced significantly by  $a/D$ , and insignificantly by  $L/D$ . The influence of  $a/D$  relates to the mode of failure.
- (ii) While the diagonal cracking capacity of deep beams is not influenced significantly by there is an overall tendency for the diagonal cracking capacity to increase with an increase in  $a/D$  from 0.3 to 1.00.
- (iii) The extent of arch action for beams of constant shear at any load level is reduced as the length of beam increases. The effect of  $a/D$  on the extent of arch action at any load level was not apparent in the beams tested.
- (iv) Maximum flexural and diagonal crack widths were not influenced by  $a/D$  but appear to be reduced slightly by increase in  $L/D$  for a constant  $a/D$ .
- (v) Deflections are seriously underestimated even at working load levels if cracked section theory is used. To compute deflections accurately, it is necessary to consider the influence of diagonal cracking.

### **2.3.6 Study of Singh, Ray and Reddy<sup>(12)</sup>**

In 1980 Singh, Ray and Reddy developed a rational equation for the shear strength of deep reinforced concrete beams. The results of 11 reinforced concrete deep beams tested under four-point loading condition simulating approximately the distributed loading, were reported.

The proposed equation is based on the identity of the state of stresses in diagonal cracking mode of failure and rupture phenomenon in Mohr-Coulomb fracture criterion. It was assumed that the diagonal mode of failure, frequently encountered in problems involving deep beams was a state of failure akin to the rupture phenomenon in the Mohr-Coulomb failure criterion with straight line envelopes. Equilibrium equations involving cohesion  $c$ , and tangent of angle of internal friction  $\tan\phi$  of the Mohr diagram had been developed with normal and tangential forces acting on the ruptured inclined plane at failure of the beam.

In its simple final form the ultimate shear force at failure had been shown to be made up of contributions from three distinct shear resistance mechanisms. The first term represents the contribution of concrete, the second represents the contribution of tensile steel while the third represents the contribution of inclined web reinforcement to the ultimate shear strength of the beam. Certain modifying factors were proposed to account for the shear-span to depth ratio and other web opening parameters. Finally, using there proposed formula, the ultimate loads were computed for deep beams reported in the recent literature and a good correlation between the computed loads and the observed loads were shown.

### **2.3.7 Study of Smith and Vantsiotis <sup>(19)</sup>**

In the year 1982 Smith and Vantsiotis reported the results of tests on 52 deep reinforced concrete beams under symmetrically placed two equal point loads. The objectives of the investigation were to study the effect of vertical and horizontal web reinforcements and shear span to effective depth ratio ( $a/D$ ) on inclined cracking shear, ultimate shear strength mid-span deflection, tension reinforcement strain, and crack width.

They reported that cracking patterns were essentially the same for beams with or without web reinforcement. However, less damage at failure was observed in beams with web reinforcements. Presence of a minimum amount of vertical and horizontal reinforcement (0.18% and 0.23% respectively) as was found to considerably reduce crack widths and deflections after inclined cracking. Inclined cracking loads were considerably lower than ultimate loads for beams with or without web reinforcement. Test results show that inclined cracking loads vary between 40 and 50 percent of the ultimate loads.

They also concluded that the presence of vertical (ranging 0.18% to 1.25%) and horizontal (ranging 0.23% to 0.91%) web reinforcements had no effect on inclined cracking load. But the presence of vertical web steel increased ultimate shear strength of deep beams. However, the effectiveness of vertical stirrups seemed to diminish for beams with  $a/D < 1$ . Horizontal web steel appears to had little influence on the ultimate shear strength but its influence was more noticeable in beams with  $a/D < 1$ .

### **2.3.8 Study of Barry and Ainso <sup>(20)</sup>**

In 1983 J.E Barry and Heino Ainso in the paper titled "Single Span Deep Beams" used the multiple Fourier technique to compare the stress fields in single span deep beams due to uniform loading at the top edge and at the bottom edge. It was believed that the multiple Fourier method could be effectively used to handle the analysis of a single span deep beam. Nothing inherent in the method would prevent the extension of the analysis to cover deep beams with different load configurations or deep beams extending over two or three bays. They suggested that when the span to depth ratio ( $L/D$ ) was equal to 2, the bending stress distribution was reasonably well with that predicted by ordinary bending theory. This might be considered as limiting span to depth ratio so that ordinary bending theory might be used to obtain the bending stress distribution. However, the shear stress distribution near the interior face of the support would be significantly different than that predicted by ordinary bending theory at this span to depth ratio.



### **2.3.9 Study of Rogowsky, MacGregor, and Ong<sup>(21)</sup>**

In 1986 the tests on the behaviors of 7 simply supported and 17 two-span deep beams were reported by Rogowsky, MacGregor, and Ong. The behavior ranged from brittle for beams without vertical web reinforcement to ductile for beams with large amounts of vertical web reinforcements. They observed that the horizontal web reinforcement had no effect on the capacity.

They found that beams without stirrups or with minimum stirrups approached tied arch action at failure. This was true regardless of the amount of horizontal web reinforcement present. These failures were sudden with little or no plastic deformation. On the other hand beams with large amounts of stirrups failed in a ductile manner.

### **2.3.10 Study of Selvam and Kuruvilla<sup>(22)</sup>**

In 1987 Selvam and Kuruvilla tested 24 single span and simply supported deep beams with span to depth ratio (L/D) varying from 0.89 to 3.0 and subjected to two point loading. They studied the mode of failure and for computing the ultimate load capacity in shear, two equations were proposed.

They reported that the ultimate load carrying capacity of deep beam in the shear compression mode was very high. There was no sign of flexural distress in the crushing mode which was purely a localized one. Failure in crushing mode was found to occur at a load very much lower than the shear capacity of the beams.

### **2.3.11 Study of Mau and Hsu<sup>(23)</sup>**

In the year 1989, S. T. Mau and T. C. Hsu gave a rational formula for the shear strength of deep beams. Using the three equilibrium equations from the truss model theory, this explicit formula was derived. The constants in the formula were calibrated utilizing test data available in the literature.

The formula is dimensionless and contains four variables that express the horizontal and vertical reinforcement ratios, the concrete strength, and the shear span ratio.

The above mentioned formula has four nondimensionalized variables. It gives accurate predictions in the range where the horizontal shear steel ratio is less than 0.009, vertical shear steel ratio is less than 0.0245, and span to depth ratio is less than 3.3.

## **2.4 STRESSES IN STONE AGGREGATE R.C. DEEP BEAMS**

### **2.4.1 STUDY OF CHOW ET AL<sup>(24)</sup>**

In 1952 Chow et al studied the deep beam with finite difference method. The suggestions given in the study are:-

For shallower beams, the normal pressures on the longitudinal edges have little effect on stress distributions at sections a small distance from supports or concentrated loads. The stresses at these section depend only on the bending moment and shear force, and the values computed by ordinary beam formulas are accurate for practical purposes. The stresses in deep beams however, depend not only on the bending moment, but also on the variations of normal pressures along the loaded edges. The greater the height to span ratio, the more significant becomes the later factor. Thus, for deep beams in which the load is applied to the bottom edge, the stress distribution are quite different from those caused by the same loading applied at the top edge. In general, the ordinary beam formulas may be considered valid for computing stresses in beams whose height to span ratio is less than  $1/2$  and in which the sections under study are not too near to loads and reactions.

#### **2.4.2 STUDY OF E. Geer<sup>(25)</sup>**

E. Geer reported on an analytical study of deep beam using finite difference method. The variables were the width of the supports, the span/depth ratio, types of loadings etc. The findings could be summarized as:-

- (i) Compressive stresses in the top fiber increases as load is added near center of span but decreases when load is added in outer thirds of the top, tension is caused on the top fiber.
- (ii) In deeper beams, with load on the entire top, the maximum compressive stress occurs below mid height of beam.
- (iii) The greatest tensile stress is not at the mid span but is near the face of support. Maximum tensile stress is practically independent of the location of the load, even to the extent that load placed only directly over the supports causes maximum stress nearly the same amount as that caused by the same load placed on the central portion of the beam. The maximum intensity of stress in a deep beam depends on the amount of the reaction, not on the location of the load which caused it.

#### **2.4.3 STUDY OF Holmes and Meeson<sup>(26)</sup>**

M. Holmes and P. M. Meson reported on the study on 'Stress in Deep Beams'. The deep beams considered were simply supported.

An approximate polynomial stress function solution was first obtained which does not satisfy all the necessary boundary condition. Subsequently, a correction was superimposed into the first solution so that all the necessary boundary conditions were satisfied.

The conclusions of the study are:-

- (i) For a span/depth ratio greater than 1.25 the approximate solution (with ordinary shallow beam theory) gives stress values sufficiently accurate for most purposes.

- (ii) For span/depth ratio less than 1.25 a correction to be superimposed into the first approximate stress function to meet all the boundary conditions.
- (iii) Bending stresses are critical for  $L/D$  ratio greater than 0.7 whilst the shear stress (or diagonal tension/compression stress) is critical for span/depth ratio less than 0.7

## CHAPTER 3

### AVAILABLE THEORIES AND DESIGN METHODS

#### 3.1 GENERAL

The behavior of ordinary shallow beams under both service and ultimate load conditions are relatively more well understood as compared to deep beams. The stresses in a deep beam differ radically from stresses predicted by the ordinary theory of beam bending for shallow beams. Numerous text books on reinforced concrete design give theories for analysis and design of shallow beams. But, the provision of empirical methods of design for deep beams in the available code of practice is a relatively recent development. Some of the theories and design practices available in the literature are presented in this chapter.

#### 3.2 MECHANISM OF SHEAR RESISTANCE IN REINFORCED CONCRETE BEAM WITHOUT WEB REINFORCEMENT

##### 3.2.1 Formation of Diagonal Tension Cracks

It is well known that the flexure and shearing stresses combine to create a biaxial state of stress in a reinforced concrete beam. The principal stresses so generated may at one stage exceed the tensile strength of concrete. In the region of large bending moments principal tension are greatest at the extreme tensile fibres and are obviously responsible for the initiation of vertical flexural cracks. In the region of high shear forces, significant principal tensile stresses may be generated near the neutral plane at about 45 inclination with the beam axis. These may result in inclined cracks which are usually the extensions of flexural cracks.

With the formation of diagonal cracks not only the effective sectional properties of a beam change abruptly but also a total redistribution of stress takes place. This redistribution of stress may also be gradual as the initial vertical flexural cracks slowly extends beyond the flexural steel and turns to join the diagonal crack due to shear or a combination of shear and flexural stresses. After such a crack was extended a certain distance into the compression zone, a critical condition is reached when further crack propagation due to shear depends on the ability of the beam to resist the dowel force at the level of longitudinal bar <sup>(28)</sup>. The formation and further propagation of these cracks are possibly delayed by the action of the loads and support reactions acting directly on the beam. Their effect is the vertical compressive stress  $\sigma_y$  which in turn reduce the intensity of inclined principal tensile stress according to the following relationship:

$$\sigma_{1 \text{ or } 2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \quad \dots \dots \dots (3.1)$$

Since these  $\sigma_y$  may have a high value close to the supports or load points, it is conceivable to attribute the high shear strength for small values of  $a/d$  ratios to this favourable effect of local stress concentration <sup>(29)</sup>.

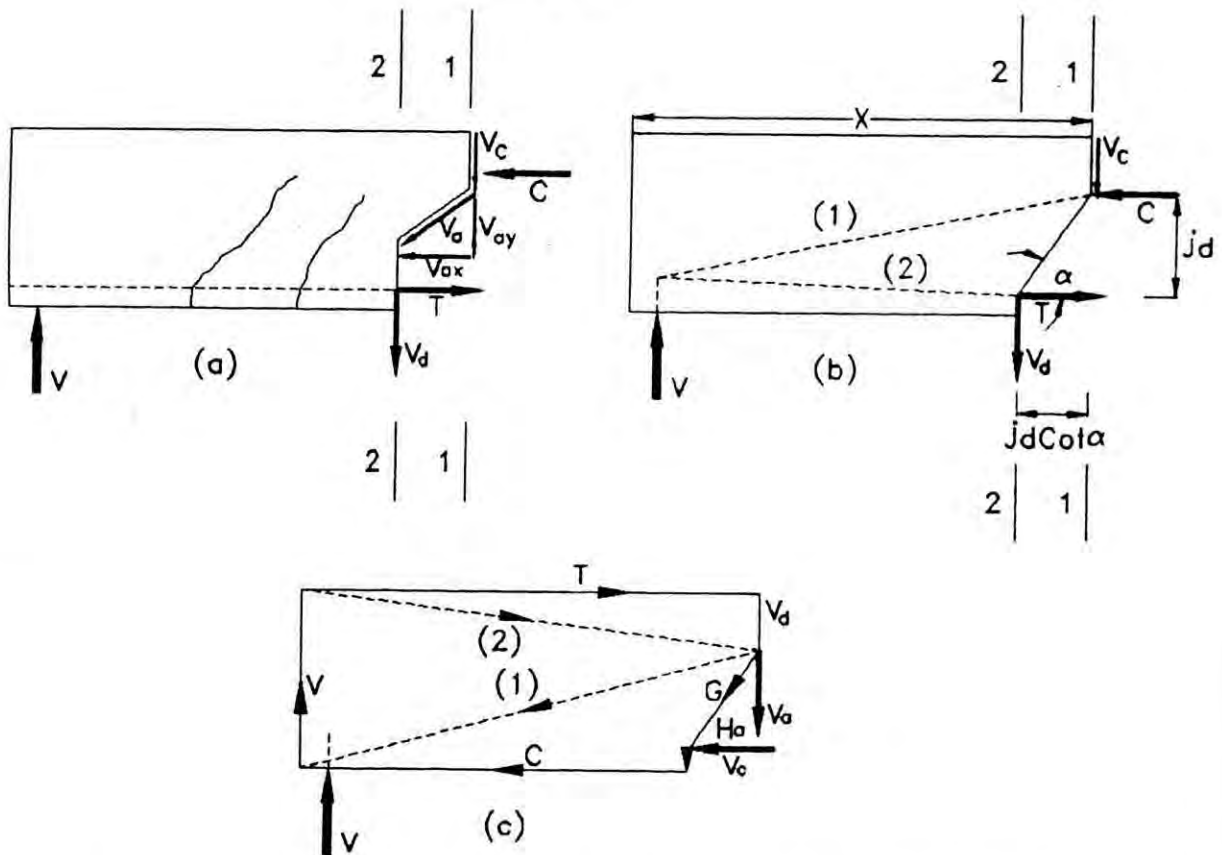


Fig. 3.1 EQUILIBRIUM REQUIREMENTS IN THE SHEAR SPAN OF A BEAM

### 3.2.2 Equilibrium in the Shear Span of a Beam

The internal and external forces that maintain equilibrium of the part of a beam with well developed inclined crack is shown in Fig. 3.1a. It is seen that the external transverse force  $V$  is resisted by a combination of (i) a shear force  $V_c$  across the compression zone (ii) a dowel force  $V_d$  carried by the flexural reinforcement and (iii) the vertical components of the inclined shearing stress  $V_a$  transmitted across the inclined crack by means of interlocking of the aggregate particles. For

simplification the inclined shear stresses may be lumped into a single force  $G$  whose line of action pass through two distinct points of the section in Fig. 3.1b and hence the force polygon in Fig. 3.1c, represents the equilibrium of the free body

This condition can also be stated as

$$V = V_c + V_a + V_d \quad \dots \dots \dots (3.2)$$

The moment of resistance is expressed by,

$$M = V \cdot x = jd (T + V_d \cot \alpha) \quad \dots \dots \dots (3.3)$$



If the contribution of dowel force towards flexural resistance is ignored, the moment of resistance simplifies to

$$M = T \cdot jd \quad \dots \quad (3.4)$$

It should be noted that the moment  $M$  in the above two equations and tension  $T$  occur at different two sections.

### 3.2.3 The Principal Mechanisms of Shear Resistance

The well known differential relation between shear and moment can be combined with Eq<sup>n</sup> 3.4 to give the following modes of internal resistance

$$V = \frac{dM}{dX} = \frac{d}{dX}(T \cdot jd) = jd \frac{dT}{dX} + T \cdot \frac{d(jd)}{dX} \quad \dots \quad (3.5)$$

The first term  $jd \frac{dT}{dX}$  expresses the behaviour of a true prismatic flexural member in which the internal tensile force  $T$  changes from point to point along the beam to balance the external moment intensity while the moment arm  $jd$  remains unchanged. The term  $\frac{dT}{dX}$ , the rate of change of internal tension is termed the bond force,  $q$  applied to the flexural steel per unit length of beam. On the assumption that the internal lever arm  $jd$  remains constant the Second term in Eq<sup>n</sup> 3.5,  $T \frac{d(jd)}{dX}$  becomes zero and the equation of perfect beam action is obtained.

$$V = jd \frac{dT}{dX} = q \cdot jd \quad \dots \quad (3.6)$$

It is obvious that such simplification of behaviour is possible only if the bond force or shear flow can be efficiently transmitted between the flexural reinforcement and the concrete surrounding it. But when the bond between steel and concrete is destroyed over the entire ; length of shear span, the tensile force  $T$  becomes constant through out and hence  $\frac{dT}{dX} = 0$ . Under such circumstances the external shear force can be resisted only by inclined internal compression and this extreme mechanism is termed "arch action". And so its shear resistance is expressed by the second term on the right hand side of Eq<sup>n</sup> 3.5,

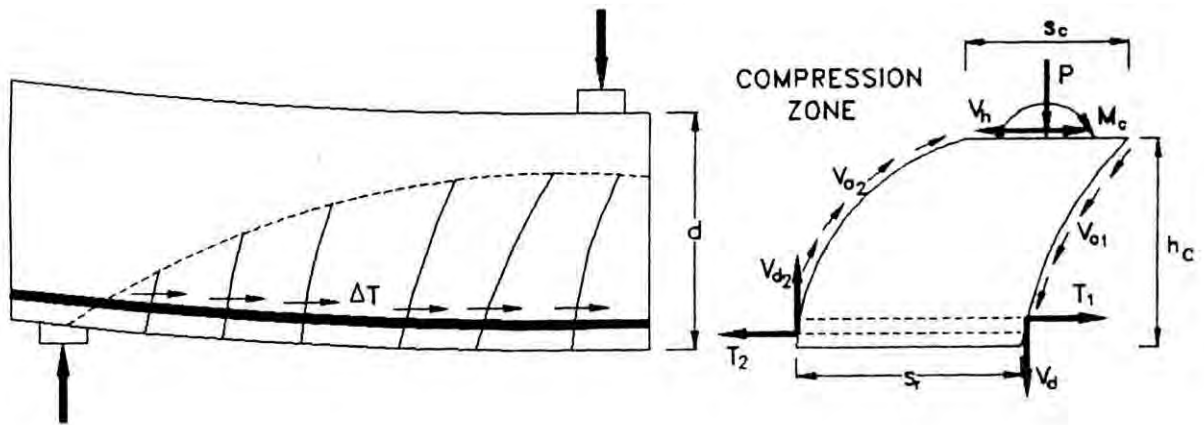
$$V = T \frac{d(jd)}{dX} = C' \frac{d(jd)}{dX} \quad \dots \quad (3.7)$$

The internal tension  $T$  is replaced by  $C'$  (horizontal component of internal arch compressive force) to indicate that vertical component of arch compression balances the external shear.

#### 3.2.3.1 Beam action

In its simple form, beam action of a flexural member is characterized by the presence of a prominent neutral surface and distinct compressive and tensile zone lying on either side of neutral surface. Stresses in the flexural reinforcement remain approximately proportional to and follow the distribution of external moments along the length of the beam.





**Fig. 3.2 ACTIONS ON A CONCRETE CANTILIVER**

Cracks induced by load on a simply supported beam divide the tension zone into a number of blocks resembling more or less the tooth of a comb. Each of these blocks may be considered to act as a cantilever with its base at the compression zone of the concrete (Fig. 3.2). The actions which a typical cantilever experiences is shown distinctively in Fig. 3.2. The components of the cantilever actions are described below:

- ii) The increase of the tensile force in the flexural reinforcement between adjacent cracks produces a bond force  $\Delta T = T_2 - T_1$ .
- ii) Provided a shear displacement has occurred at the two faces of a crack, shear stresses  $V_{a1}$  and  $V_{a2}$  are generated by means of aggregate interlocking.
- iii) Shear displacement may also result in dowel forces  $V_{d1}$  and  $V_{d2}$  across the flexural reinforcement.
- iv) In order to equilibrate the above mentioned forces, an axial force P, a transverse force  $V_h$  and a moment  $M_c$  may be generated at the "built-in" end of the cantilever.

Shear resistance is customarily referred to the shear strength of the compression zone of a beam, on the assumption that aggregate interlocking and dowel actions are not efficient means of shear resistance. But Taylor<sup>(30)</sup> has found that the shear carried in the compressive zone increased slowly to a maximum of 25 to 40% of the total shear force across the section as the beam approached failure. The remainder must therefore be carried below the neutral axis in the tension zone. After the breakdown of the aggregate interlock and the dowel mechanism, the compression zone is generally unable to carry the increased shear and the beam may fail.

### 3.2.3.2 Arch action

It has already been mentioned that the second term of eqn. 3.5 signifies that shear can be sustained by inclined compression in a beam and this is illustrated in Fig. 3.3.

Thus the failure of concrete cantilevers is not always accompanied by complete collapse and rather transforms the beam into a tied arch. This transformation is usually followed by the lowering of the thrust line in the shear span <sup>(31)</sup>

In a simply supported beam, the substantial horizontal reaction due to the development of arch action is provided by the tensile reinforcement. And this imposes heavy demands on the anchorages. In the idealized beam of Fig. 3.3, full anchorage is assumed so that constant tensile force can be developed in the bottom reinforcement.

In real beams, the transition from beam action to arch action is gradual and can be observed by measuring the strain changes in flexural steel at different locations and hence the variation in the internal lever arm. The full strength of arch and beam actions cannot be combined because of the gross incompatibility of deformations associated with the two mechanisms <sup>(32)</sup>.

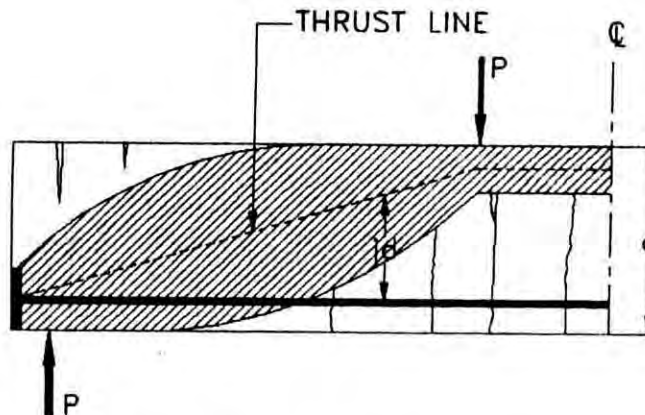


Fig. 3.3 ARCH ACTION IN SHEAR SPAN

### **3.3 MECHANISM OF SHEAR RESISTANCE IN REINFORCED CONCRETE BEAMS WITH WEB REINFORCEMENT**

#### **3.3.1. The Role of Web Reinforcement**

The inclusion of web reinforcement such as stirrups does not altogether change the fundamental mechanisms of shear resistance described earlier. The stirrups rather act as the tie bars for the concrete cantilevers. The web reinforcement comes into play their role of transmitting the shear force only after the cracks have developed in the concrete beams.

The bond force  $\Delta T$  as described earlier is resisted by the combined action of aggregate interlock, dowel and flexural action of the cantilevers. But now further bond force  $\Delta T$  can be sustained by a mechanism traditionally called "truss action". In this truss the concrete cantilevers act as the compression members.

The web reinforcement, adds strength to the shear mechanism by improving the contribution of dowel action, suppresses initial tensile stresses in concrete cantilevers by means of the diagonal compressive force, limits the crack openings and thereby preserves the shear transfer by aggregate interlock. In addition it carries the extra shear force  $V_s$  by truss mechanism.

### **3.4 INTERACTION OF FLEXURE AND SHEAR**

Normally it has been observed that shear force does not affect significantly the development of flexural capacity of reinforced concrete beams with adequate web reinforcement. But in the previous discussion it has been pointed out that after formation of a diagonal crack the internal tension in the flexural steel at a section is due to the external moments at some other section away from it. Thus an intimate relation does exist between flexure, shear bond and anchorage in the shear span of a beam. When large shear forces are to be transmitted across a section at the ultimate moment, the distribution of the flexural strains in concrete and steel can be affected.

In simply supported or continuous deep beams, where the external loads and reactions are applied to the top or bottom compression face of the beam, the mode of shear transfer after the formation of diagonal cracks is mainly arch action. Shear forces in such beams can be so dominant that they govern the strength of the member by inhibiting the development of full flexural capacity.

### **3.5 DEEP BEAMS**

Deep beams are flexural members of considerable depth compared to their span over which they are placed. Usually when the span/depth ratio of a simply supported beam is less than 2 or less than 2.5 for any span of a continuous beam, it is customary to define them as deep beams. The walls of rectangular suspended containers such as silos, water tanks and bunkers with pyramidal hoppers, the foundation walls supporting strip footings or raft slabs, the parapet walls and the shear walls are commonplace examples of deep beams.

### 3.5.1. Web Reinforcement in Deep Beams

Gravity load, introduced along the top edge of a wall beam is disposed of mainly by arch action. The critical path along which the diagonal tension cracks usually develop in deep beams are steep and almost parallel to the conventional vertical stirrups. This can be also expected from truss analogy applied to deep beams <sup>(33)</sup>. Fewer number of vertical stirrups are crossed by diagonal cracks in deep beams as the load will naturally chose to dispose itself through the stiffer of two possible resisting systems <sup>(32)</sup>. In deep beams the arch is always stiffer than the truss mechanism and normally stirrups are not necessary. A minimum reinforcement of 0.2% in the form not small diameter bars placed in both directions, as in reinforced concrete walls is adequate. Near the supports, however, additional bars of the same size used for mesh reinforcement should be introduced to alleviate the excessive compressive stress developed.

### 3.5.2 Stress Pattern In Deep Beams

The usual methods developed for stress analysis for shallow beams are neither suitable nor adequate to determine the strength of reinforced concrete deep beams. The stresses in isotropic homogeneous deep beams before cracking can be studied using the methods of two dimensional elasticity, photoelasticity, or finite element analysis. Such studies confirm that the usual hypothesis , " plane sections before bending remain plane after bending" does not hold good for deep beams. Significant warping of the cross Section occurs because of high shear stresses. Consequently, flexural stresses are not linearly distributed, even in the elastic range.

Deep beam is rather sensitive with respect to the loading at the boundaries. The length of the bearing surfaces of the beam in Fig. 3.4 would affect the principal stresses, which can be very critical in the immediate vicinity of these supports. Similarly, stiffening ribs , cross walls or extended columns at the supports would markedly influence the stress patterns. One of the most significant aspects of stress analysis would be the manner of application of the load, which is uniformly distributed in the case depicted in Fig. 3.4.

It was found that smaller the span/depth ratio (i.e. less than 2.5) the more pronounced the deviation of the stress pattern from that of Bernoulli and Navier. Fig. 3.4 shows the distribution of horizontal flexural stresses at the mid-span of simply supported beams having different span/depth (L/D) ratios, when carrying a uniformly distributed load of intensity  $w$  per unit length. The mid-span moment being  $wL^2/8$ , the usual extreme fiber stress at mid-span would be  $f_t = f_c = 6M/bD^2 = 0.075wL^2/bD^2$  and which becomes  $0.75w/b$  for a square panel beam i.e.  $L/D=1.0$

But Fig. 3.4 indicates that the tensile stresses at the bottom fiber are more than twice this intensity. Similar deviations occur in the distribution of shear stresses.

It is interesting to note that the internal lever arm is not greatly affected by span/depth ratio and the tension zone in the bottom is relatively small. The internal lever arm for very deep beams does not appear to increase greatly after cracking and for design purpose the following approximation for the internal lever arm  $z$  may be made <sup>(32)</sup>

$$\begin{array}{ll} Z = 0.2 (L + 2D) & \text{when } 1 \leq L/D \leq 2 \\ Z = 0.6 L & \text{when } L/D < 1 \end{array}$$

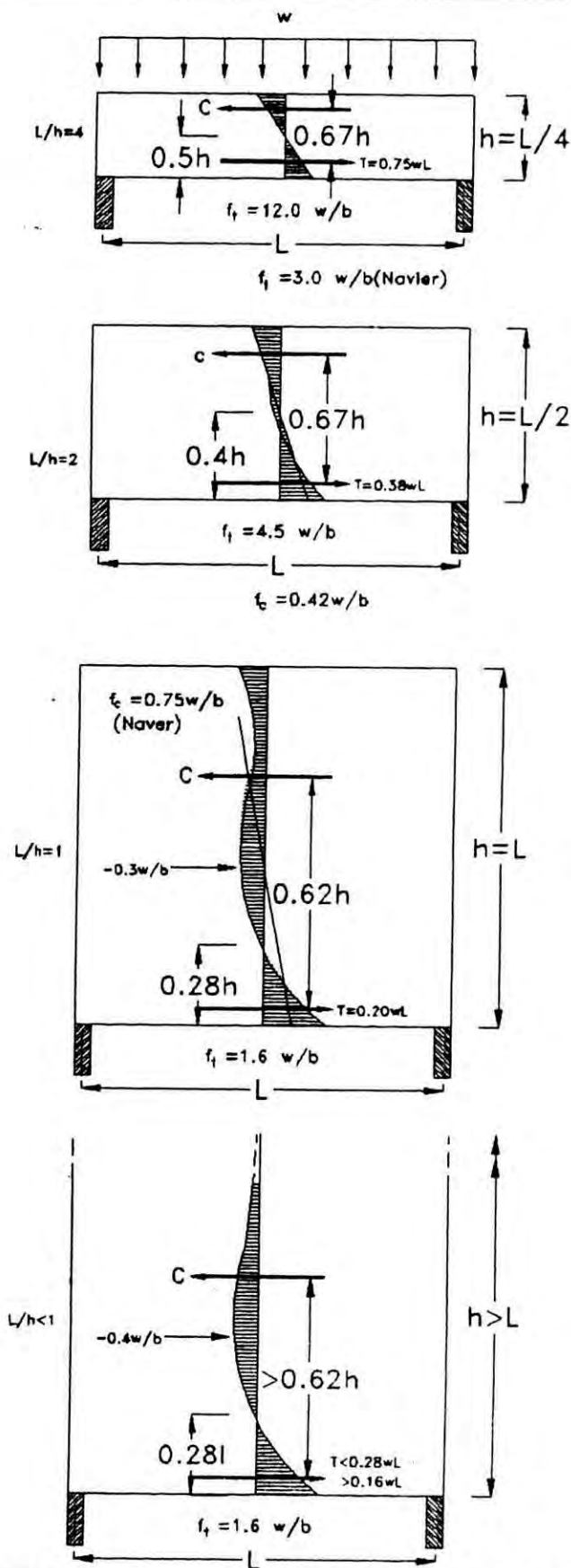


FIG-3.4 DISTRIBUTION OF FLEXURAL STRESSES IN HOMOGENEOUS SIMPLY SUPPORTED BEAMS



### **3.6 DISTRIBUTION OF STRESSES IN DEEP BEAMS (OTHER APPROACHES)**

#### **3.6.1 Heino Ainso and J. E. Barry's <sup>(20)</sup> Approach**

A multiple fourier technique was used to compare the stress fields in single span deep beams due to uniform loading at the top edge. The Method involves the superposition of three stress functions. The first stress function is used to satisfy the boundary conditions on the upper and lower edges of the beam. The second and third stress functions are used to satisfy the boundary conditions on the vertical edges of the beam. The deep beam they analyzed is shown in Fig. 3.5.

Letters a, b, c, h, p have the meanings exactly as shown in Fig. 3.5. Some of the findings are shown in Fig. 3.6 through Fig. 3.9

#### **3.6.2 Krishna Raju <sup>(34)</sup> Approach.**

Fig. 3.10 shows the flexural stress at mid-span of a simply supported single span deep beam subjected to uniformly distributed loads and for different ratios of  $\beta$  (a function of  $L/D$ ) having values of 0.5, 0.67 and 1.0 . As  $\beta$  increases from 0.5 to 1.0 the compressive stress decreases rapidly at the top and the neutral axis moves towards the soffit of the beam.

#### **3.6.3 Coke and Filon <sup>(35)</sup> Approach**

For the simply supported single span deep beam subjected to mid-span concentrated load, Coker and Filon presented the principal stress trajectories of the uncracked state of the beam. They used photoelasticity and their finding is shown in Fig. 3.11.

#### **3.6.4 Leonhardt <sup>(16)</sup> Approach**

The principal stress trajectories of single span and simply supported deep beam under uniformly distributed load were reported by Fritz Leonhardt which is presented here in Fig. 3.12.

### **3.7 ULTIMATE STRENGTH AND BEHAVIOR OF DEEP BEAMS.**

Because of the proportions of deep beams, they are likely to have strength controlled by shear. On the other hand, their shear strength is likely to be significantly greater than predicted by the usual equations for shallow beams. Internal forces are redistributed before failure and develop mechanisms of force transfer quite different from beams of common proportions. Special design methods are needed to account for these differences.

F. Leonhardt<sup>(16)</sup> presented that the usual type of shear reinforcement does not increase the strength of deep beams. A shear stress indicates only that the principal stresses are not parallel to the system of coordinates on which the bending analysis is based. The direction of such principal stresses are influenced by  $\sigma_x$  and  $\sigma_y$ . In shallow beams, the directions of the principal stresses at the depth of the neutral axis ( $\sigma_x = \sigma_y$ ) is  $5^\circ$  in deep beams this inclination is much smaller, mainly because of  $\sigma_y$ , the vertical component of stresses in Fig. 3.13. The necessary amount of shear



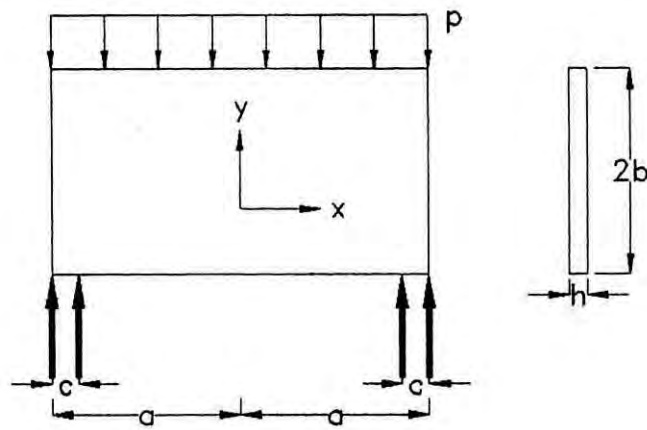


FIG-3.5 SINGLE SPAN DEEP BEAM SUBJECTED TO UNIFORMLY DISTRIBUTED LOAD<sup>(20)</sup>

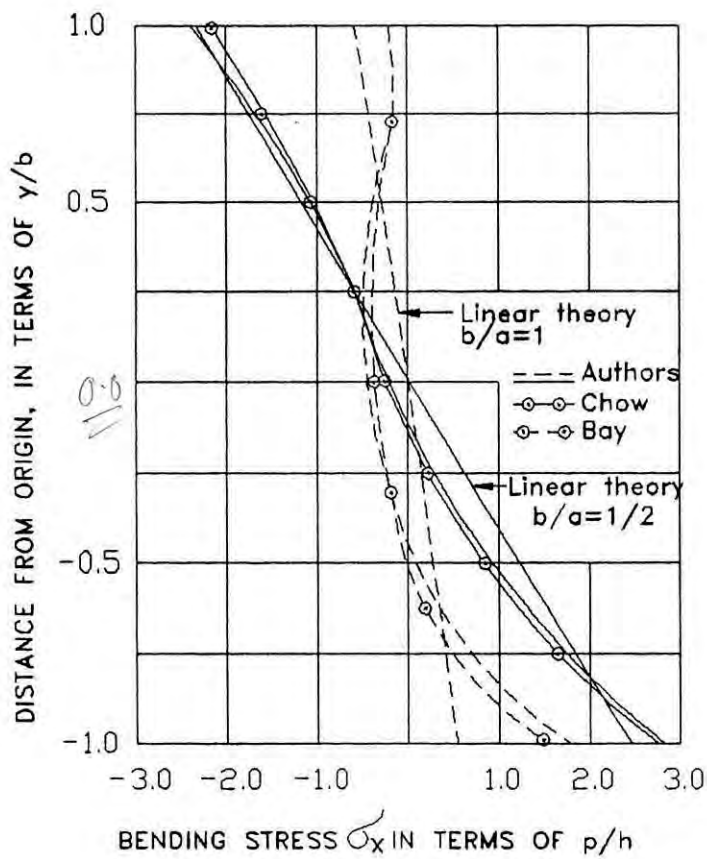


FIG-3.6 BENDING STRESS AT MIDSPAN<sup>(20)</sup>

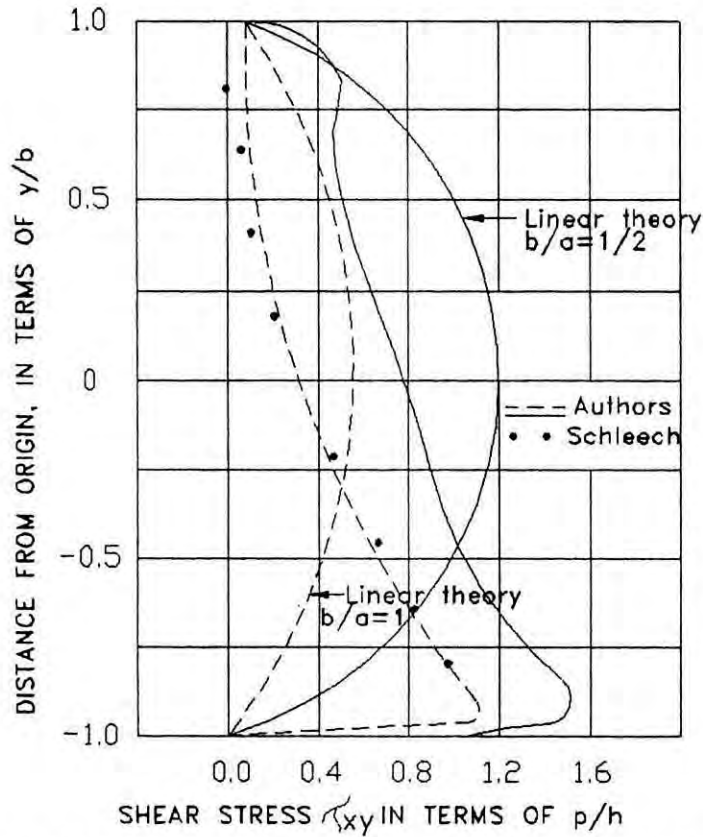


FIG-3.7 SHEAR STRESS AT  $x=4a/5$  (FACE OF SUPPORT) <sup>(20)</sup>

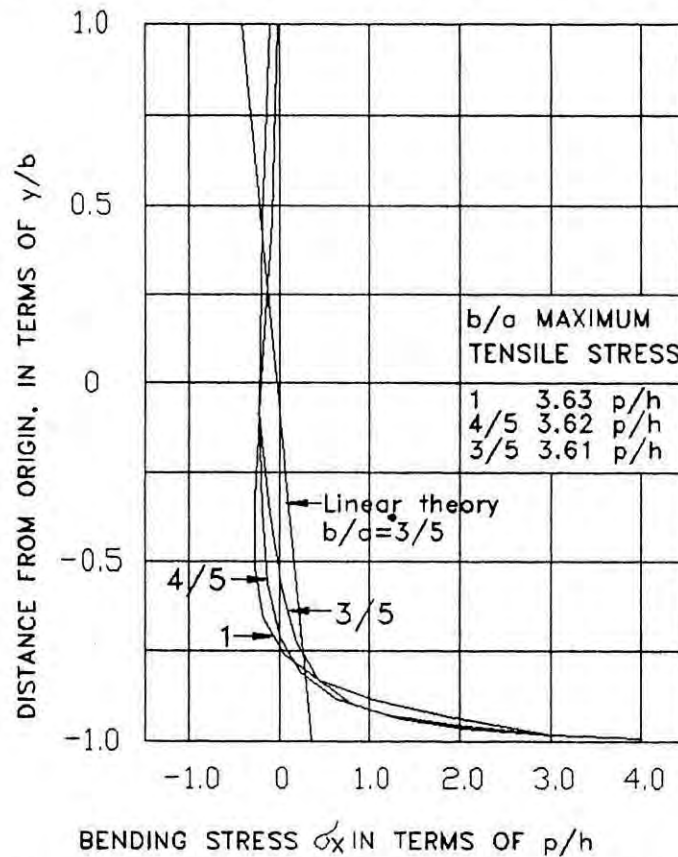


FIG-3.8 MAXIMUM BENDING STRESS AT  $x=0.77a$  <sup>(20)</sup>

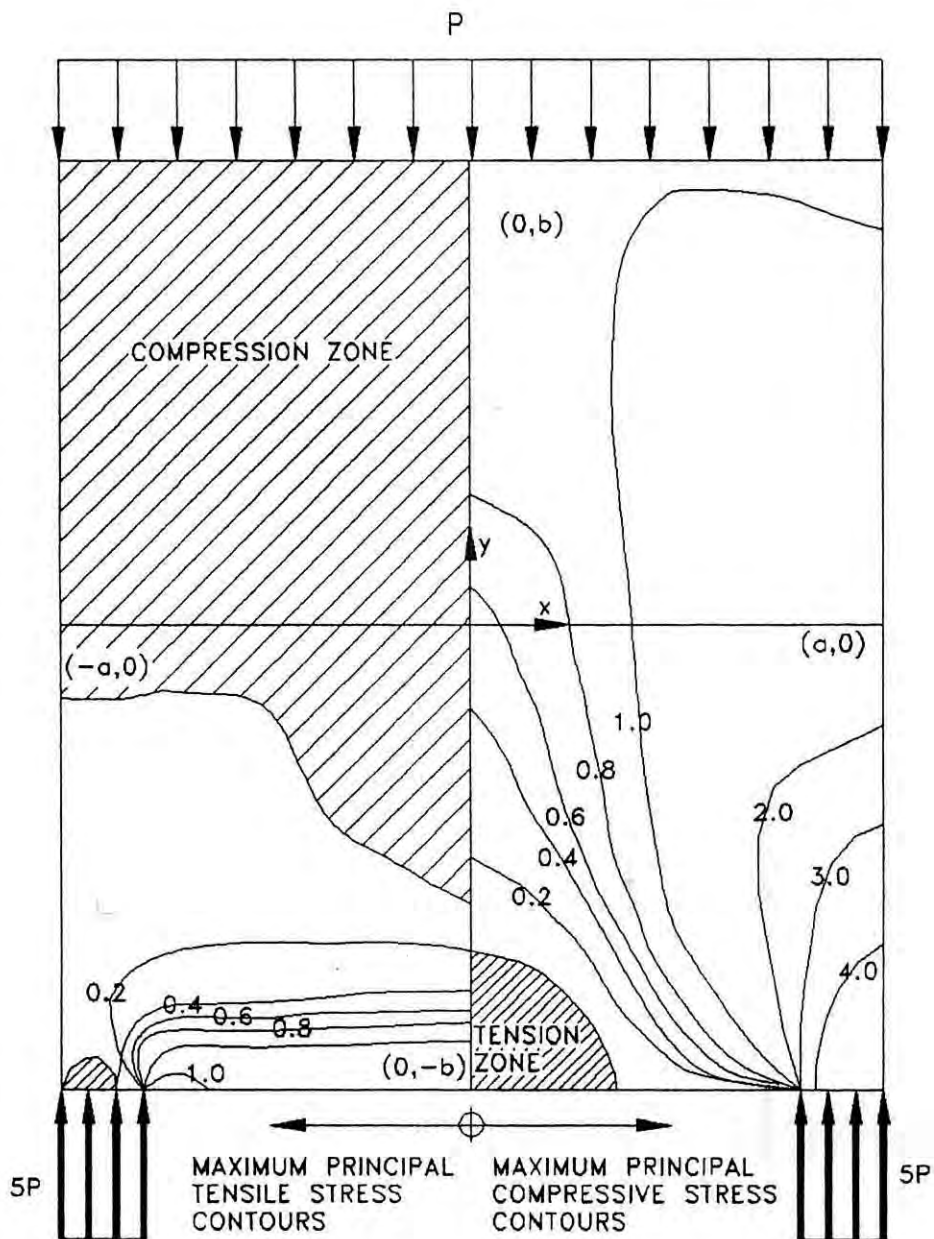


FIG-3.9 MAXIMUM PRINCIPAL STRESS CONTOURS IN TERMS OF  $p/h$  FOR TOP LOADED BEAMS<sup>(20)</sup>

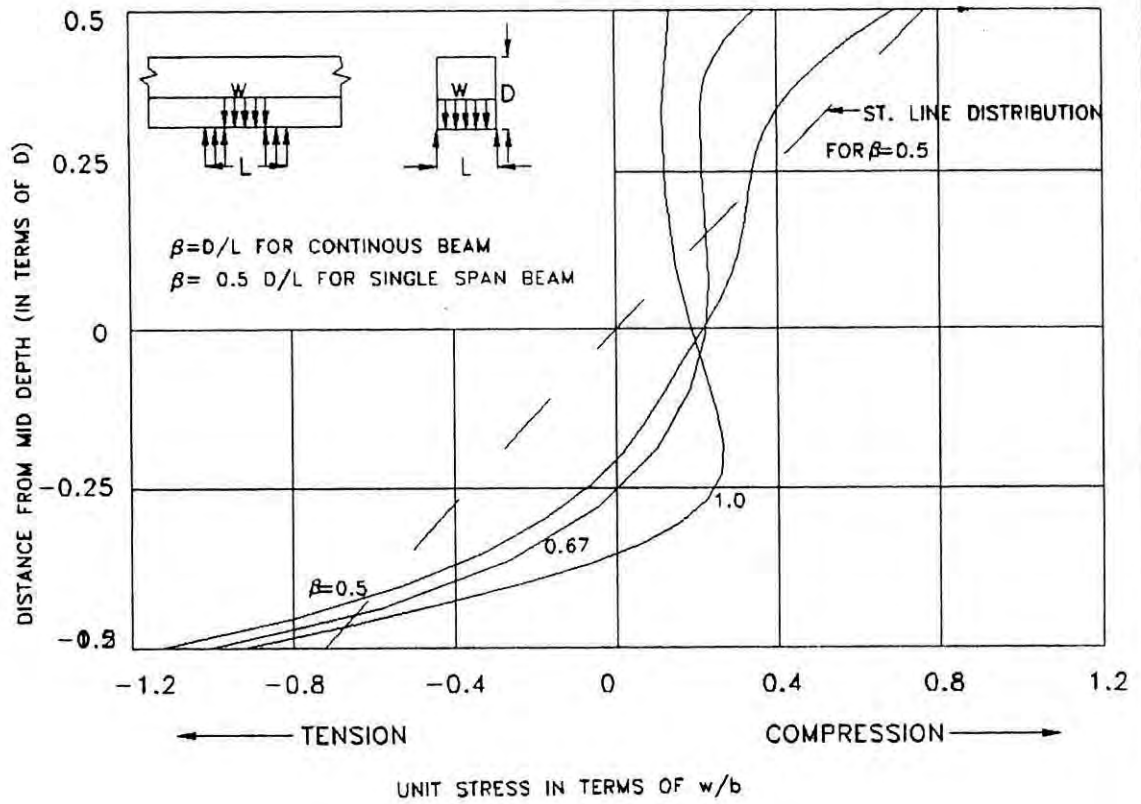


FIG. 3.10 FLEXURAL STRESSES IN SINGLY SUPPORTED SINGLE SPAN DEEP BEAM<sup>(34)</sup>

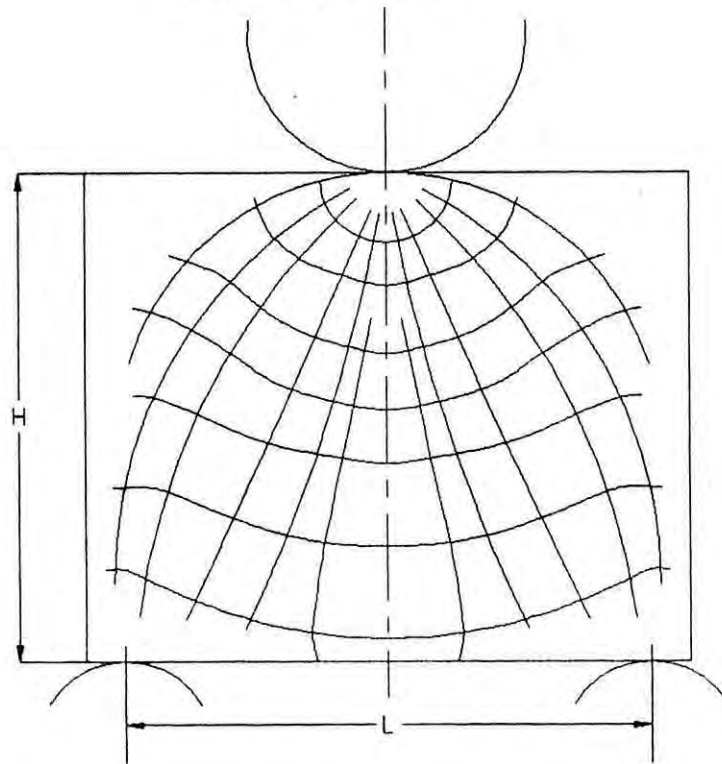


FIG-3.11 PRINCIPAL STRESS TRAJECTORIES OF THE UNCRACKED STATE OF DEEP BEAM UNDER CONCENTRETED LOAD<sup>(35)</sup>

reinforcement with vertical or inclined stirrups under  $45^\circ$  to  $60^\circ$  decreases, with decreasing inclination of the principal tensile stress.

If the truss analogy for the cracked state is considered, then the necessary amount of tension bars between the chord members decreases mainly by the inclination of the corresponding chord, which increases with decreasing slenderness ratio (Fig. 3.13). This inclination of the compression chord of the truss corresponds to the arching effect. The truss analogy helps to show that the usual shear reinforcement is practically useless in deep beams with  $L/D = 1.0$ ; the necessary quantity of shear reinforcement can be decreased proportionately to  $L/D$  as shown in Fig. 3.14 beginning with a span/ depth ratio  $L/D = 8.0$ .

The principal stress trajectories of a deep beam with  $L/D = 1.0$  (Fig. 3.13) indicates that a distribution of the horizontal tie bars over approximately  $1/5$  th to  $1/10$  th of the depth will be helpful against the propagation of inclined cracks.

### 3.7.1 Ultimate Shear Strength of Deep Beams

#### 3.7.1.1 ACI building code approach

Provisions for the assessment of the shear strength of deep beams were included for the first time in 1971 ACI building code. The recommendations are restricted to simply supported beams with a clear span to effective depth ratio of less than 5 and load applied to the top face and supports placed at the bottom face. The background of the design approach was outlined by Joint ACI-ASCE Task Committee 426 in 1973. It is postulated that the shear capacity of a member is obtained by superposition of the capacity of concrete and that of the web reinforcement. Recognition of the reserve shear capacity of a deep beam without web reinforcement led to the development of the semiempirical expression.

$$V_c = (3.5 - 2.5 \frac{M_u}{V_u d}) (1.9 \sqrt{f'_c} + 2500 P \frac{V_u d}{M_u}) b d \quad \dots \quad (3.8)$$

The second term gives the inclined cracking shear for normal beams and the first term represents the increase in the shear capacity over that causing cracking. The maximum value of the first term is limited to 2.5.

In the ACI approach, the derivation of web reinforcement's contribution towards shear resistance is based on the shear friction concept. It is assumed that when a steep diagonal crack is developed, shear displacement will occur. The component of the yield force, acting at right angles to the inclined crack will naturally supply the clamping force for the shear friction mechanism to operate. Accepting an apparent co-efficient of friction of 1.0 along the potential diagonal failure crack, the additional shear stress resisted by the web steel was developed as where the following limitations should apply.

$$V_s = V_u - V_c = \left[ \frac{A_v}{12S} \left( 1 + \frac{L_n}{d} \right) + \frac{A_{vh}}{12S_h} \left( 1 - \frac{L_n}{d} \right) \right] \frac{f_y}{b} \quad \dots \quad (3.9)$$

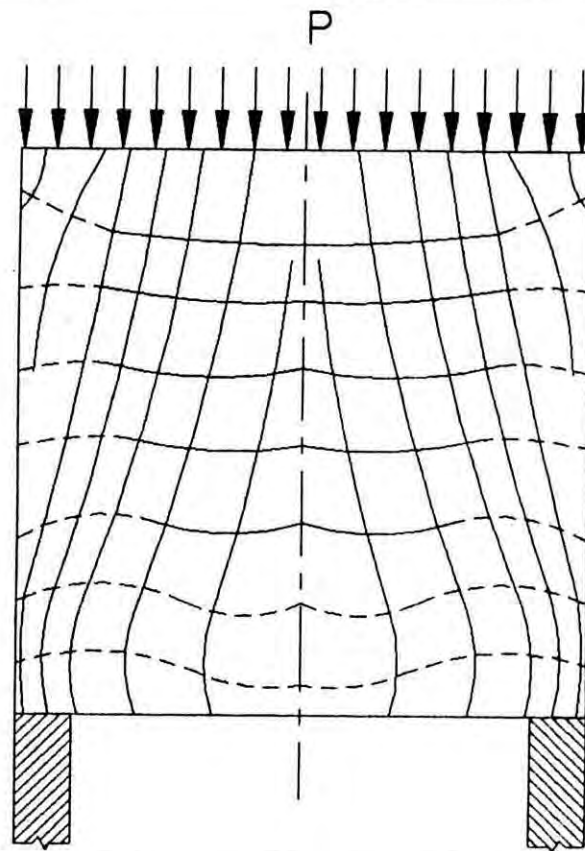
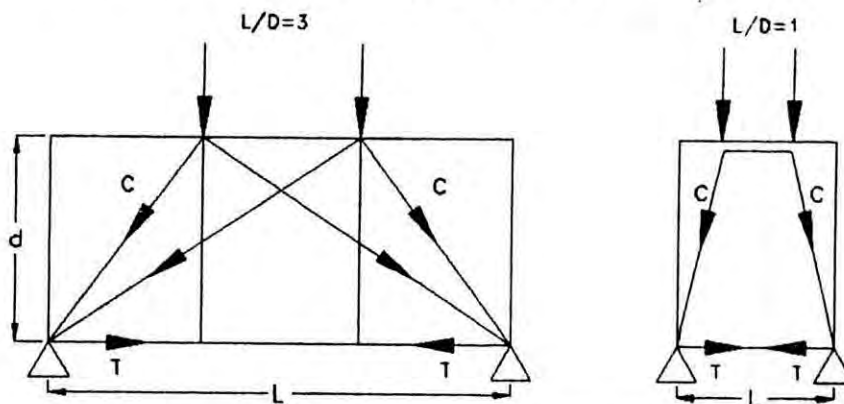


FIG. 3.12 PRINCIPAL STRESS TRAJECTORIES OF SINGLE SPAN DEEP BEAM UNDER UNIFORM LOADING <sup>(16)</sup>



C = COMPRESSION CHORD MEMBER

FIG-3.13 TRUSS ANALOGY FOR THE CRACKED STATE OF DEEP BEAM <sup>(16)</sup>

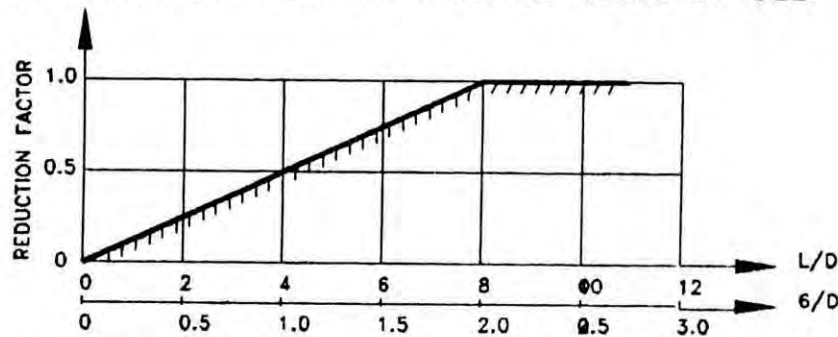


FIG-3.14 REDUCTION OF THE SHEAR REINFORCEMENT IN DEEP BEAM <sup>(16)</sup>



(i) The area of the shear reinforcement  $A_v$  perpendicular to the main steel, shall not be less than  $0.0015bs$  and their spacing 's' shall not exceed  $d/5$ .

(ii) The area of shear reinforcement  $A_{vh}$  parallel to the main steel shall not be less than  $0.0025bs_h$  and their spacing 's<sub>h</sub>' shall not exceed  $d/3$  or 18 inch.

(iii) When  $\frac{L_n}{d} \leq 2, V_u \leq 8\sqrt{f'_c} (psi)$

(iv) When  $2 \leq \frac{L_n}{d} \leq 5, V_u \leq \frac{2}{3} \left( 10 + \frac{L_n}{d} \right) \sqrt{f'_c} (psi)$

These provisions of 1971 ACI code are endorsed almost unchanged in ACI 318-77 building code which have been subsequently followed to estimate the ultimate loads of the test beams.

### 3.7.1.2 Ray and Reddy approach <sup>(37)</sup>

In their approach of estimating the ultimate shear capacity of deep beams, Ray and Reddy have assumed that the diagonal tension mode of failure is akin to the rupture phenomenon in the Mohr-Coulomb failure criterion with straight line envelopes. Equilibrium equations involving cohesion of concrete 'c' and angle of internal friction  $\phi$  ( $\tan \phi$ ) of the Mohr diagram have been developed with the normal and tangential forces acting on the ruptured diagonal crack plane at failure of the beam. On simplification of the equilibrium equations, the ultimate shear strength equation is developed as

$$Q_u = \frac{cbD}{\sin \beta \cos \beta (\tan \beta + \tan \phi)} + A_s f_y \left( \frac{\tan \beta \tan \phi - 1}{\tan \beta + \tan \phi} \right) + \sum A_w f_{wy} \left[ \frac{\sin \alpha \cot \beta + \cot \alpha}{(\tan \beta + \tan \phi) / (\tan \beta \tan \phi)} - \frac{\cos \alpha}{(\tan \beta + \tan \phi) / (1 - \tan \alpha \tan \beta)} \right] \dots \dots \dots (3.10)$$

Where,  $\alpha$  = inclination of the web steel with horizontal.

$\beta$  = angle of inclination of potential diagonal crack with the horizontal.

When the web steels are placed in horizontal and vertical directions only, the equation reduces to

$$Q_u = \lambda_1 P_c + \psi_s P_s + \psi_w P_w \quad \dots \dots \dots (3.11)$$

Where,

$$P_c = \frac{cbD}{\sin \beta \cos \beta (\tan \beta + \tan \phi)}$$

$$= (1 - \frac{1}{3} \cdot \frac{X_v}{D}) \quad \text{For } \frac{X}{D} \leq 1$$

$$P_s = A_s f_{sy} \left( \frac{\tan \beta \tan \phi - 1}{\tan \beta + \tan \phi} \right)$$

$$P_w = P_{wv} + P_{wh}$$

$$P_{wv} = \sum_{n1} A_{sv} \left( \frac{\tan \phi}{\tan \beta + \tan \phi} \right)$$

$$P_{wh} = \sum_{n2} A_{sh} \left( \frac{\tan \beta \cdot \tan \phi - 1}{\tan \beta + \tan \phi} \right)$$

$$\psi_s = 1.0 \quad \text{for solid beams}$$

$$\psi_w = 0.5 \quad \text{for solid beams}$$

$\lambda_1$ ,  $\psi_s$  and  $\psi_w$  are proposed factors to account for the shear span/depth ratio and other web opening parameters.

### 3.7.1.3 Ramkrishnan and Ananthanarayana's approach <sup>(38)</sup>

Ramkrishnan and Ananthanarayana have derived the equation for predicting the ultimate load of deep beams from the similarity of diagonal tension splitting along the potential crack with that of a cylinder under diametral compression. It is one of the simplest formula available at present to assess the ultimate shear strength of deep beams. Their equation in its general form is

$$P_u = \beta K f'_{sp} b D \quad \dots \dots \dots (3.12)$$

where  $\beta$  = a co-efficient for shear span and loading condition effect.

K = splitting co-efficient which is 1.57 for cylinder splitting and 1.12 suggested by them for deep beams.

For deep beam under concentrated load at mid span, it is reduced to

$$P_u = 2.24 f'_{sp} b D$$

### 3.8 SELVAM AND KURUVILLA<sup>(22)</sup> APPROACH

V.K. Manicka Selvam and Kuruvilla Thomas proposed an equation for computing the ultimate load capacity of deep beams in shear. They also proposed a guideline for the quantity of main flexural reinforcement to be used so that shear mode of failure is effected in deep beams, eliminating flexural failure.

The quantity of reinforcement to be used in deep beams for bringing about shear mode of failure is established in the form of the following equation.

$$P \geq \frac{1}{2\beta} \dots \dots \dots (3.13)$$

where,

$P = 100 A_s / (bD)$  = steel index

$A_s$  = Area of main flexural reinforcement

$b$  = Thickness of the beam

$D$  = Total depth of beam

$\beta$  = Deep beam parameter =  $D/L$

$L$  = Effective span of beam

They suggested the following empirical equation for the computation of ultimate load capacity of deep beams.

$$P_u = \left[ 2.2\alpha^{0.1} + 1.1\beta^{0.2} \right] \epsilon^{0.5} f'_{sp} bD$$

where,  $\alpha = a/D$

$a$  = Shear span.

$\epsilon$  = Ratio of the yield value of reinforcement used in the beam to the yield value of mild steel (2500 Kg/cm<sup>2</sup>).

$f'_{sp}$  = Cylinder split tensile strength of concrete.

### 3.9 MAU AND HSU <sup>(23)</sup> APPROACH

This is one of the latest formula for the determination of shear strength capacity of simply supported deep beams. It is an explicit formula and is derived by using the three equilibrium equations from the truss model theory. The formula is dimensionless and contains four variables that express the horizontal and vertical reinforcement ratios, the concrete strength, and shear span ratio. The formula is as follows:

$$\frac{V}{f'_c} = 0.5 \left[ K(W_h + 0.03) + \sqrt{ \left\{ k \frac{2}{3} (W_h + 0.03)^2 + 4(W_h + 0.03)(W_v + 0.03) \right\} } \right] \leq 0.3 \quad (3.15)$$

with the limitations:

$$W_h = (p_h f_y) / f'_c \leq 0.26$$

$$W_v = (p_v f_y) / f'_c \leq 0.12$$

where,  $p_h$  = total horizontal reinforcement ratio =  $A_h / bd$

$p_v$  = vertical web reinforcement ratio =  $\frac{A_v}{bs}$ , and

the value of  $K$  depends on the shear span to depth ratio  $a/D$  as follows:

$$K = \frac{2d_v}{D} \quad \text{for } 0 < \frac{a}{D} \leq 0.5$$

$$\text{or, } K = \frac{d_v}{D \left\{ \frac{D}{a} \left( \frac{4}{3} - \frac{2a}{3D} \right) \right\}} \quad \text{for } 0.5 < \frac{a}{D} \leq 2$$

$$= 0 \quad \text{for } \frac{a}{D} > 2$$

where,  $d_v$  = distance between the centers of flexural steel and the topmost horizontal steel.

This formula gives accurate predictions in the range where the horizontal shear steel ratio is less than 0.009, vertical shear steel ratio is less than 0.0245 and the span-depth ratio is less than 3.3.

### **3.10 MECHANISM OF SHEAR RESISTANCE IN RC DEEP BEAMS**

In the case of deep beams with relatively small percentage of reinforcement, the cracks develop vertically from the soffit and remains practically vertical in comparison with the diagonal tension cracks observed in conventional shallow beams as shown in Fig. 3.15.

It is clear from the figures that the diagonal tension which is characteristic of a shallow beam changes gradually into plain horizontal tension as the beam becomes a deep girder. Hence the conventional shear investigations are not strictly applicable to deep beams.

For deep beams, a significant part of the shear force is transferred directly from the loads to the supports by tied-arch action (Fig. 3.16).

The effectiveness of this mechanism clearly depends upon the proportions of the member as well as on the placement of the loads and reactions. The tied-arch mechanism is effective only if the shear span/depth ratio is about 2 or less. For a deep beam with load uniformly distributed along the compression face or top edge, this mechanism is effective<sup>(34)</sup> when

$$\frac{M_u}{V_u d} \leq 1.0$$

#### **3.10. 1 Role of Shear Reinforcements**

Because of the orientation of the principal stresses in deep beams, when diagonal cracking occurs, it will be at a slope steeper than 45 in most cases. Consequently, while it is important to include vertical stirrups, they are apt to be less effective than the horizontal web steel. The horizontal bars are effective not only because they act more in the direction perpendicular to the diagonal crack. Better dowel action in turn, helps to improve shear transfer by aggregate interlock.

#### **3.10. 2 Role of Main Flexural Reinforcements**

Main flexural reinforcements in deep beam provides the necessary tensile force for tied-arch mechanism to equilibrate the loads. Besides, the flexural reinforcements also contribute to shear transfer by dowel action. Flexural reinforcements must have sufficient embedment or anchorage over the supports so that the arch action can develop fully.

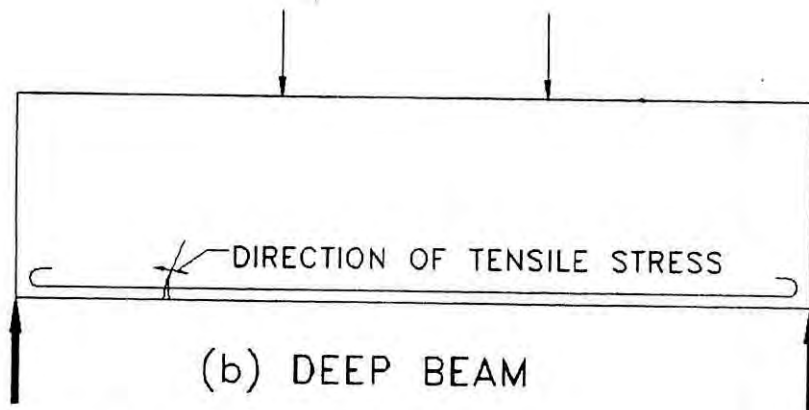
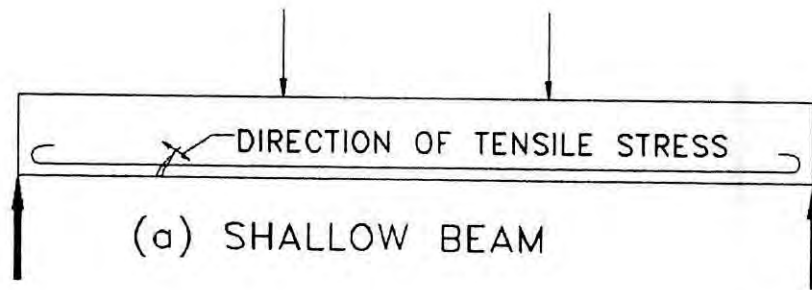


FIG-3.15 DIAGONAL TENSION CRACKS IN SHALLOW & DEEP BEAMS <sup>(34)</sup>

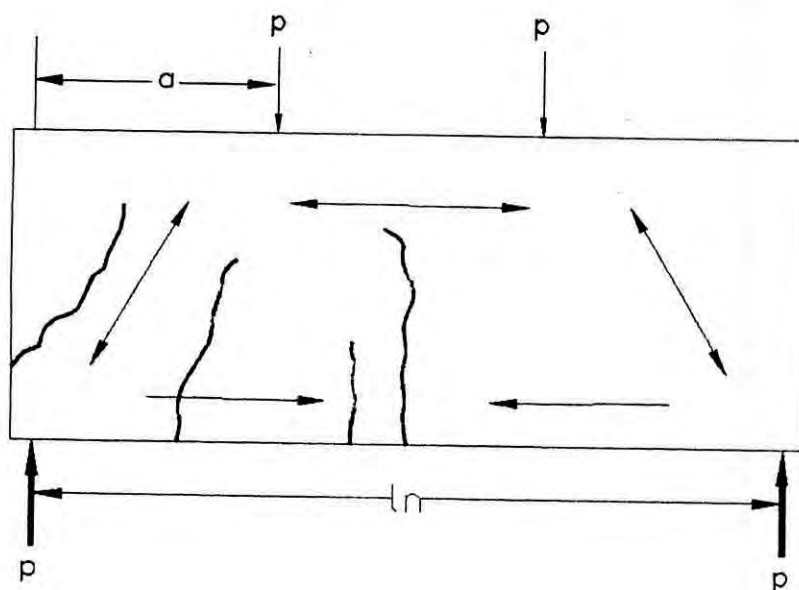


FIG-3.16 SHEAR TRANSFER BY TIED-ARCH MECHANISM <sup>(11)</sup>



### **3.11 MODE OF SHEAR FAILURE**

Shear failure may be described as the failure of the shear resistance mechanisms discussed in the preceding articles. However, it seems necessary to mention some of the characteristics features that are inherent to each type of shear failures.

#### **3.11. 1 Beam Action Failure**

The beam action mechanism, developed in a reinforced concrete flexural member has been described in a previous article (3.1.3). Its characteristic feature is the formation of diagonal cracks as an extension of flexural cracks and the tension zone is therefore divided into a comb like structure. As previously mentioned, the beam action failure may result in a total collapse shortly after the application of diagonal cracking load indicating that the subsequent arch mechanism is incapable of sustaining the cracking load. This type of failure is common in beams with  $a/D$  ratio ranging between 3 and 7.

#### **3.11.2 Shear Compression Failure**

Rectangular reinforced concrete beams with relatively low  $a/D$  ratio ( $2 \leq a/D \leq 3$ ) experience this type of failure. This is basically the failure of the arch mechanism already enumerated earlier. When  $a/D$  ratio is relatively low, considerably higher load can be sustained by arch action after the failure of beam action mechanism. The diagonal cracks penetrating slowly into the compression zone at higher loads may reduce the area under arch compression excessively. At one stage, the available area of concrete in the vicinity of the load point becomes too small to resist the compressive force and the arch fails by crushing of concrete at the crown. This type of failure are usually accompanied by the formation of flexural cracks and the inclined cracks in the shear span and the slow progress of the latter. Crushing of concrete below or near the loading point is the distinctive feature.

#### **3.11.3 Diagonal Tension or Diagonal compression Failure**

Failure by crushing or splitting of concrete in the shear span of a reinforced concrete beam are frequent with  $a/D$  ratio below 2.5. This is obviously the failure of the arch action. But this time the failure is in the inclined rib of the arch. When the line of thrust is quite steep, considerable reserve strength may be available owing to more effective arch action. Ultimately, the failure may be accompanied by either diagonal compression crushing or diagonal tension splitting.

In the diagonal tension mode of failure under concentrated load, a clear and sudden fracture is observed along a line joining either support with the loading point. This type of failure is similar to the splitting of a concrete cylinder under diametral compression.

In diagonal compression failure, an inclined crack is developed first nearly along a line joining the load and the support points. With the increase in load, a second crack nearly parallel to the first is developed closer to the support and extends with further increase in load. The final failure is due to the destruction of the concrete strut between these two cracks. These type of failure usually occur with little or no inelastic deformation and are often referred to as 'shear-proper' failure <sup>(39)</sup>.

# CHAPTER 4

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## LABORATORY INVESTIGATION

### 4.1 GENERAL

This investigation essentially includes the experimental stage of the research study. This stage may be divided into three phases.

- (i) Determination of physical properties of aggregates, reinforcements and design of concrete mix:- specific gravity, absorption, unit weight, fineness modulus of coarse aggregate and sand, yield strength and modulus of elasticity of both flexural and web reinforcements, compressive strength and split cylinder strength of concrete were some of the major physical properties investigated.
- (ii) Fabrication and casting of test beams:- This phase includes the cutting, bending and binding of reinforcements welding of anchor plates to the main steel bar ends, bonding of electrical resistance strain gauges to the reinforcement surface, casting of the beams along with associated cylinders and finally the curing of these specimens.
- (iii) Testing of the beams to investigate the relevant behaviors of interest:- Total twenty five test beams investigated were divided into five series according to their span/depth (L/D) ratio. The first series (DBA) included five beams with L/D ratio equal to unity while the second series (DBB) consisted of five beams with L/D= 1.75 and in the series DBC, DBD, DBE the L/D ratio are 3.00, 4.00 and 5.00 respectively.

### 4.2 AGGREGATE PROPERTIES

Manually crushed, local variety of first class bricks were used as the coarse aggregate for the preparation of concrete in this investigation. The brick chips were initially sieved through 3/4 inch to No. 4 size sieves and the aggregates passing 3/4 inch size and retained on No. 4 were stored separately for use.

Ordinary Sylhet sand passing through sieve no. 4. were used as the fine aggregate. The absorption, specific gravity, unit weight and fineness modules of the aggregates were determined as per ASTM recommendation. The grading and other physical properties of the coarse and fine aggregates are shown in Table 4.1 and 4.2.

**Table 4.1 Grading of Aggregates**

| Sieve Size       | Cumulative percentage retained for |                |                    |
|------------------|------------------------------------|----------------|--------------------|
|                  | Brick aggregate                    | Fine aggregate | Combined Aggregate |
| 3/4              | 0.0                                | 0.0            | 0.00               |
| 3/8              | 73.0                               | 0.0            | 38.32              |
| No. 4            | 100.0                              | 0.0            | 52.50              |
| No. 8            | 100.0                              | 1.8            | 53.36              |
| No.16            | 100.0                              | 17.0           | 60.58              |
| No. 30           | 100.0                              | 42.4           | 72.64              |
| No. 50           | 100.0                              | 83.5           | 92.16              |
| No.100           | 100.0                              | 94.8           | 97.53              |
| Fineness Modulus | 6.73                               | 2.4            | 4.67               |

**Table 4.2 Physical Properties of Aggregates**

| Property                     | Brick Aggregate | Fine Aggregate (sand) |
|------------------------------|-----------------|-----------------------|
| Fineness Modulus             | 6.73            | 2.40                  |
| Unit weight (loose)          | 79.16           | 85.20                 |
| Unit weight (SSD, compacted) | 88.20           | 98.00                 |
| Bulk Sp. Gravity             | 2.08            | 2.76                  |
| Absorption (% of Dry weight) | 12.35           | 2.88                  |

### 4.3 REINFORCEMENT

Mild steel plain bars of # 6 and # 10 whose 3/4 inch nominal diameter(3/4)" and (10/8)" were used as the main flexural reinforcement. The bars procured from the local market were slightly oversized and the actual area of these bars were used for computations.

1/4 inch nominal diameter plain bars were used as web reinforcements. The two bars used in the compression zone as the stirrup holder were also 1/4 inch diameter bars. Three specimens from each size of bars were tested as per ASTM A 370 in order to determine the yield strength, ultimate strength, percent elongation and modulus of elasticity. Test results are shown in Table 4.3 and a typical stress-strain diagram is shown in Fig. 4.1

**Table 4.3 Physical properties of Reinforcement used in the test beams**

**A. 10/8 inch nominal diameter M.S. bar.**

| Specimen No.    | Actual diameter (inch) | Actual area (in <sup>2</sup> ) | Yield strength (psi) | Ultimate strength (psi) | Percent elongation in 2" gage length | Modulus of elasticity, E (psi) |
|-----------------|------------------------|--------------------------------|----------------------|-------------------------|--------------------------------------|--------------------------------|
| 1               | 1.258                  | 1.243                          | 55419                | 65,890                  | 44.50                                | 30.09×10 <sup>6</sup>          |
| 2               | 1.257                  | 1.241                          | 53920                | 71,230                  | 43.50                                | 29.78×10 <sup>6</sup>          |
| 3               | 1.234                  | 1.197                          | 54,762               | 67,801                  | 44.00                                | 30.19×10 <sup>6</sup>          |
| <b>Average:</b> | <b>1.249</b>           | <b>1.227</b>                   | <b>54,700</b>        | <b>68,307</b>           | <b>44.00</b>                         | <b>30.02×10<sup>6</sup></b>    |

**B. 3/4 inch nominal diameter M.S. bar.**

| Specimen No.    | Actual diameter (inch) | Actual area (in <sup>2</sup> ) | Yield strength (psi) | Ultimate strength (psi) | Percent elongation in 2" gage length | Modulus of elasticity, E (psi) |
|-----------------|------------------------|--------------------------------|----------------------|-------------------------|--------------------------------------|--------------------------------|
| 1               | 0.742                  | 0.432                          | 54,679               | 67,271                  | 44.00                                | 29.99×10 <sup>6</sup>          |
| 2               | 0.758                  | 0.452                          | 53,621               | 64,132                  | 46.00                                | 30.42×10 <sup>6</sup>          |
| 3               | 0.749                  | 0.441                          | 55,800               | 66,829                  | 43.00                                | 29.52×10 <sup>6</sup>          |
| <b>Average:</b> | <b>0.750</b>           | <b>0.442</b>                   | <b>54,700</b>        | <b>66,077</b>           | <b>44.33</b>                         | <b>30.00×10<sup>6</sup></b>    |

**C. 1/4 inch nominal diameter M.S. bar.**

| Specimen No.    | Actual diameter (inch) | Actual area (in <sup>2</sup> ) | Yield strength (psi) | Ultimate strength (psi) | Percent elongation in 2" gage length | Modulus of elasticity, E (psi) |
|-----------------|------------------------|--------------------------------|----------------------|-------------------------|--------------------------------------|--------------------------------|
| 1               | 0.262                  | 0.054                          | 51,292               | 65,291                  | 45.50                                | 29.98×10 <sup>6</sup>          |
| 2               | 0.267                  | 0.056                          | 51,310               | 64,892                  | 44.50                                | 29.89×10 <sup>6</sup>          |
| 3               | 0.279                  | 0.061                          | 51,298               | 64,991                  | 46.00                                | 30.12×10 <sup>6</sup>          |
| <b>Average:</b> | <b>0.269</b>           | <b>0.057</b>                   | <b>51,300</b>        | <b>65,058</b>           | <b>45.33</b>                         | <b>29.99×10<sup>6</sup></b>    |

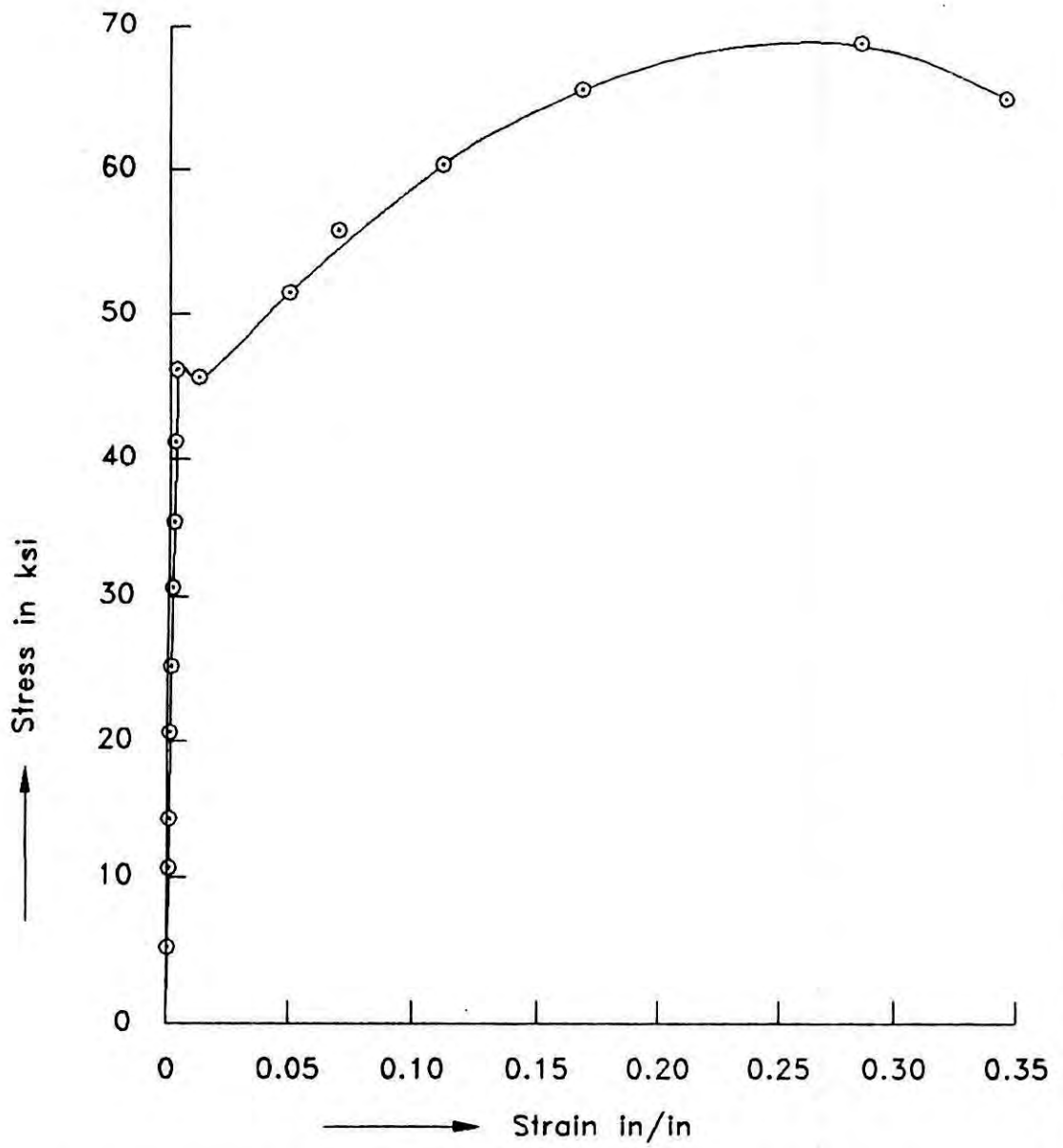


FIG-4.1 TYPICAL STRESS-STRAIN DIAGRAM OF MAIN STEEL SPECIMEN



## 4.4 DESIGN OF CONCRETE MIX

As there is no specific standard method for the design of concrete with brick aggregates, the ACI method for proportioning concrete mix (C 211.1-70) was followed for a trial mix. On the basis of the test results of the trial mix, the ratio of cement, sand and aggregate were finally selected. Ordinary portland cement of Type I 'HUNDAI' brand was used throughout the test programme. The mix was designed to attain a nominal cylinder crushing strength of 5000 psi at 28 days of curing. Mix details are given below:

Mix proportion Designed strength: 5000 psi  
(by weight): 664.9 : 1280 : 1407.8  
Cement: Sand: Brick Aggregate = 1 : 1.9 : 2.1  
Water cement ratio = 0.45

The slump of the fresh concrete was maintained at 2 to 2.5 inch.

The mix contents of each batch for the two series of beams (including cylinder specimens) are given in Table 4.4.

**Table 4.4 Contents of Concrete-mix Batch**

| Beam Series      | Quantity (by Weight) |             |                        |              | Water Cement Ratio<br>w/c |
|------------------|----------------------|-------------|------------------------|--------------|---------------------------|
|                  | Cements<br>lbs       | Sand<br>lbs | Brick Aggregate<br>lbs | Water<br>lbs |                           |
| For all 25 beams | 112.0                | 212.8       | 235.2                  | 50.4         | 0.45                      |

## 4.5 THE TEST BEAMS

A total of 25 rectangular deep beams divided into five series DBA /DBE were designed to fail in shear. Nominal cross section of to either end of the tension bars to prevent any premature bond failure. The centered of the tension steel was maintained at 1.5 inch from the bottom face of the beams. The vertical and horizontal web reinforcements were provided by 1/4 inch mild steel bars. Arrangement and the amount of web steels were the variables in each series of test beams. The details of flexural and web reinforcement are described in Table 4.5 DBA series of beams were 6 inch by 21 inch while that of DBB and DBC series were 6 inch by 12 inch DBD series were 8" by 12" and DBE series were 12" by 12". The span to overall depth ratio of these series were 1.0, 1.75, 3.0, 4.0 and 5.0. The total length of first two series of beams were kept invariable at 33 inches and that of 3rd to fifth series were 48 inches, 60 inches and 72 inches. The longitudinal tension reinforcement of first two series were provided by two 3/4 inch diameters. Mild steel and that of in 3rd to 5th series two three and four (10/8)" diameter Mild steel bars are provided as longitudinal tension reinforcement. Two 1/2 inch thick and 3 inch depth steel plate having same width of the respective beam width were welded.

**Table 4.5 REINFORCEMENT DETAILS OF DIFFERENT DEEP BEAMS**

| Beam Designation        | Flexural Reinforcement     |                |                   | Web Reinforcement          |                |                   |                            |                |                   |
|-------------------------|----------------------------|----------------|-------------------|----------------------------|----------------|-------------------|----------------------------|----------------|-------------------|
|                         |                            |                |                   | Vertical Web Stirrup       |                |                   | Horizontal Web Stirrup     |                |                   |
|                         | Single Steel Area (Sq. in) | Spacing (Inch) | Total Nos. of Bar | Single Steel Area (Sq. in) | Spacing (Inch) | Total Nos. of Bar | Single Steel Area (Sq. in) | Spacing (Inch) | Total Nos. of Bar |
| Series DB-A: L/D = 1.0  |                            |                |                   |                            |                |                   |                            |                |                   |
| DB-A1                   | 0.442                      | 4.5            | 2                 | 0.057                      | 3              | 7                 | 0.057                      | 6              | 3                 |
| DB-A2                   | 0.442                      | 4.5            | 2                 | 0.057                      | 4.5            | 5                 | 0.057                      | 4.5            | 3                 |
| DB-A3                   | 0.442                      | 4.5            | 2                 | 0.057                      | 2.25           | 9                 | 0.057                      | 7              | 2                 |
| DB-A4                   | 0.442                      | 4.5            | 2                 | 0.057                      | 3              | 7                 | 0.057                      | 12             | 1                 |
| DB-A5                   | 0.442                      | 4.5            | 2                 | 0.057                      | 6              | 3                 | 0.057                      | 6              | 3                 |
| Series DB-B: L/D = 1.75 |                            |                |                   |                            |                |                   |                            |                |                   |
| DB-B1                   | 0.442                      | 4.5            | 2                 | 0.057                      | 2              | 12                | 0.057                      | 3.5            | 2                 |
| DB-B2                   | 0.442                      | 4.5            | 2                 | 0.057                      | 1.5            | 16                | 0.057                      | 4.5            | 1                 |
| DB-B3                   | 0.442                      | 4.5            | 2                 | 0.057                      | 5              | 5                 | 0.057                      | 2.5            | 3                 |
| DB-B4                   | 0.442                      | 4.5            | 2                 | 0.057                      | 3              | 8                 | 0.057                      | 6              | 1                 |
| DB-B5                   | 0.442                      | 4.5            | 2                 | 0.057                      | 4              | 6                 | 0.057                      | 3.5            | 2                 |
| Series DB-C: L/D = 3.0  |                            |                |                   |                            |                |                   |                            |                |                   |
| DB-C1                   | 1.277                      | 4.5            | 2                 | 0.057                      | 2              | 18                | 0.057                      | 3.5            | 2                 |
| DB-C2                   | 1.277                      | 4.5            | 2                 | 0.057                      | 1.5            | 23                | 0.057                      | 4.5            | 1                 |
| DB-C3                   | 1.277                      | 4.5            | 2                 | 0.057                      | 5              | 7                 | 0.057                      | 2.5            | 3                 |
| DB-C4                   | 1.277                      | 4.5            | 2                 | 0.057                      | 3              | 12                | 0.057                      | 6              | 1                 |
| DB-C5                   | 1.277                      | 4.5            | 2                 | 0.057                      | 4              | 9                 | 0.057                      | 3.5            | 2                 |
| Series DB-D: L/D = 4.0  |                            |                |                   |                            |                |                   |                            |                |                   |
| DB-D1                   | 1.277                      | 4.365          | 3                 | 0.057                      | 2              | 23                | 0.057                      | 3.5            | 2                 |
| DB-D2                   | 1.277                      | 4.365          | 3                 | 0.057                      | 1.5            | 31                | 0.057                      | 4.5            | 1                 |
| DB-D3                   | 1.277                      | 4.365          | 3                 | 0.057                      | 5              | 8                 | 0.057                      | 2.5            | 3                 |
| DB-D4                   | 1.277                      | 4.365          | 3                 | 0.057                      | 3              | 15                | 0.057                      | 6              | 1                 |
| DB-D5                   | 1.277                      | 4.365          | 3                 | 0.057                      | 4              | 11                | 0.057                      | 3.5            | 2                 |
| Series DB-E: L/D = 5.0  |                            |                |                   |                            |                |                   |                            |                |                   |
| DB-E1                   | 1.277                      | 2.91           | 4                 | 0.057                      | 2              | 28                | 0.057                      | 3.5            | 2                 |
| DB-E2                   | 1.277                      | 2.91           | 4                 | 0.057                      | 1.5            | 39                | 0.057                      | 4.5            | 1                 |
| DB-E3                   | 1.277                      | 2.91           | 4                 | 0.057                      | 5              | 11                | 0.057                      | 2.5            | 3                 |
| DB-E4                   | 1.277                      | 2.91           | 4                 | 0.057                      | 3              | 19                | 0.057                      | 6              | 1                 |
| DB-E5                   | 1.277                      | 2.91           | 4                 | 0.057                      | 4              | 14                | 0.057                      | 3.5            | 2                 |

The beams were designed with the intention to achieve either diagonal tension or shear compression failure. To accomplish this, the following procedures were adopted:

- (i) Steel ratio was kept well below the balanced condition to check against failure by crushing of concrete.
- (ii) Adequate tension reinforcement was provided to safeguard against flexure tension failure prior to shear failure.
- (iii) Anchor plates were provided to prevent any premature bond failure of the tension steel. Thus in order to achieve shear failure the following relation was satisfied for all test beams.

$$M_{us} < M_{uf}$$

Where,  $M_{us}$  = The ultimate moment corresponding to available shear capacity.

$M_{uf}$  = The ultimate moment capacity of the beam in flexure.

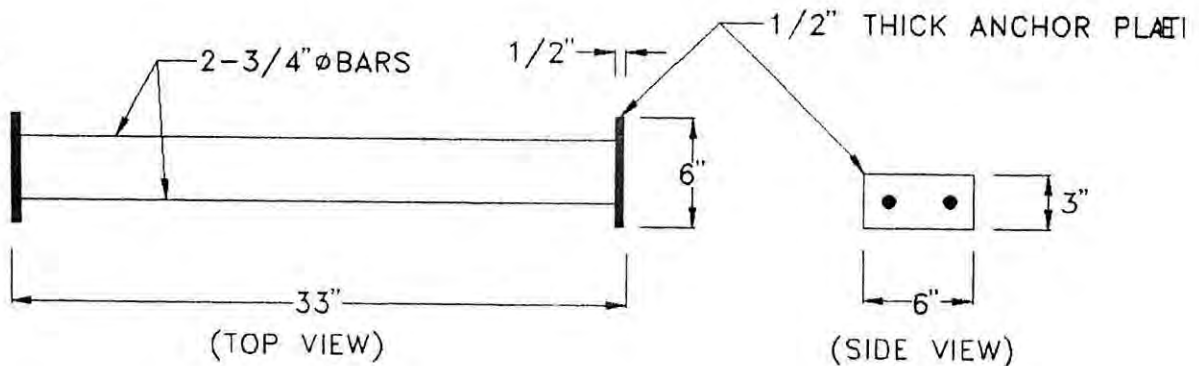
Design calculations were based on the ACI 318-89<sup>(11)</sup> code provision. In appendix-A, example of design of test beam DB-A1 is shown. Besides, in order to prevent the bearing failure, extra vertical and / or horizontal web reinforcements were provided near the supports of the beams according to ACI requirements. The code recommendations have been outlined previously in Art. 3.5 of this thesis.

## 4.6 FABRICATION OF TEST SPECIMENS

In total, twenty five beams were fabricated. Steel mould was used to cast the test beams. Six standard size concrete cylinders were cast along with each test beam from the same batch of concrete as used in beams.

As shown in Fig. 4.2 two 3 inch by 1/2 inch steel plates having same width of respective beam section were welded on either end of the tension reinforcement to guard against premature bond failure. 1/4 inch diameter mild steel bars bent in the form of closed rectangles were used as vertical web reinforcement, clear cover was provided at the top and bottom of the beam. 7/8 inch clear cover on two sides of the beam was 3/4 inch. Horizontal web reinforcement were also 1/4 inch. diameter bars placed inside the vertical ones and tied to it by G.I. wires at every junctions. In addition to the normal web reinforcements, a number of vertical and horizontal bars were placed near the supports of the beams to prevent bearing failure of concrete over supports. Details of reinforcement arrangement of different test beams are shown in Fig. 4.3. through Fig. 4. 27. Seven typical photographs are shown in Fig. 4.29 and Fig. 4.36.

On completion of the reinforcement assembly, certain selective location on the reinforcement were prepared for the instalation of electrical resistance strain gauges. The surface of the reinforcement at those locations was rubbed with sand paper to remove rust completely



**Fig.4.2 TENSION STEEL ASSEMBLY WITH ANCHOR PLATES**

and then cleaned with wet clothes. Finally the locations were treated with carbon tetrachloride solution to remove oil and loose particles if any. Five millimeter 120 ohms Kyowa (KFC) electrical resistance strain gauges were then installed on those prepared locations with the help of strain gauge adhesives. After 24 hours, Lead wires were soldered to the strain gauge leads. The following measures were employed to protect the gauges and the open leads along with the portion of steel rod were wrapped around by plastic tapes. Then gypsum plaster (plaster of paris) was applied over this location covering the entire portion wrapped with plastic tape. A tag with identification of the gauge location was tied to the free end of the lead wire.

Compaction of concrete was achieved by vibrating the mould filled with fresh concrete on a table vibrator. Control cylinder specimens were cast and compacted in the similar manner.

The first set of beams were stripped off the moulds after about 48 hours and the beams of smaller depths (second set) were lifted off the moulds after about 24 hours of casting. Two extended stirrups were provided near the ends of each beam and these were used as lifting hooks. The beam specimens and the control cylinders were then cured for 28 days by wrapping the beams with moist gunny bags. These gunny bags were moistened thrice daily. The beams were then air dried for the next 3 days. The tests were performed on the 28th day after casting.

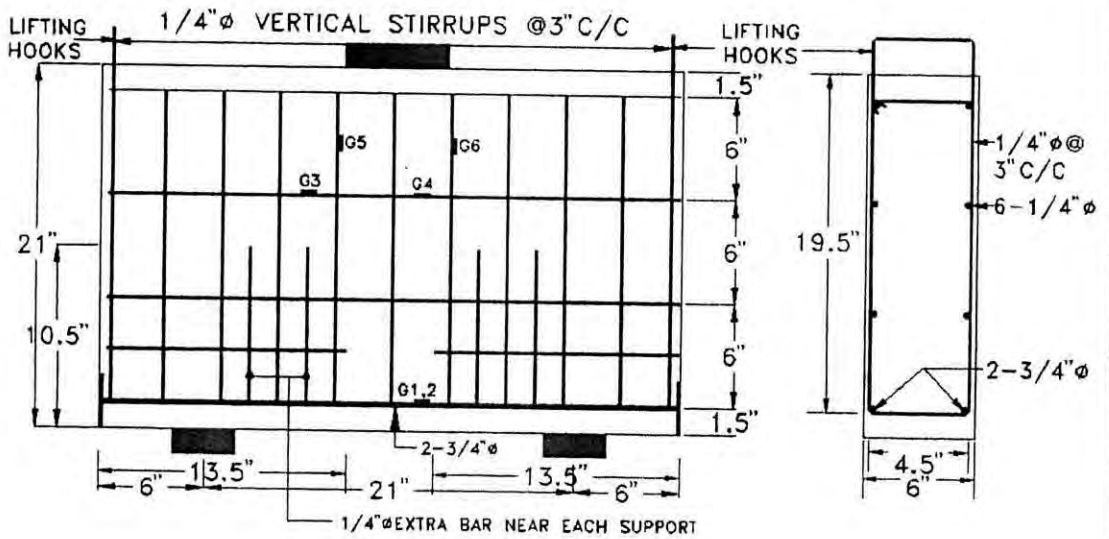


FIG-4.3 REINFORCEMENT ARRANGEMENT OF BEAM DB-A1

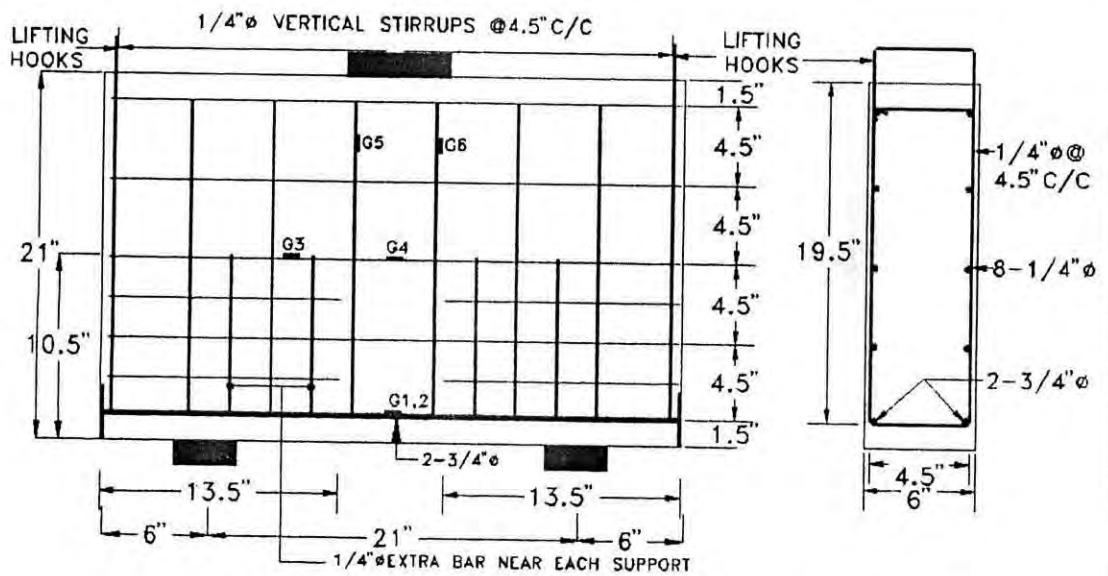


FIG-4.4 REINFORCEMENT ARRANGEMENT OF BEAM DB-A2



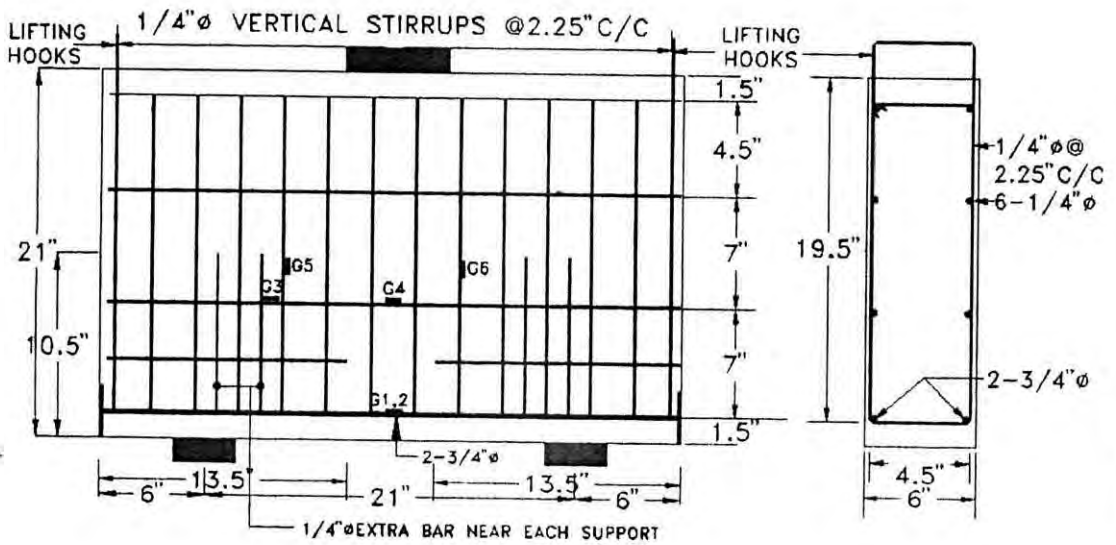


FIG-4.5 REINFORCEMENT ARRANGEMENT OF BEAM DB-A3

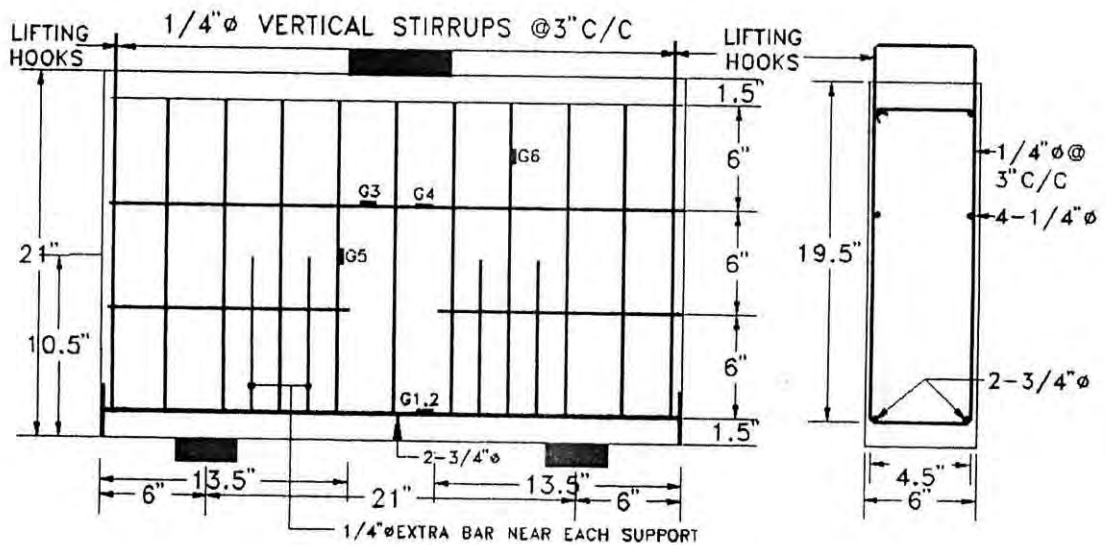


FIG-4.6 REINFORCEMENT ARRANGEMENT OF BEAM DB-A4



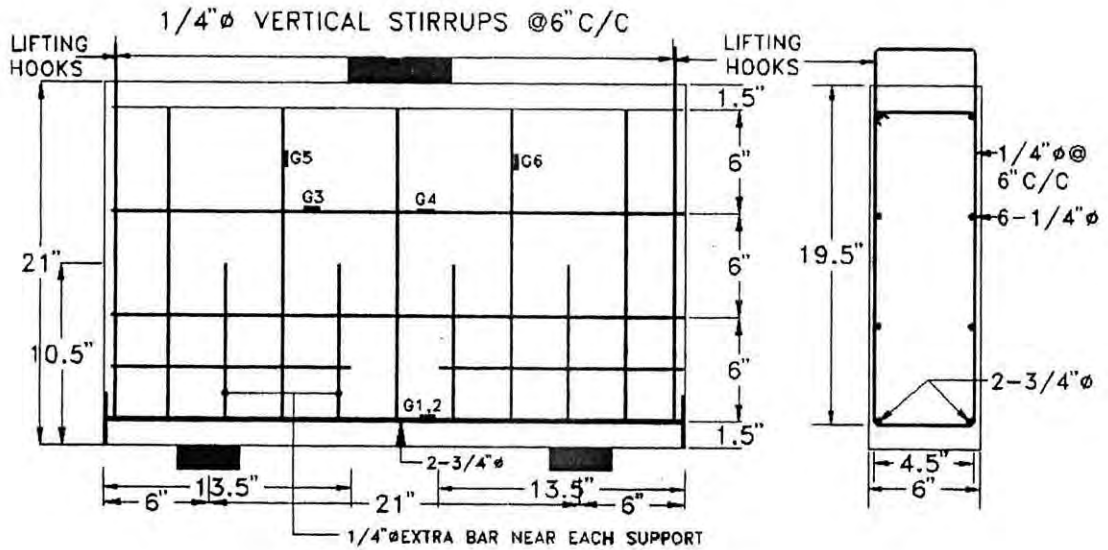


FIG-4.7 REINFORCEMENT ARRANGEMENT OF BEAM DB-A5

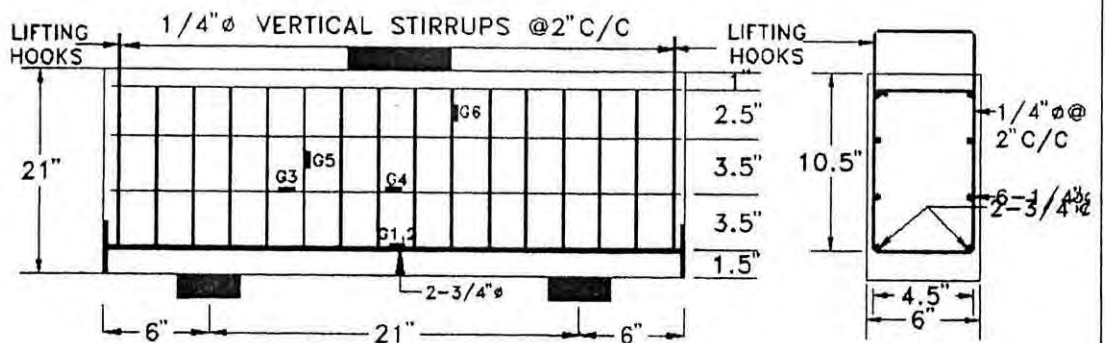


FIG-4.8 REINFORCEMENT ARRANGEMENT OF BEAM DB-B1

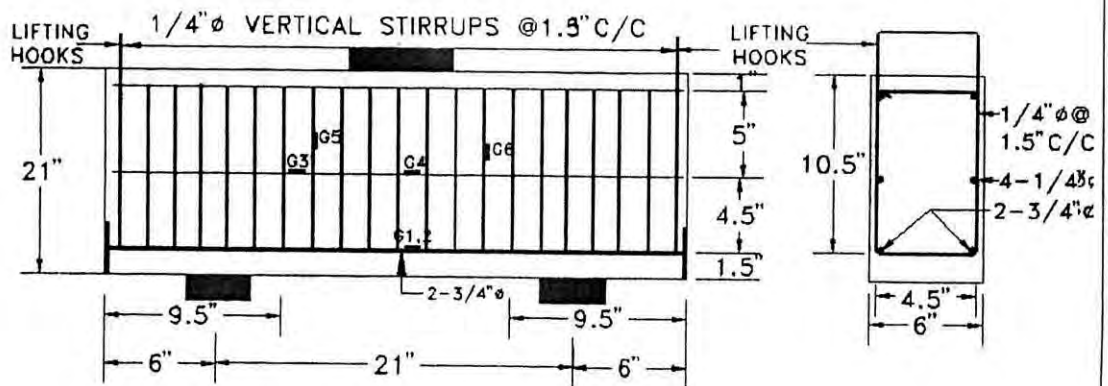


FIG-4.9 REINFORCEMENT ARRANGEMENT OF BEAM DB-B2

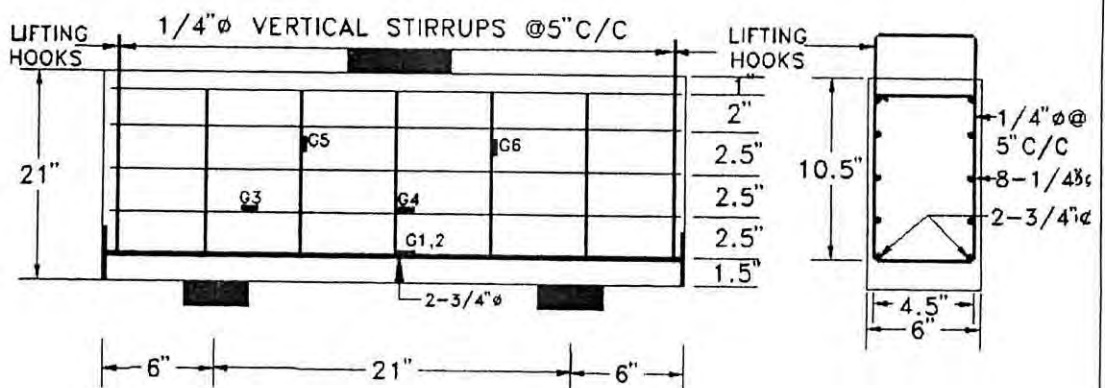


FIG-4.10 REINFORCEMENT ARRANGEMENT OF BEAM DB-B3

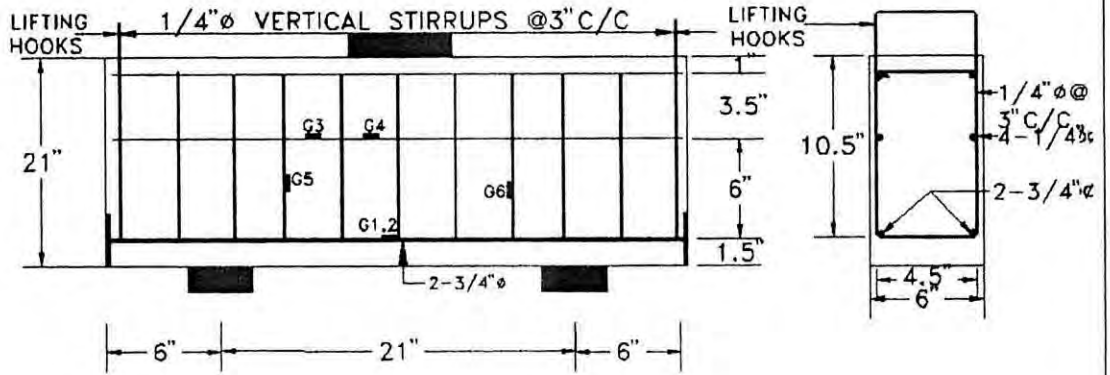


FIG-4.11 REINFORCEMENT ARRANGEMENT OF BEAM DB-B4

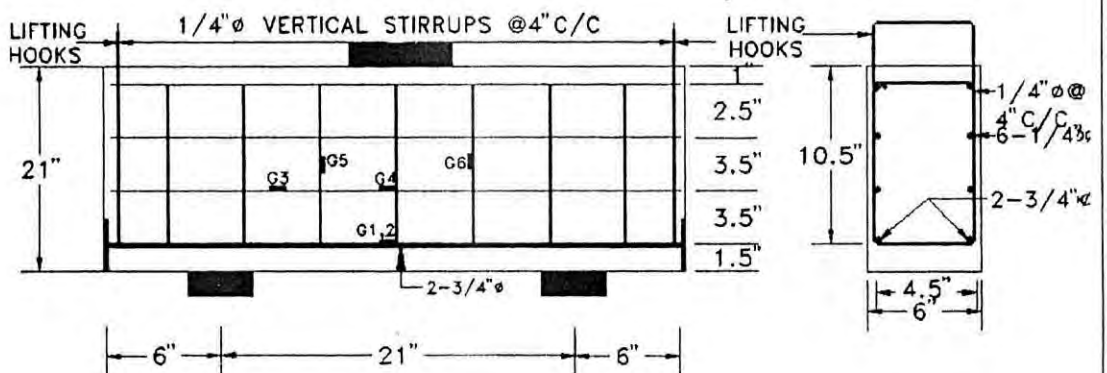


FIG-4.12 REINFORCEMENT ARRANGEMENT OF BEAM DB-B5

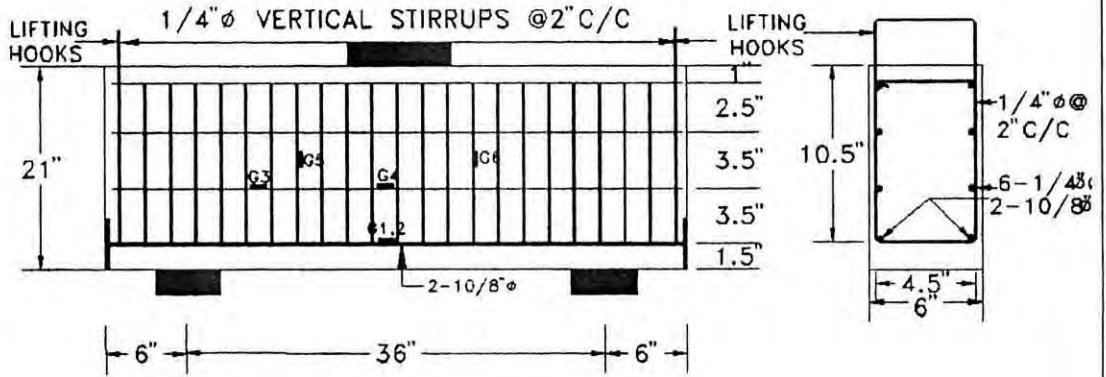


FIG-4.13 REINFORCEMENT ARRANGEMENT OF BEAM DB-C1

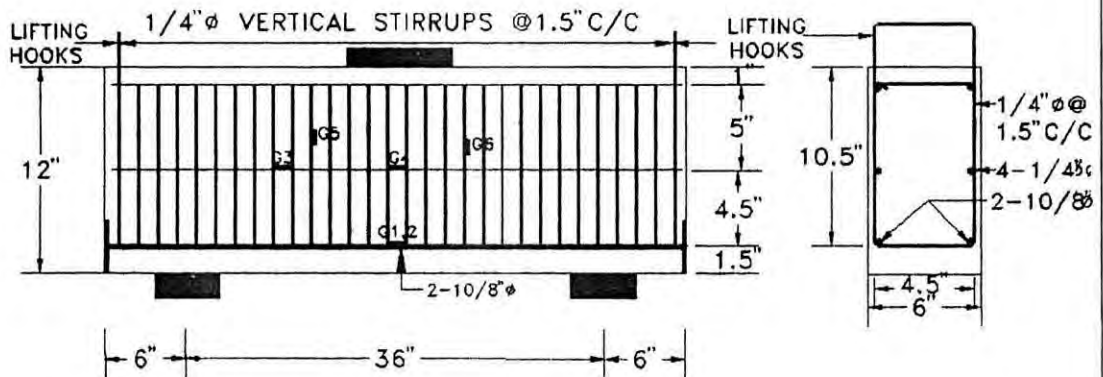


FIG-4.14 REINFORCEMENT ARRANGEMENT OF BEAM DB-C2

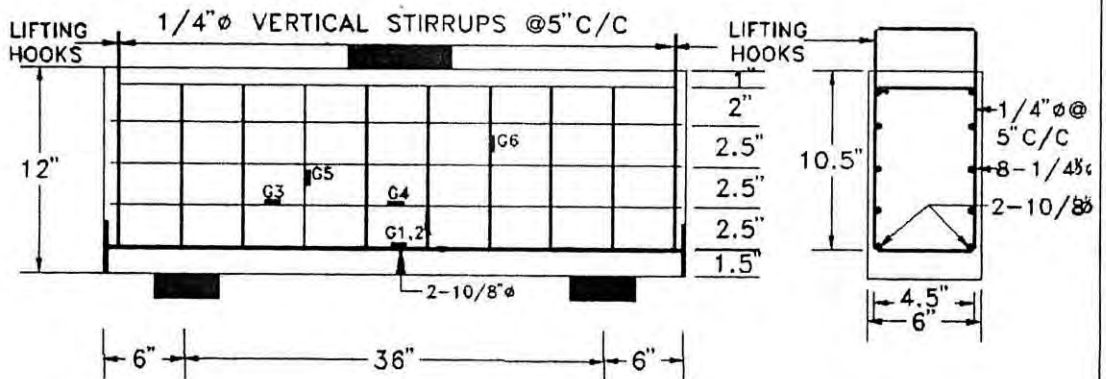


FIG-4.15 REINFORCEMENT ARRANGEMENT OF BEAM DB-C3

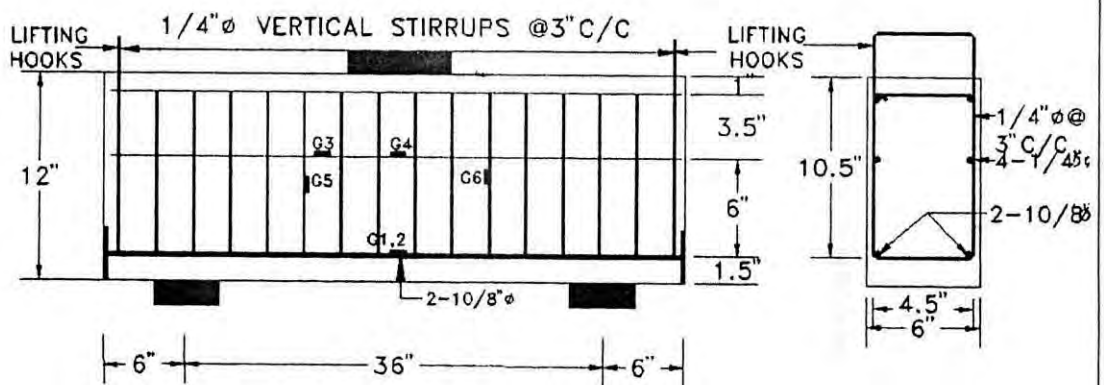


FIG-4.16 REINFORCEMENT ARRANGEMENT OF BEAM DB-C4

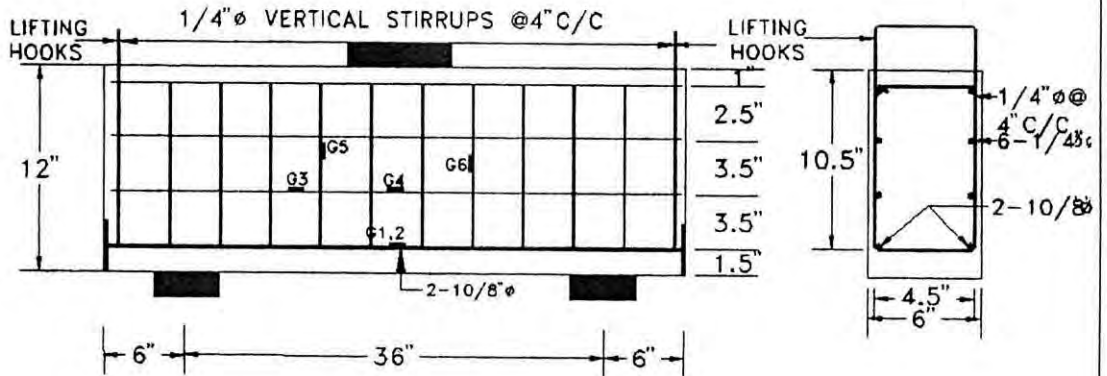


FIG-4.17 REINFORCEMENT ARRANGEMENT OF BEAM DB-C5

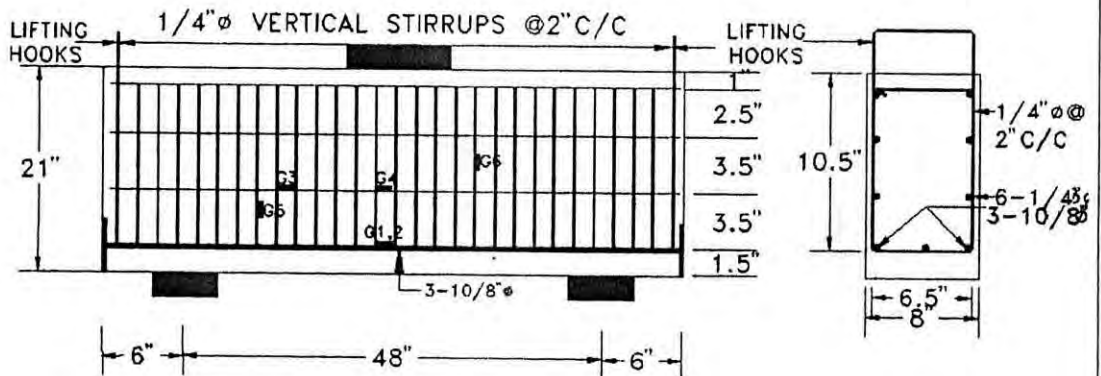


FIG-4.18 REINFORCEMENT ARRANGEMENT OF BEAM DB-D1



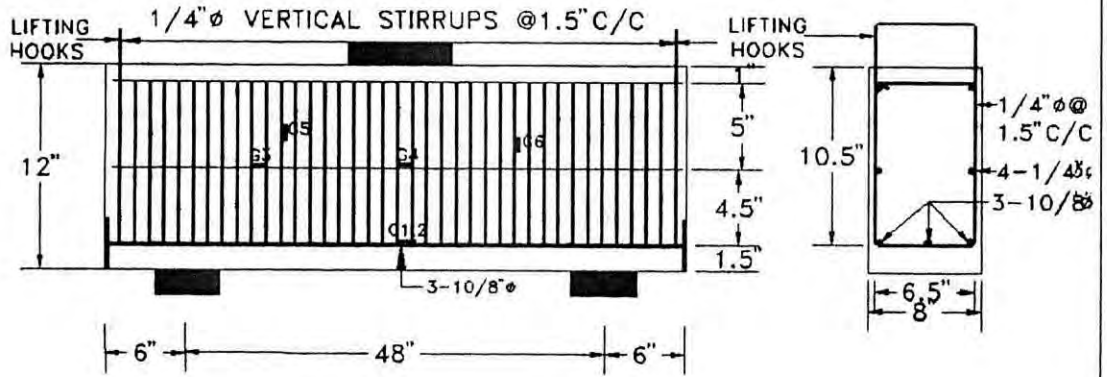


FIG-4.19 REINFORCEMENT ARRANGEMENT OF BEAM DB-D2

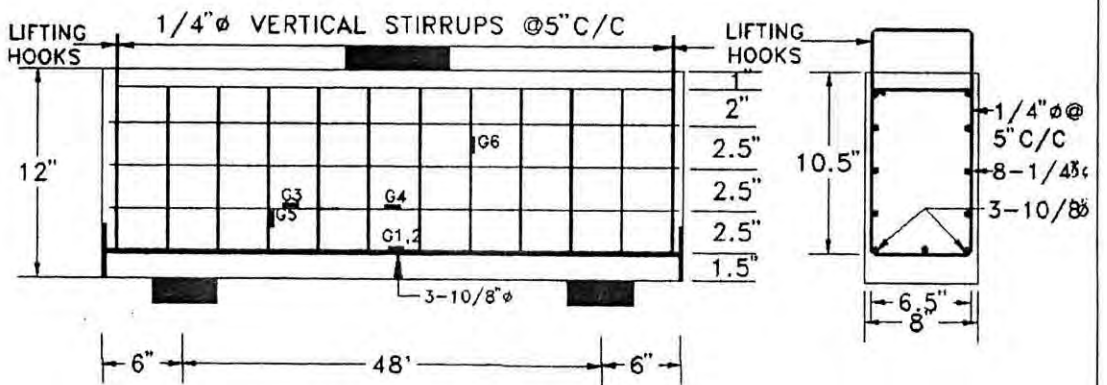


FIG-4.20 REINFORCEMENT ARRANGEMENT OF BEAM DB-D3

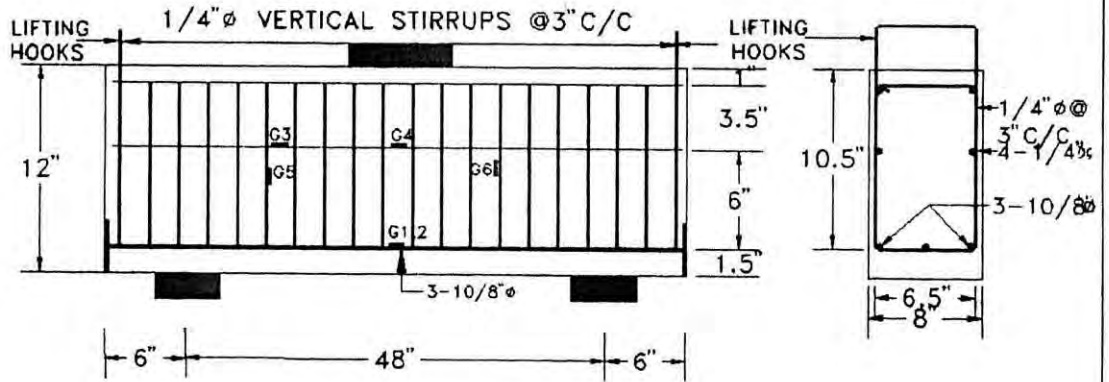


FIG-4.21 REINFORCEMENT ARRANGEMENT OF BEAM DB-D4

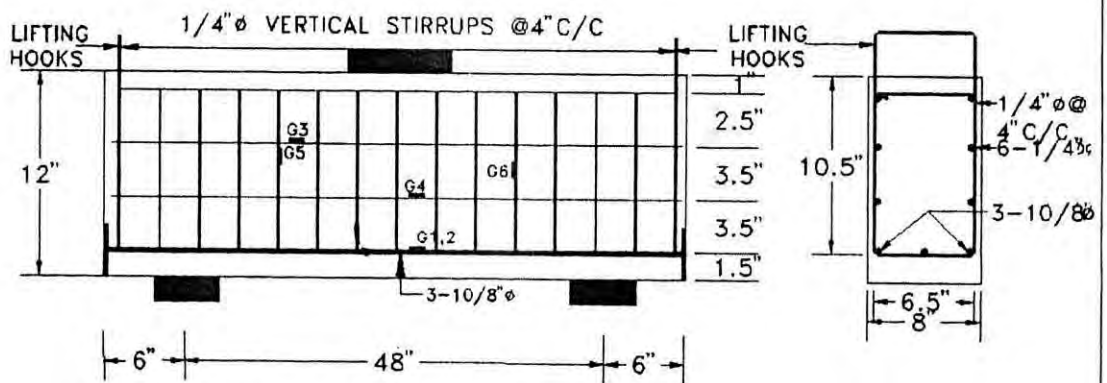


FIG-4.22 REINFORCEMENT ARRANGEMENT OF BEAM DB-D5

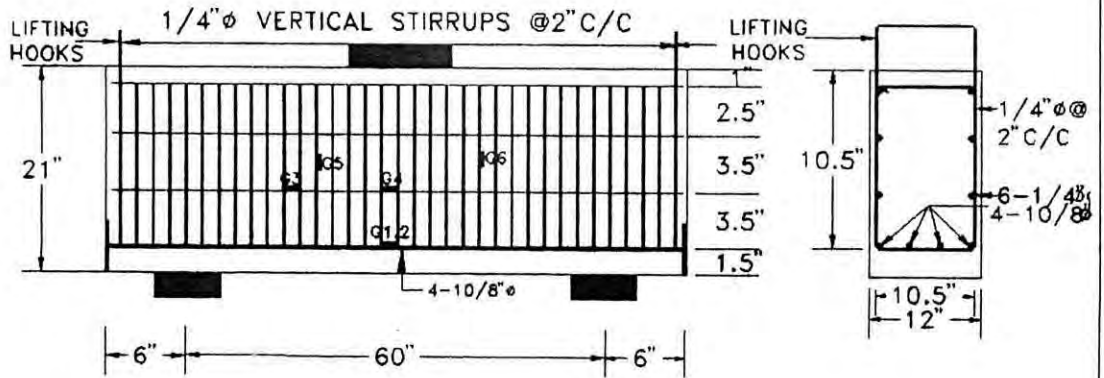


FIG-4.23 REINFORCEMENT ARRANGEMENT OF BEAM DB-E1

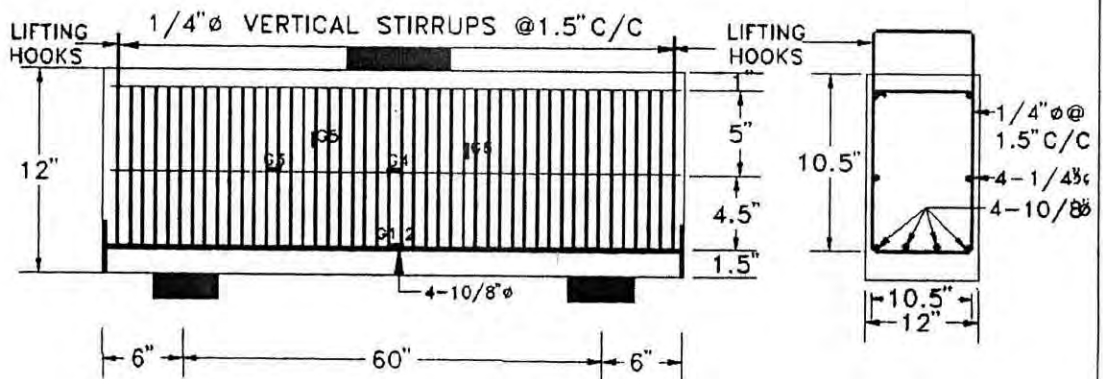


FIG-4.24 REINFORCEMENT ARRANGEMENT OF BEAM DB-E2

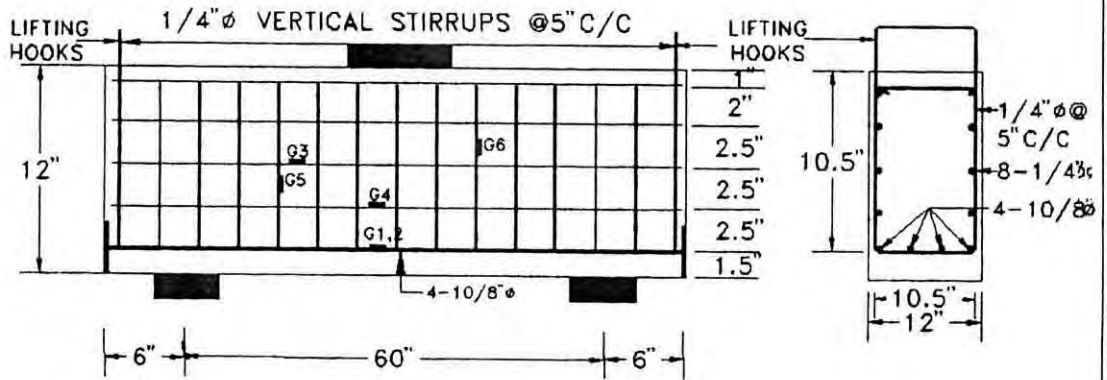


FIG-4.25 REINFORCEMENT ARRANGEMENT OF BEAM DB-E3

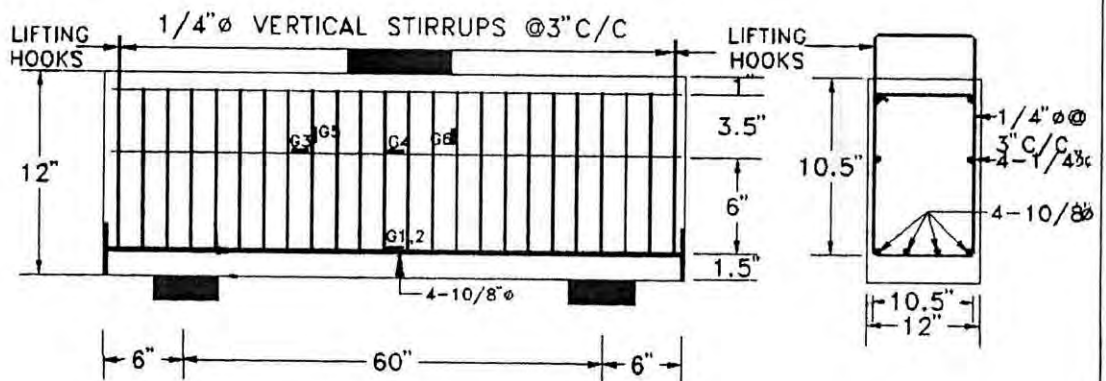


FIG-4.26 REINFORCEMENT ARRANGEMENT OF BEAM DB-E4

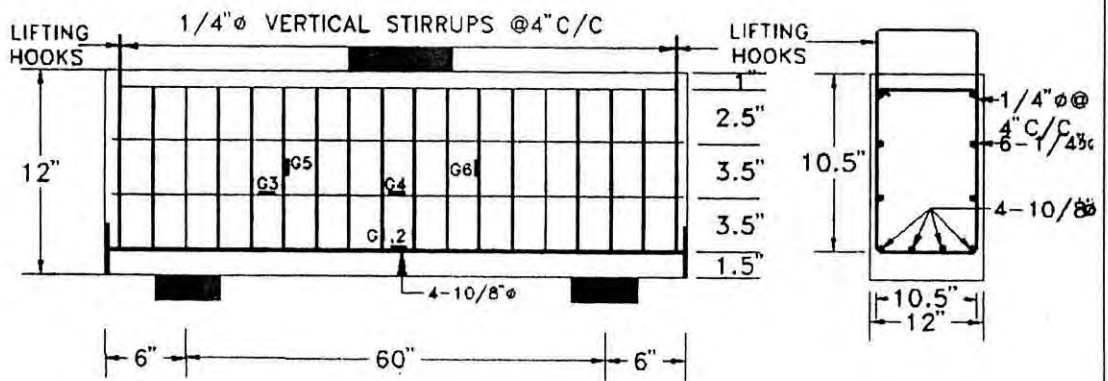


FIG-4.27 REINFORCEMENT ARRANGEMENT OF BEAM DB-E5

what are  $G_1, G_2, G_3$  etc ?

## **4.7 TESTING OF BEAMS**

Each beam was tested with a single concentrated load applied at mid-span in a 400 kip capacity universal testing machine (hydraulic type). The load was applied on the top surface through a  $1\frac{1}{2}$  inch thick, 6 inch by 6 inch steel plate and the reactions were supported by two 1 inch thick 3 inch by 6 inch steel plates placed at the bottom of the beam. One of the reaction plate rested on a steel block that itself was placed on the anvil of testing machine. The other reaction plate was placed over a steel block supported by  $\frac{5}{8}$  inch dia. steel rollers. These rollers were placed on a steel block which was supported on the anvil of the machine. Details of the arrangement stated above are shown in Fig.4.28 support lines were clearly marked on both sides of the beam. The loading blocks were also marked on either sides at their centres.

Two deflectometers graduated in 0.001 inch division were employed to measure the central deflection of the beam. One of them was placed at the mid span. The other was placed under a plate extended from the support to account for the support settlement. Deflectometer readings were recorded at each load increment and the difference of readings of the two deflectometers were noted as the mid span deflection. Each test beam was initially loaded upto 5 kips and then released. This operation was done twice before the deflectometer dials were set to zero to achieve a uniform and better setting of the beam specimen with the loading system. The beam was then loaded and deflection and strain readings were observed at regular interval of load increment.

Test beams were white washed on one side to facilitate visul observation of the propagation of cracks on the beam surface. A 2 to 3 inch square grid mesh was drawn on the white washed face between the supports only to establish the relative location of cracks with ease. A magnifying glass was used to help searching of cracks. Cracks were deeply marked with a soft pencil upon their formation on the beam surface and the load intensity at which it was formed was noted beside the crack.

## **4.8 COMPRESSIVE AND TENSILE STRENGTH OF CONCRETE**

Three of the six cylinders cast along with each of the test beam were tested under axial compression to determine the ultimate compressive strength ( $f'_c$ ) of concrete. The remaining three were tested under diametral compression to find the split cylinder tensile strength ( $f'_{sp}$ ).



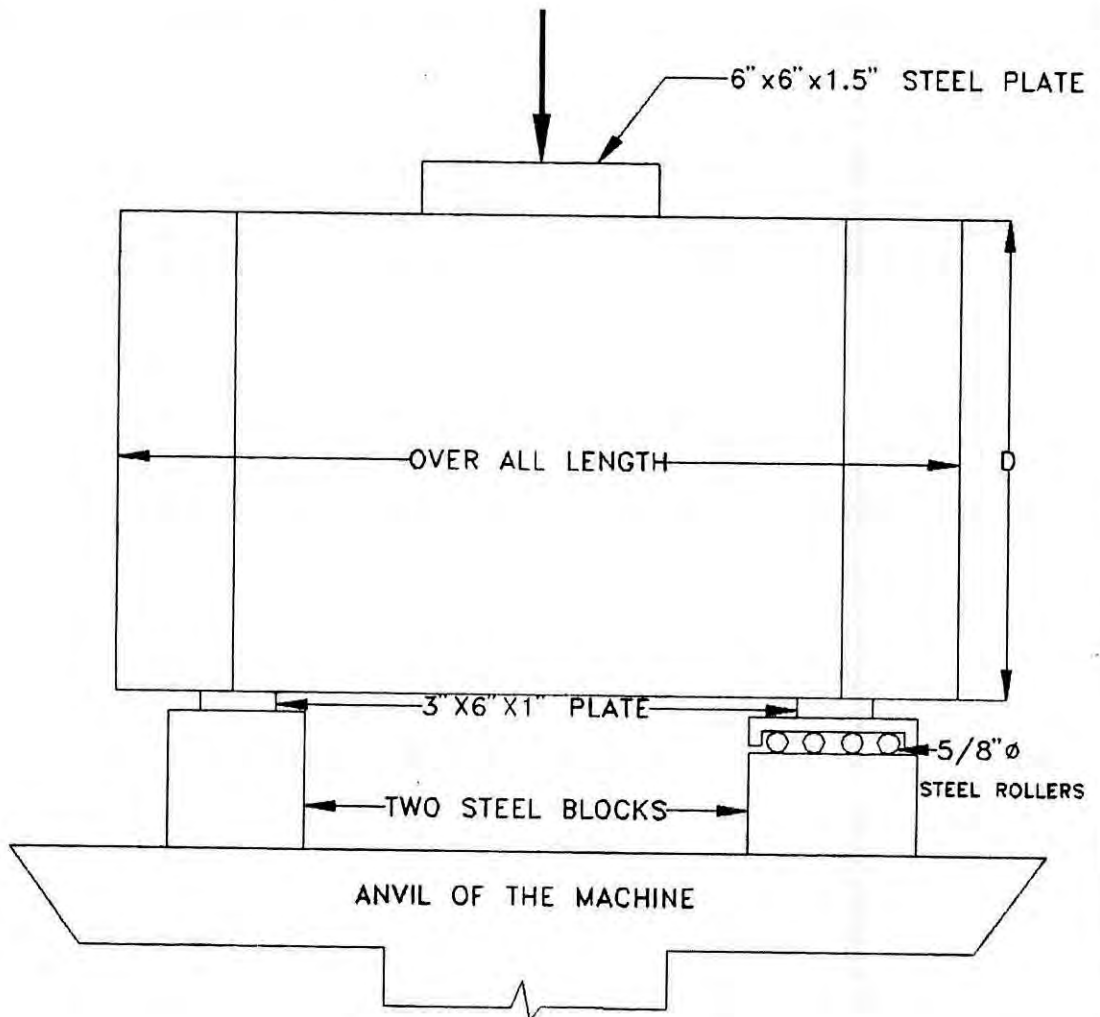


FIG-4.28 TEST SET-UP FOR LOADING

NOTE: WIDTH OF THE STEEL PLATE VARIES FROM 6" TO 12"

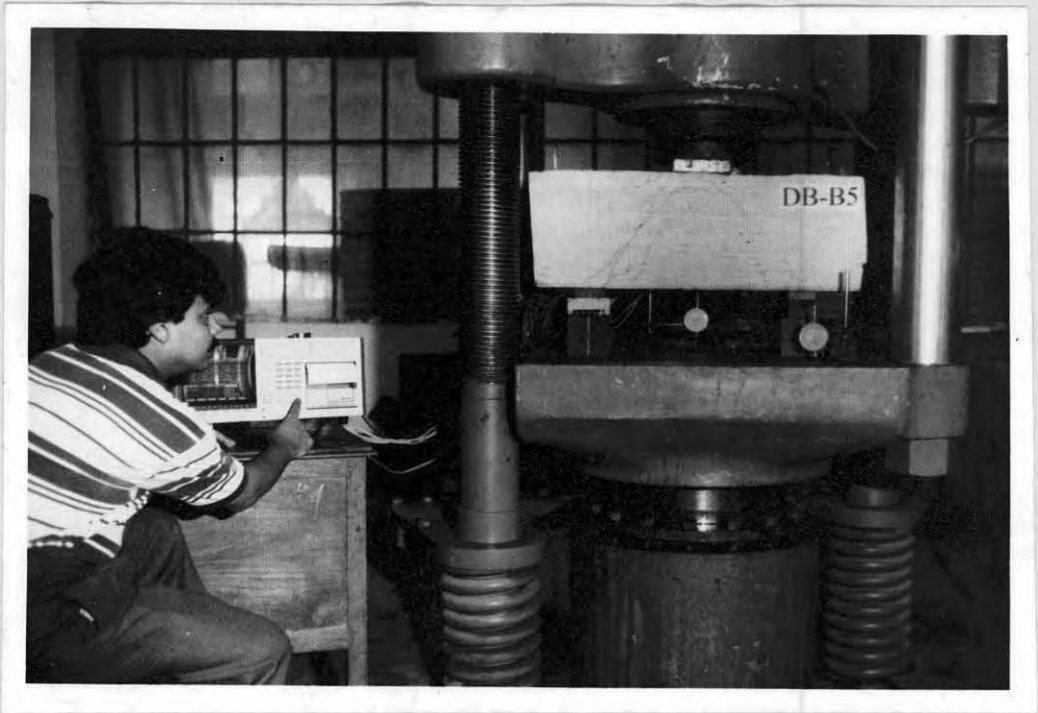


Fig. 4.29 Photograph of Test Set -up for Loading



Fig. 4.30 Photograph of Beam Testing

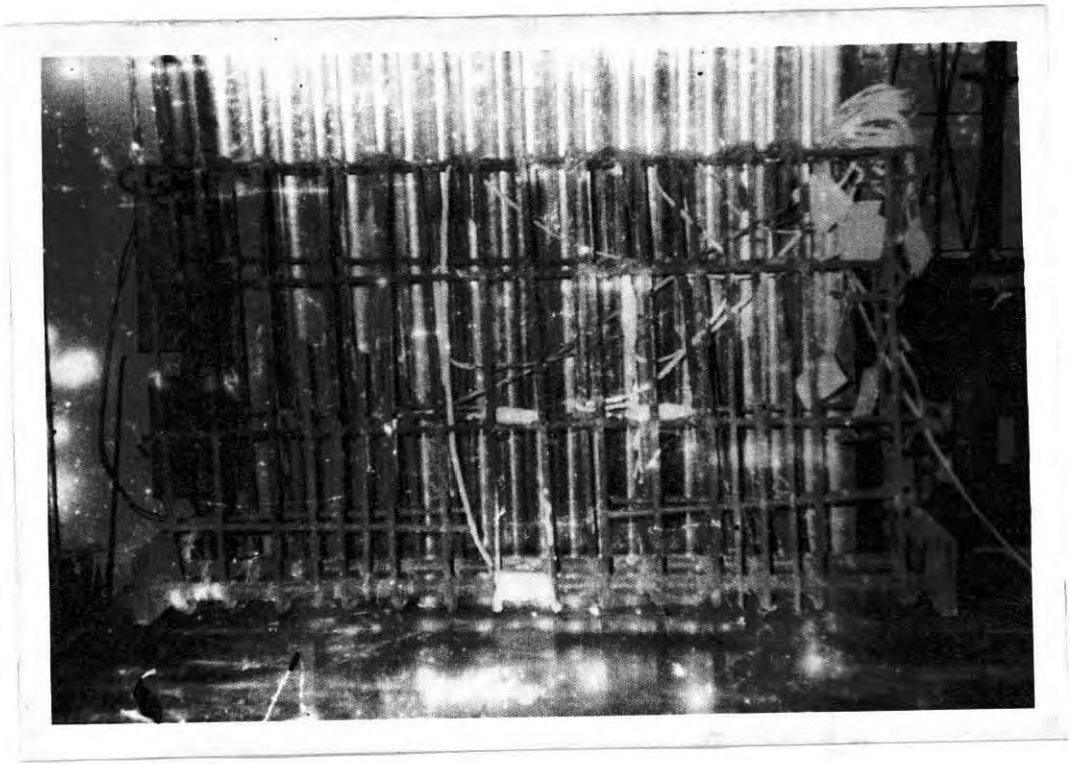


Fig. 4.31 Reinforcement Assembly for the Beam DB-A1

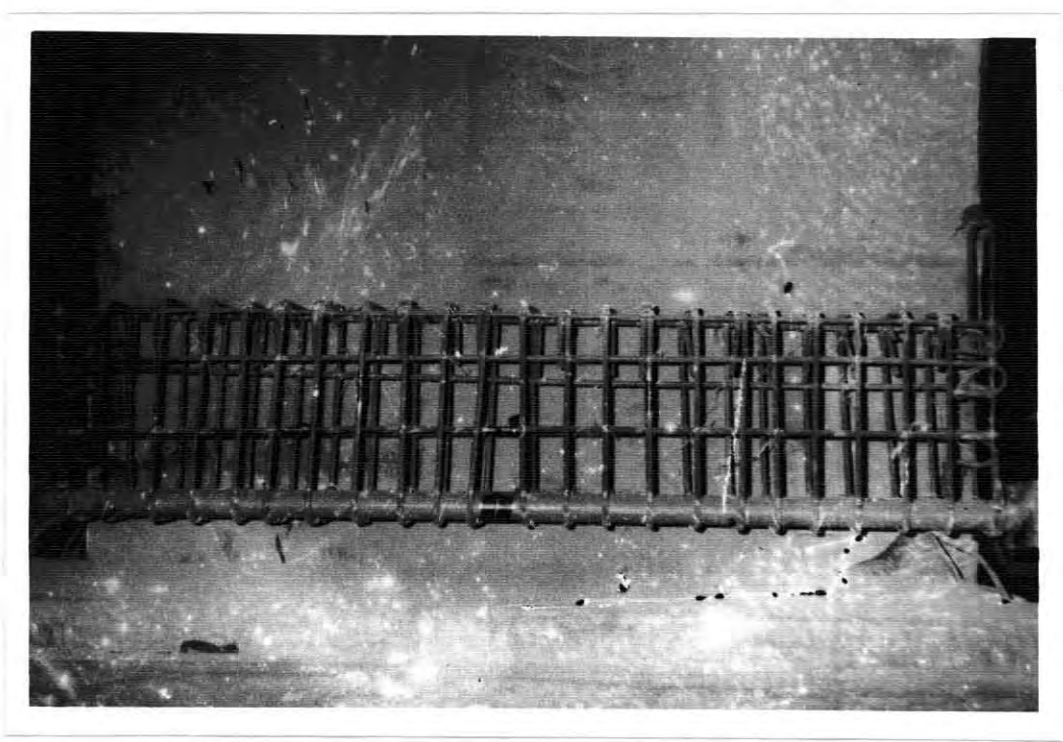


Fig. 4.32 Reinforcement Assembly for the Beam DB-B1

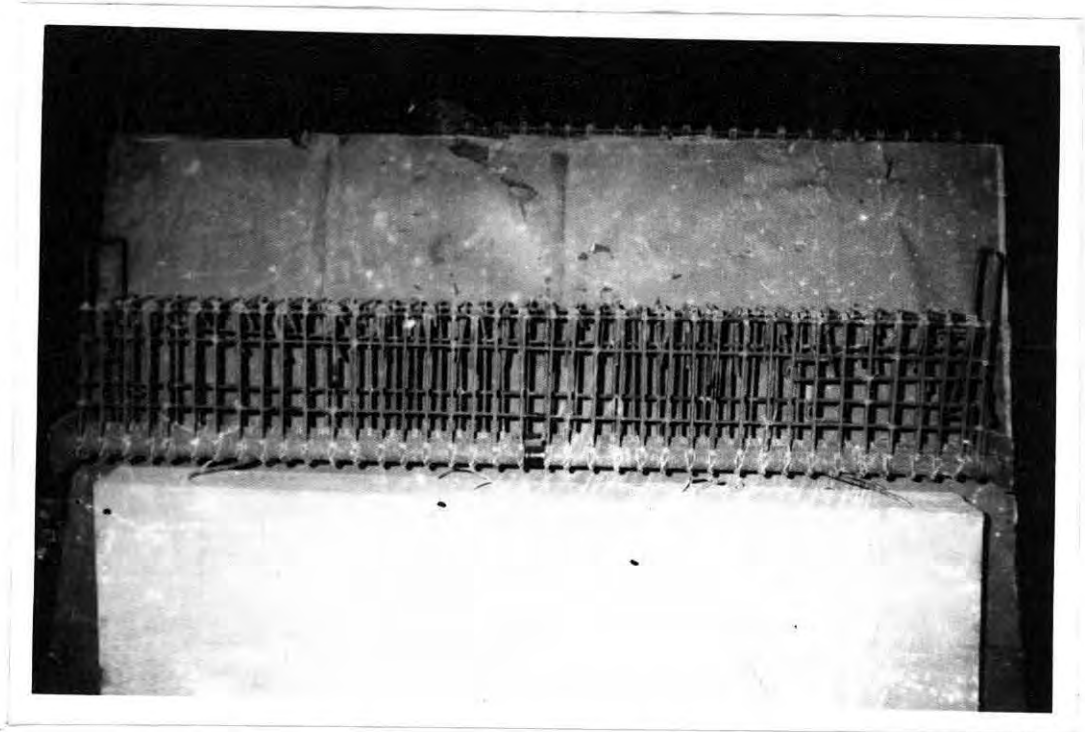


Fig. 4.33 Reinforcement Assembly for the Beam DB-C1

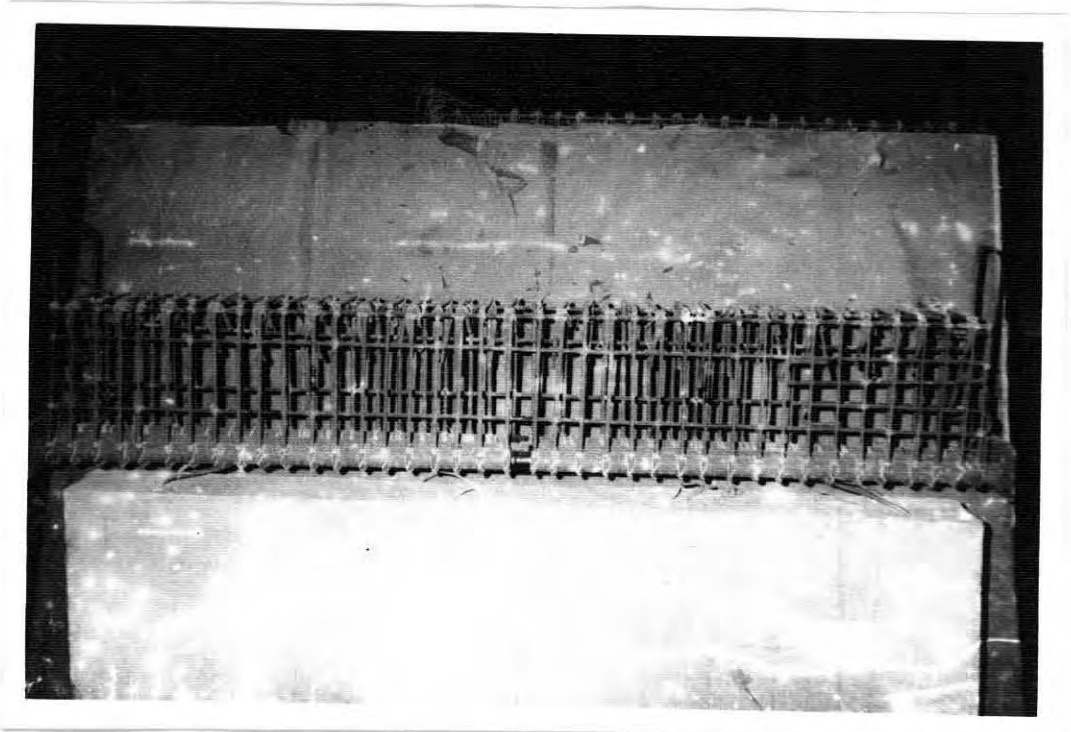


Fig. 4.34 Reinforcement Assembly for the Beam DB-D1

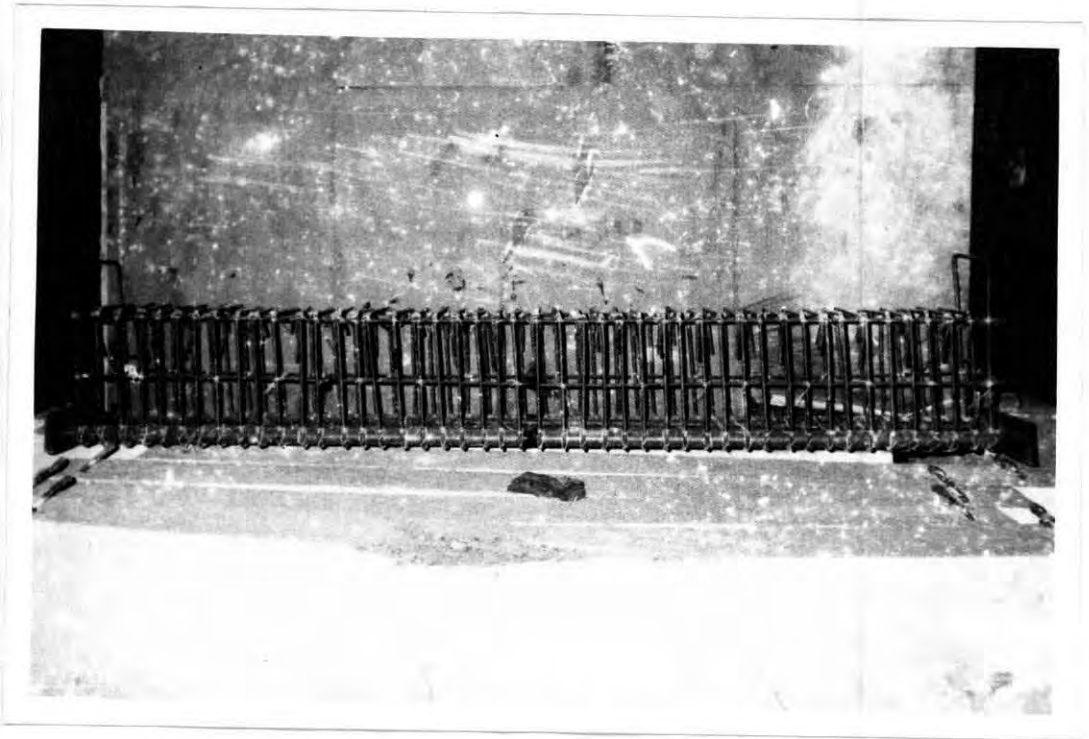


Fig. 4.35 Reinforcement Assembly for the Beam DB-E1

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# CHAPTER 5

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## TEST RESULTS

### 5.1 GENERAL

A total of 25 (twenty five) reinforced concrete deep beams were tested under static mid point concentrated loading system. The beams were divided into five series each consisting of five beams. The length to overall depth ratio of the five series of beams and the web reinforcement arrangements have been described in the preceding chapter. The test programme was undertaken to study the influence of span to depth ratio on the shear strength of deep beams and also to study effects of variation of the vertical and the horizontal web reinforcements on the following characteristic parameters. These are:

- (i) The cracking load.
- (ii) The ultimate load.
- (iii) The cracking pattern.
- (iv) The mid-span deflections.
- (v) Stresses in reinforcements.

The specific observations of interest during the tests had been recorded and are being presented in this chapter.

### 5.2 SUMMARY OF THE TEST RESULTS

The critical load at diagonal cracking, the load at flexural cracking, the ultimate load, the deflections and strains at the selective locations under different load intensities had all been recorded in a systematic manner during the test. The overall performance of the beams the test results are presented here in tabular forms. A general description of the contents of the different tables containing various test data is furnished below:

In Table 5.1 the details of the concrete strength (both compressive and the split cylinder strength) are described for all the 25 beams from DBA series to DBE series. For each series of beams six control cylinder were cast, out of which three were tested for compressive strength and the rest three for split cylinder test.

Some of the basic properties of brick aggregate concrete like compressive strength, split cylinder strength and the relation between them as given by Brazilian Ratio and the unit weight of hardened concrete are presented in Table 5.2.



**Table 5.1 Compressive and Split Cylinder strength of the beams**

| Beam Marks | Compressive Load (ton) | Area of Concrete Cylinder (in <sup>2</sup> ) | Compressive Strength (psi) | Average Compressive Strength, $f'_c$ (psi) | Maximum Load for Split (ton) | Split Area (in <sup>2</sup> ) | Split Cylinder Strength (psi) | Average Split Cylinder Strength, $f'_{sp}$ (psi) |
|------------|------------------------|----------------------------------------------|----------------------------|--------------------------------------------|------------------------------|-------------------------------|-------------------------------|--------------------------------------------------|
|------------|------------------------|----------------------------------------------|----------------------------|--------------------------------------------|------------------------------|-------------------------------|-------------------------------|--------------------------------------------------|

**Series DB-A : L/D =1.0**

|           |    |        |      |      |    |    |     |     |
|-----------|----|--------|------|------|----|----|-----|-----|
| DB: A1-A5 | 53 | 28.274 | 4199 |      | 19 | 72 | 591 |     |
|           | 58 | 28.274 | 4595 | 4886 | 23 | 72 | 716 | 622 |
|           | 74 | 28.274 | 5863 |      | 18 | 72 | 560 |     |

**Series DB-A: L/D =1.75**

|           |    |        |      |      |    |    |     |     |
|-----------|----|--------|------|------|----|----|-----|-----|
| DB: B1-B5 | 68 | 28.274 | 5387 |      | 15 | 72 | 467 |     |
|           | 72 | 28.274 | 5704 | 5704 | 17 | 72 | 529 | 519 |
|           | 76 | 28.274 | 6021 |      | 18 | 72 | 560 |     |

**Series DB-B: L/D =3.0**

|           |    |        |      |      |    |    |     |     |
|-----------|----|--------|------|------|----|----|-----|-----|
| DB: C1-C5 | 55 | 28.274 | 4357 |      | 23 | 72 | 716 |     |
|           | 60 | 28.274 | 4753 | 4621 | 14 | 72 | 436 | 498 |
|           | 60 | 28.274 | 4753 |      | 11 | 72 | 342 |     |

**Series DB-C: L/D =4.0**

|           |      |        |      |      |    |    |     |     |
|-----------|------|--------|------|------|----|----|-----|-----|
| DB: D1-D5 | 47.5 | 28.274 | 3763 |      | 14 | 72 | 436 |     |
|           | 48   | 28.274 | 3803 | 4080 | 21 | 72 | 653 | 570 |
|           | 59   | 28.274 | 4674 |      | 20 | 72 | 622 |     |

**Series DB-D: L/D =5.0**

|           |    |        |      |      |    |    |     |     |
|-----------|----|--------|------|------|----|----|-----|-----|
| DB: E1-E5 | 52 | 28.274 | 4120 |      | 14 | 72 | 436 |     |
|           | 46 | 28.274 | 3644 | 3856 | 12 | 72 | 373 | 436 |
|           | 48 | 28.274 | 3803 |      | 16 | 72 | 498 |     |

**Table 5.2 Some Properties of Concrete**

| Beam Marks | Average Compressive Strength, $f'_c$ (psi) | Average Split Cylinder Strength, $f'_{sp}$ (psi) | Brazilian Ratio $F'_{sp} = f'_{sp} / \sqrt{f'_c}$ | Unit Weight of Concrete $\gamma$ , (pcf) |
|------------|--------------------------------------------|--------------------------------------------------|---------------------------------------------------|------------------------------------------|
|------------|--------------------------------------------|--------------------------------------------------|---------------------------------------------------|------------------------------------------|

**Series DB-A : L/D =1.00**

|        |      |     |     |       |
|--------|------|-----|-----|-------|
| DB: A1 | 4886 | 622 | 8.9 | 132.2 |
| DB: A2 | 4886 | 622 | 8.9 | 132.2 |
| DB: A3 | 4886 | 622 | 8.9 | 132.2 |
| DB: A4 | 4886 | 622 | 8.9 | 132.2 |
| DB: A5 | 4886 | 622 | 8.9 | 132.2 |

**Series DB-B : L/D =1.75**

|        |      |     |      |       |
|--------|------|-----|------|-------|
| DB: B1 | 5704 | 519 | 6.87 | 135.1 |
| DB: B2 | 5704 | 519 | 6.87 | 135.1 |
| DB: B3 | 5704 | 519 | 6.87 | 135.1 |
| DB: B4 | 5704 | 519 | 6.87 | 135.1 |
| DB: B5 | 5704 | 519 | 6.87 | 135.1 |

**Series DB-C : L/D =3.0**

|        |      |     |      |       |
|--------|------|-----|------|-------|
| DB: C1 | 4621 | 498 | 7.33 | 131.7 |
| DB: C2 | 4621 | 498 | 7.33 | 131.7 |
| DB: C3 | 4621 | 498 | 7.33 | 131.7 |
| DB: C4 | 4621 | 498 | 7.33 | 131.7 |
| DB: C5 | 4621 | 498 | 7.33 | 131.7 |

**Series DB-D : L/D =4.0**

|        |      |     |      |       |
|--------|------|-----|------|-------|
| DB: D1 | 4080 | 570 | 8.92 | 130.1 |
| DB: D2 | 4080 | 570 | 8.92 | 130.1 |
| DB: D3 | 4080 | 570 | 8.92 | 130.1 |
| DB: D4 | 4080 | 570 | 8.92 | 130.1 |
| DB: D5 | 4080 | 570 | 8.92 | 130.1 |

**Series DB-E : L/D =5.0**

|        |      |     |      |       |
|--------|------|-----|------|-------|
| DB: E1 | 3856 | 436 | 7.02 | 129.9 |
| DB: E2 | 3856 | 436 | 7.02 | 129.9 |
| DB: E3 | 3856 | 436 | 7.02 | 129.9 |
| DB: E4 | 3856 | 436 | 7.02 | 129.9 |
| DB: E5 | 3856 | 436 | 7.02 | 129.9 |

In Table 5.3 properties of beams in DBA to DBE series are presented. It may be mentioned here that both vertical and horizontal web reinforcements were selected according to the minimum requirements of ACI 318-89 code <sup>(1)</sup>. According to this code, the flexural reinforcements for beams DBA to DBE were provided to ensure shear failure. It is specified that the minimum vertical web steel ratio is 0.15% and minimum horizontal web steel ratio is 0.25%. However, the code specification states that the spacings of vertical web steel shall not exceed  $d/5$  and those of horizontal web steel shall not exceed  $d/3$ . In the first set of each beams (DBA1 to DBE1) under study, 1/4" diameter bar was used as web reinforcement with the limits of  $d/5$  and  $d/3$  for maximum spacings. On the other hand, in four other beams in each of the series DBA to DBE, the amount of both vertical and horizontal web steels were varied in relation to those of the first beam of each series (DBA1 to DBE1) respectively. The variation in the amount of the vertical and the horizontal web reinforcements as percentages of ACI requirements is presented in Table 5.3

The critical load ( $P_{cr}$ ) at diagonal tension cracking, the load ( $P_f$ ) at the initiation of flexural crack, the ultimate load ( $P_u$ ) are all listed in Table 5.4. The ratio of diagonal cracking load to ultimate load are computed for all the beams and are represented in this table.

Table 5.5 shows the nominal shear stresses  $v_{cr}$  and  $v_u$  at the observed initial diagonal tension cracking load ( $P_{cr}$ ) and at ultimate load ( $P_u$ ) respectively. The maximum bending moments  $M_{cr}$  and  $M_u$  respectively at initial diagonal cracking load and at ultimate load for the test beams of all the series are also shown in the same table.

The nominal shear stresses  $v_{cr}$  and  $v_u$  as given in Table 5.5 were determined by using the relations  $v_{cr} = V_{cr}/bd$  and  $v_u = V_u/bd$ ,  $V_{cr}$  and  $V_u$  were the maximum shear force at the critical section corresponding to the initial diagonal tension cracking load ( $P_{cr}$ ) and the ultimate load ( $P_u$ ) sustained by the test beam. The maximum bending moments  $M_{cr}$  and  $M_u$  at initial diagonal tension cracking load and at ultimate load respectively were obtained by multiplying the corresponding maximum shear force by the nominal shear span  $X_N$  of the test beam.

### 5.3 LOAD DEFLECTION RECORD

Mid span deflection was recorded at a regular interval of increasing load with a deflectometer (graduated in .01 mm division) placed at the bottom edge of the beam. Compensation was made for the support settlement by placing another similar deflectometer under an extended plate located at the bottom of the supporting block. The net difference of the readings of the two deflectometers has been noted as the observed central deflection. The computed and observed load-deflection curves of the 25 test beams are presented graphically in Figs. 5.1 through 5.8. The deflection recorded represents the mid span deflection with appropriate compensation made for support settlement. In Figs. 5.9 to 5.13 the load - deflection curves for five set of beams under each series are compared and found that the beams imposed under a particular load shows different values of deflection due to change of shear reinforcement in the beams.

**Table 5.3 Properties of Test Beams**

| Beam Mark                        | Measured Overall Depth D, (inch) | Beam Width, b (inch) | Beam Length, L (inch) | Nominal L/D | Nominal L/d Ratio | Tension Steel Ratio As/bd | Web Steel Ratio Vertical $P_v = A_v/(s_v b)$ | Web Steel Ratio Horizontal $P_h = A_h/(s_h b)$ | % Change of Vertical Web Reinforcement over 1 <sup>st</sup> beam | % Change of Horizontal Web Reinforcement over 1 <sup>st</sup> beam | Cylinder Crushing Strength $f'_c$ (psi) | Cylinder Split Strength, $f'_{sp}$ (psi) |
|----------------------------------|----------------------------------|----------------------|-----------------------|-------------|-------------------|---------------------------|----------------------------------------------|------------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------------|-----------------------------------------|------------------------------------------|
| <b>Series D B-A : L/D = 1.00</b> |                                  |                      |                       |             |                   |                           |                                              |                                                |                                                                  |                                                                    |                                         |                                          |
| D B-A1                           | 21.4                             | 6.5                  | 22.1                  | 1.033       | 1.11              | 0.006973                  | 0.005846                                     | 0.002923                                       | -                                                                | -                                                                  |                                         |                                          |
| D B-A2                           | 21.5                             | 6.4                  | 23.4                  | 1.088       | 1.17              | 0.007047                  | 0.003958                                     | 0.003958                                       | -28.6                                                            | -50.0                                                              |                                         |                                          |
| D B-A3                           | 21.4                             | 6.0                  | 22.3                  | 1.042       | 1.12              | 0.007554                  | 0.008444                                     | 0.002714                                       | 28.6                                                             | 50.0                                                               | 4886                                    | 622                                      |
| D B-A4                           | 21.5                             | 6.5                  | 22.4                  | 1.042       | 1.12              | 0.006938                  | 0.005846                                     | 0.002923                                       | 00.0                                                             | -50.0                                                              |                                         |                                          |
| D B-A5                           | 21.2                             | 6.0                  | 22.7                  | 1.071       | 1.15              | 0.007631                  | 0.003166                                     | 0.003166                                       | -57.1                                                            | 00.0                                                               |                                         |                                          |
| <b>Series D B-B : L/D = 1.75</b> |                                  |                      |                       |             |                   |                           |                                              |                                                |                                                                  |                                                                    |                                         |                                          |
| D B-B1                           | 12.2                             | 6.3                  | 21.4                  | 1.754       | 2.00              | 0.013381                  | 0.009047                                     | 0.005170                                       | -                                                                | -                                                                  |                                         |                                          |
| D B-B2                           | 12.2                             | 6.3                  | 21.5                  | 1.762       | 2.01              | 0.013381                  | 0.012063                                     | 0.004021                                       | 33.3                                                             | -50.0                                                              |                                         |                                          |
| D B-B3                           | 12.3                             | 6.3                  | 21.6                  | 1.756       | 2.00              | 0.013257                  | 0.003619                                     | 0.007238                                       | -58.3                                                            | 50.0                                                               | 5704                                    | 519                                      |
| D B-B4                           | 12.0                             | 6.4                  | 21.7                  | 1.808       | 2.07              | 0.013423                  | 0.005968                                     | 0.002968                                       | -33.3                                                            | -50.0                                                              |                                         |                                          |
| D B-B5                           | 12.3                             | 6.4                  | 21.2                  | 1.724       | 1.96              | 0.01305                   | 0.004453                                     | 0.005089                                       | -50.0                                                            | 00.0                                                               |                                         |                                          |
| <b>Series D B-C : L/D = 3.00</b> |                                  |                      |                       |             |                   |                           |                                              |                                                |                                                                  |                                                                    |                                         |                                          |
| D B-C1                           | 12.2                             | 6.7                  | 36.0                  | 2.951       | 3.36              | 0.035626                  | 0.008507                                     | 0.004861                                       | -                                                                | -                                                                  |                                         |                                          |
| D B-C2                           | 12.3                             | 6.6                  | 36.1                  | 2.935       | 3.34              | 0.035831                  | 0.011515                                     | 0.003838                                       | 27.8                                                             | -50.0                                                              |                                         |                                          |
| D B-C3                           | 12.2                             | 6.5                  | 36.2                  | 2.967       | 3.38              | 0.036722                  | 0.003507                                     | 0.007015                                       | -61.1                                                            | 50.0                                                               | 4621                                    | 498                                      |
| D B-C4                           | 12.3                             | 6.4                  | 36.4                  | 2.959       | 3.37              | 0.03695                   | 0.005937                                     | 0.002968                                       | -33.3                                                            | -50.0                                                              |                                         |                                          |
| D B-C5                           | 12.3                             | 6.5                  | 36.3                  | 2.951       | 3.36              | 0.036382                  | 0.004384                                     | 0.005010                                       | -50.0                                                            | 00.0                                                               |                                         |                                          |
| <b>Series D B-D : L/D = 4.00</b> |                                  |                      |                       |             |                   |                           |                                              |                                                |                                                                  |                                                                    |                                         |                                          |
| D B-D1                           | 12.0                             | 8.1                  | 49.0                  | 4.083       | 4.67              | 0.045044                  | 0.007037                                     | 0.004021                                       | -                                                                | -                                                                  |                                         |                                          |
| D B-D2                           | 12.0                             | 8.0                  | 49.0                  | 4.083       | 4.67              | 0.045607                  | 0.009500                                     | 0.003166                                       | 34.8                                                             | -50.0                                                              |                                         |                                          |
| D B-D3                           | 12.0                             | 8.0                  | 48.7                  | 4.058       | 4.64              | 0.045607                  | 0.002850                                     | 0.005700                                       | -65.2                                                            | 50.0                                                               | 4080                                    | 570                                      |
| D B-D4                           | 12.4                             | 8.2                  | 48.7                  | 3.927       | 4.47              | 0.042862                  | 0.004634                                     | 0.002317                                       | -34.8                                                            | -50.0                                                              |                                         |                                          |
| D B-D5                           | 12.0                             | 8.0                  | 49.2                  | 4.100       | 4.69              | 0.045607                  | 0.003562                                     | 0.004071                                       | -52.2                                                            | 00.0                                                               |                                         |                                          |
| <b>Series D B-E : L/D = 5.00</b> |                                  |                      |                       |             |                   |                           |                                              |                                                |                                                                  |                                                                    |                                         |                                          |
| D B-E1                           | 12.4                             | 12.5                 | 60.8                  | 4.903       | 5.58              | 0.037490                  | 0.004560                                     | 0.002605                                       | -                                                                | -                                                                  |                                         |                                          |
| D B-E2                           | 12.1                             | 12.3                 | 60.3                  | 4.983       | 5.69              | 0.039178                  | 0.006178                                     | 0.002059                                       | 39.3                                                             | -50.0                                                              |                                         |                                          |
| D B-E3                           | 12.4                             | 12.2                 | 60.5                  | 4.879       | 5.55              | 0.038412                  | 0.001868                                     | 0.003737                                       | -60.7                                                            | 50.0                                                               | 3856                                    | 436                                      |
| D B-E4                           | 12.5                             | 12.0                 | 61.7                  | 4.936       | 5.61              | 0.038697                  | 0.003166                                     | 0.001583                                       | -32.1                                                            | -50.0                                                              |                                         |                                          |
| D B-E5                           | 12.0                             | 12.2                 | 60.6                  | 5.050       | 5.77              | 0.039875                  | 0.002336                                     | 0.002669                                       | -50.0                                                            | 00.0                                                               |                                         |                                          |



Table 5.4 Observed Cracking and Ultimate loads of Test beams

| Beam Mark                                    | Average Compressive Strength, $f_c$ (psi) | Cylinder Average Split Strength, $f'_{sp}$ (psi) | Diagonal Cracking Load, $P_{cr}$ (kips) | Flexural Cracking Load, $P_f$ (kips) | Ultimate Load, $P_u$ (kips) | Ratio $P_{cr}/P_u$        | Ratio $P_f/P_u$ |
|----------------------------------------------|-------------------------------------------|--------------------------------------------------|-----------------------------------------|--------------------------------------|-----------------------------|---------------------------|-----------------|
| <b>Series DB-A : <math>L/D = 1.00</math></b> |                                           |                                                  |                                         |                                      |                             |                           |                 |
| DB-A1                                        |                                           |                                                  | 72                                      | 72                                   | 180.5                       | 0.398892                  | 0.398892        |
| DB-A2                                        |                                           |                                                  | 70                                      | 70                                   | 201.0                       | 0.348259                  | 0.348259        |
| DB-A3                                        | 4886                                      | 622                                              | 95                                      | 110                                  | 183.0                       | 0.519126                  | 0.601093        |
| DB-A4                                        |                                           |                                                  | 75                                      | 75                                   | 190.0                       | 0.394737                  | 0.394737        |
| DB-A5                                        |                                           |                                                  | 70                                      | 95                                   | 185.0                       | 0.378378                  | 0.513514        |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>Average: 0.4078784</b> |                 |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>C : 14.32</b>          |                 |
| <b>Series DB-B : <math>L/D = 1.75</math></b> |                                           |                                                  |                                         |                                      |                             |                           |                 |
| DB-B1                                        |                                           |                                                  | 50                                      | 50                                   | 122.0                       | 0.409836                  | 0.409836        |
| DB-B2                                        |                                           |                                                  | 40                                      | 50                                   | 120.0                       | 0.333333                  | 0.416667        |
| DB-B3                                        | 5704                                      | 519                                              | 33                                      | 40                                   | 123.0                       | 0.268293                  | 0.325203        |
| DB-B4                                        |                                           |                                                  | 40                                      | 40                                   | 102.5                       | 0.390244                  | 0.390244        |
| DB-B5                                        |                                           |                                                  | 35                                      | 35                                   | 120.0                       | 0.291667                  | 0.291667        |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>Average: 0.3386746</b> |                 |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>C : 16.126</b>         |                 |
| <b>Series DB-C : <math>L/D = 3.00</math></b> |                                           |                                                  |                                         |                                      |                             |                           |                 |
| DB-C1                                        |                                           |                                                  | 37                                      | 40                                   | 105.0                       | 0.352381                  | 0.380952        |
| DB-C2                                        |                                           |                                                  | 50                                      | 50                                   | 133.0                       | 0.375940                  | 0.375904        |
| DB-C3                                        | 4621                                      | 498                                              | 43                                      | 75                                   | 095.0                       | 0.452632                  | 0.789474        |
| DB-C4                                        |                                           |                                                  | 32                                      | 40                                   | 087.5                       | 0.365714                  | 0.457143        |
| DB-C5                                        |                                           |                                                  | 38                                      | 60                                   | 088.0                       | 0.431818                  | 0.681818        |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>Average: 0.395688</b>  |                 |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>C : 9.96</b>           |                 |
| <b>Series DB-D : <math>L/D = 4.00</math></b> |                                           |                                                  |                                         |                                      |                             |                           |                 |
| DB-D1                                        |                                           |                                                  | 38                                      | 38                                   | 112.0                       | 0.339286                  | 0.339286        |
| DB-D2                                        |                                           |                                                  | 30                                      | 30                                   | 118.0                       | 0.254237                  | 0.254237        |
| DB-D3                                        | 4080                                      | 570                                              | 40                                      | 57                                   | 800.0                       | 0.500000                  | 0.712500        |
| DB-D4                                        |                                           |                                                  | 40                                      | 58                                   | 110.0                       | 0.363636                  | 0.527273        |
| DB-D5                                        |                                           |                                                  | 40                                      | 40                                   | 103.5                       | 0.386473                  | 0.386473        |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>Average: 0.3687264</b> |                 |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>C : 21.54</b>          |                 |
| <b>Series DB-E : <math>L/D = 5.00</math></b> |                                           |                                                  |                                         |                                      |                             |                           |                 |
| DB-E1                                        |                                           |                                                  | 40                                      | 64                                   | 131.0                       | 0.305344                  | 0.048855        |
| DB-E2                                        |                                           |                                                  | 50                                      | 50                                   | 126.0                       | 0.396825                  | 0.396825        |
| DB-E3                                        | 3856                                      | 436                                              | 40                                      | 40                                   | 112.0                       | 0.357143                  | 0.357143        |
| DB-E4                                        |                                           |                                                  | 38                                      | 38                                   | 130.0                       | 0.292308                  | 0.292308        |
| DB-E5                                        |                                           |                                                  | 40                                      | 40                                   | 108.5                       | 0.368664                  | 0.368664        |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>Average: 0.4078784</b> |                 |
|                                              |                                           |                                                  |                                         |                                      |                             | <b>C : 14.32</b>          |                 |

**Table 5.5 Nominal Shear Stress and Maximum Bending Moments at Cracking and at Ultimate Conditions.**

| Beam Mark | Nominal Shear Stress at                               |                                   | Maximum Bending Mement at                              |                                    |
|-----------|-------------------------------------------------------|-----------------------------------|--------------------------------------------------------|------------------------------------|
|           | Initial Diagonal Cracking Stress<br>$v_{cr}$<br>(psi) | Ultimate Stress<br>$v_u$<br>(psi) | Initial Diagonal Cracking Load<br>$M_{cr}$<br>(kip-in) | Ultimate Load<br>$M_u$<br>(Kip-in) |

**Series DB-A :  $L/D = 1.00$**

|       |        |                 |               |                |
|-------|--------|-----------------|---------------|----------------|
| DB-A1 | 278.31 | 697.72          | 397.80        | 0997.26        |
| DB-A2 | 273.44 | 785.16          | 409.50        | 1175.85        |
| DB-A3 | 397.82 | 766.33          | 529.62        | 1020.23        |
| DB-A4 | 288.46 | 730.77          | 420.00        | 1064.00        |
| DB-A5 | 296.11 | 782.57          | 397.25        | 1049.88        |
|       |        | <b>Average:</b> | <b>430.83</b> | <b>1061.27</b> |

**Series DB-B :  $L/D = 1.75$**

|       |        |                 |               |               |
|-------|--------|-----------------|---------------|---------------|
| DB-B1 | 370.86 | 904.91          | 267.50        | 652.70        |
| DB-B2 | 296.69 | 890.08          | 215.00        | 645.00        |
| DB-B3 | 242.50 | 903.88          | 178.20        | 664.20        |
| DB-B4 | 297.62 | 762.65          | 217.00        | 556.06        |
| DB-B5 | 253.18 | 868.06          | 185.50        | 636.00        |
|       |        | <b>Average:</b> | <b>212.64</b> | <b>630.79</b> |

**Series DB-C :  $L/D = 3.00$**

|       |        |                 |               |               |
|-------|--------|-----------------|---------------|---------------|
| DB-C1 | 258.06 | 732.32          | 333.00        | 0945.00       |
| DB-C2 | 350.73 | 932.94          | 451.25        | 1200.32       |
| DB-C3 | 309.13 | 682.96          | 389.15        | 0859.75       |
| DB-C4 | 231.48 | 632.96          | 291.20        | 0796.25       |
| DB-C5 | 270.66 | 626.78          | 344.85        | 0798.60       |
|       |        | <b>Average:</b> | <b>361.81</b> | <b>919.98</b> |

**Series DB-D :  $L/D = 4.00$**

|       |        |                 |              |                |
|-------|--------|-----------------|--------------|----------------|
| DB-D1 | 223.40 | 658.44          | 465.50       | 1372.00        |
| DB-D2 | 178.57 | 702.38          | 367.50       | 1445.50        |
| DB-D3 | 238.10 | 476.19          | 487.00       | 0974.00        |
| DB-D4 | 223.76 | 615.35          | 487.00       | 1339.25        |
| DB-D5 | 238.10 | 616.07          | 492.00       | 1273.05        |
|       |        | <b>Average:</b> | <b>459.8</b> | <b>1280.76</b> |

**Series DB-E :  $L/D = 5.00$**

|       |        |                 |               |                |
|-------|--------|-----------------|---------------|----------------|
| DB-E1 | 146.79 | 480.73          | 608.00        | 1991.20        |
| DB-E2 | 191.75 | 483.20          | 753.75        | 1899.45        |
| DB-E3 | 150.40 | 421.12          | 605.00        | 1694.00        |
| DB-E4 | 143.94 | 492.42          | 586.15        | 2005.25        |
| DB-E5 | 156.13 | 423.50          | 606.00        | 1643.77        |
|       |        | <b>Average:</b> | <b>631.78</b> | <b>1846.73</b> |



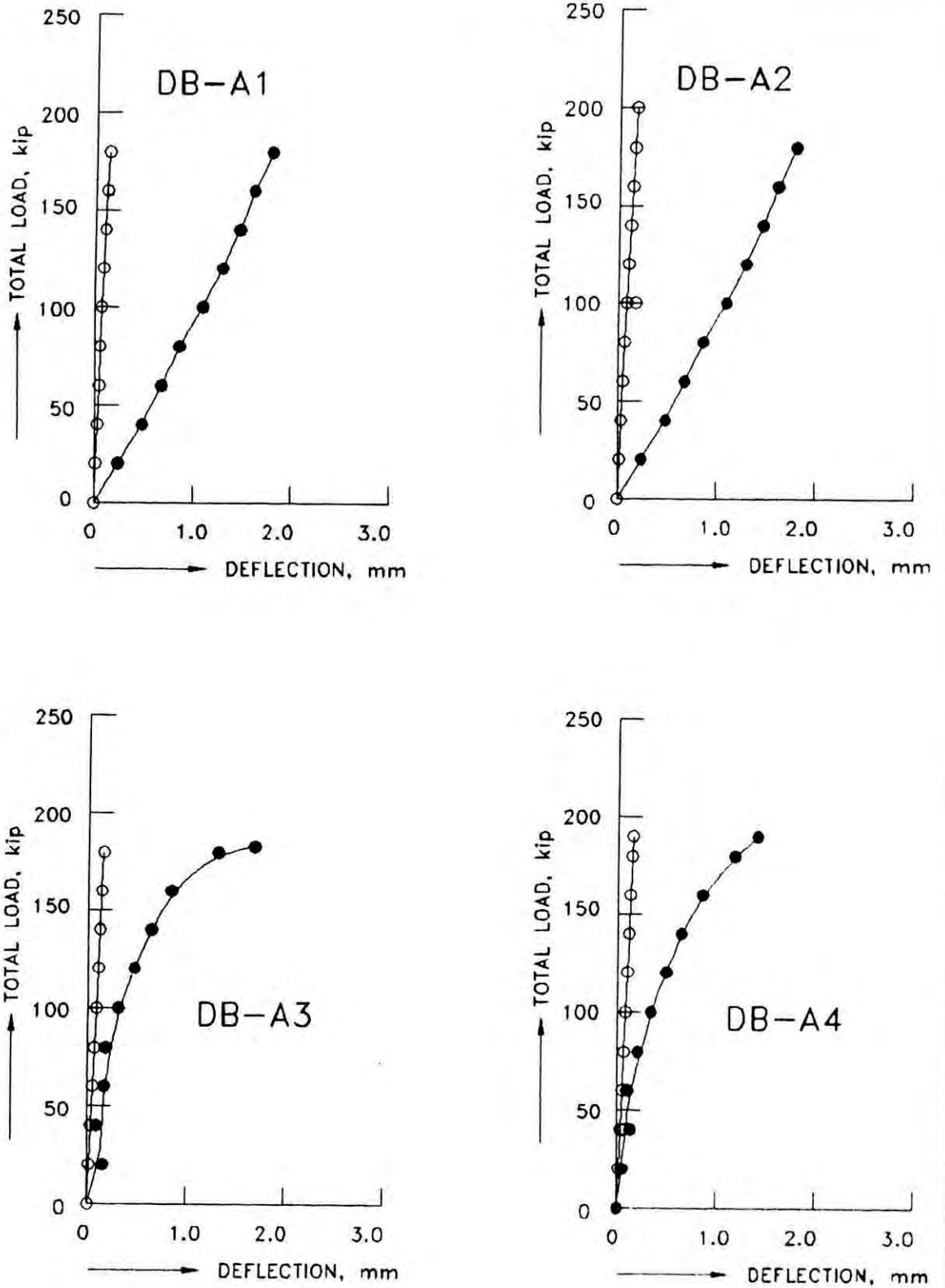
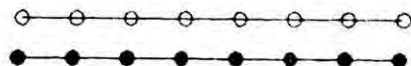


FIG. 5.1 LOAD DEFLECTION CURVES FOR BEAMS DB - A1, A2, A3, A4

Note: Computed Deflection  
Observed Deflection



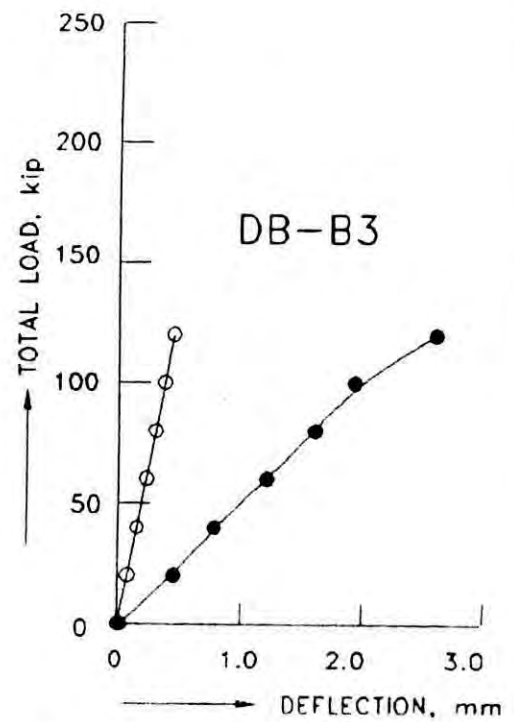
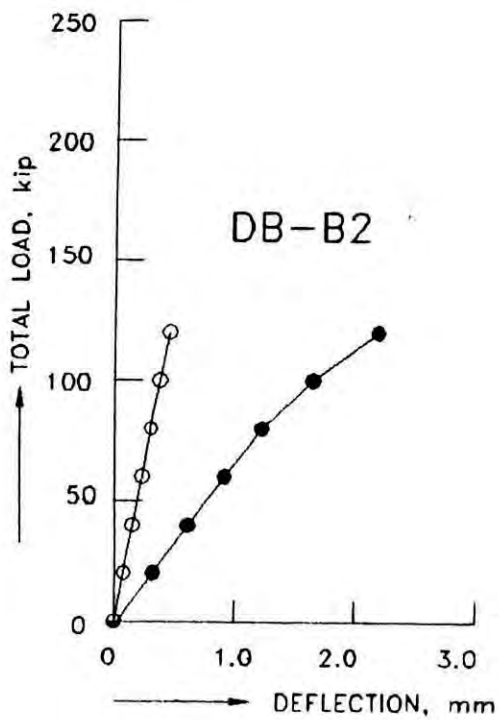
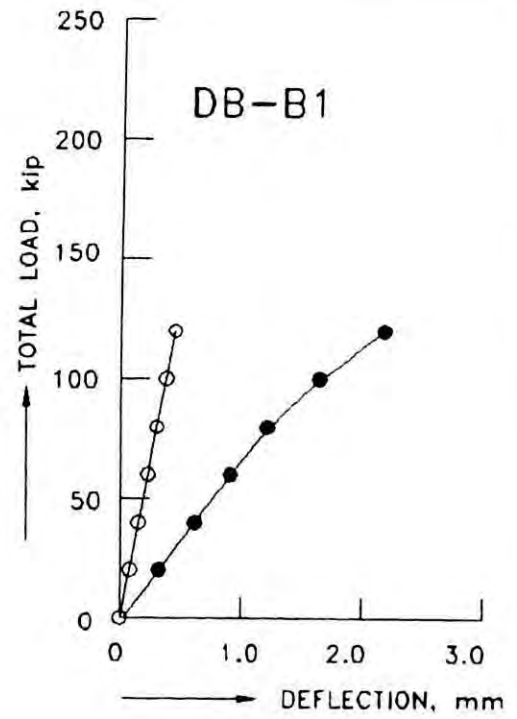
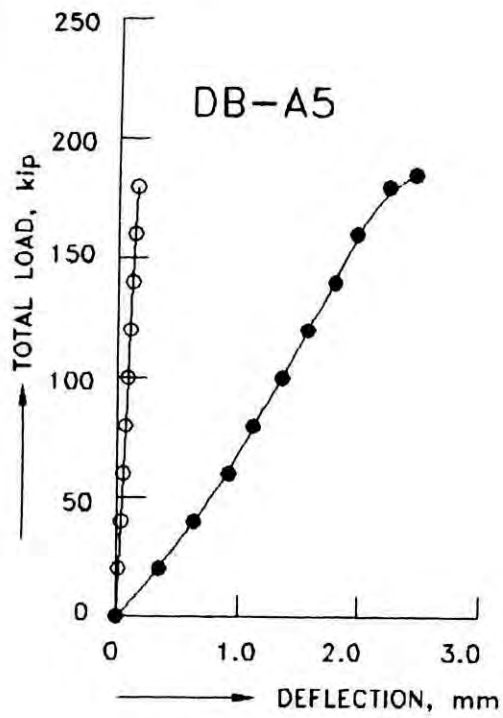
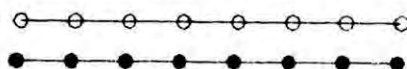


FIG. 5.2 LOAD DEFLECTION CURVES FOR BEAMS DB - A5, B1, B2, B3

Note: Computed Deflection

Observed Deflection



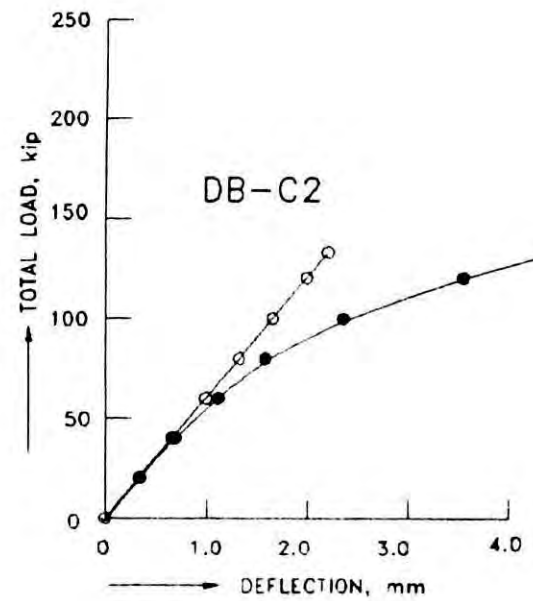
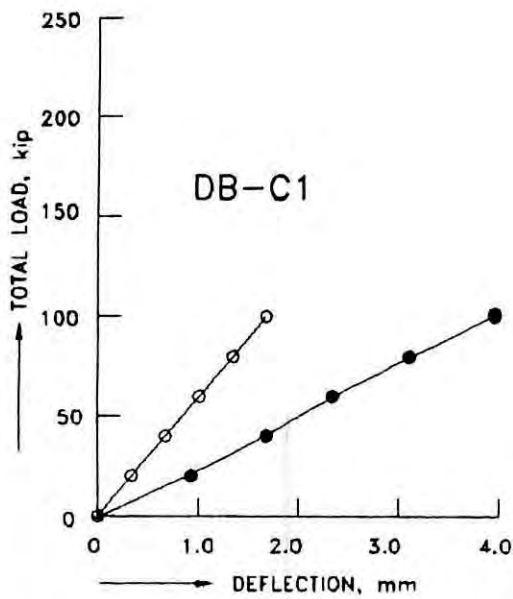
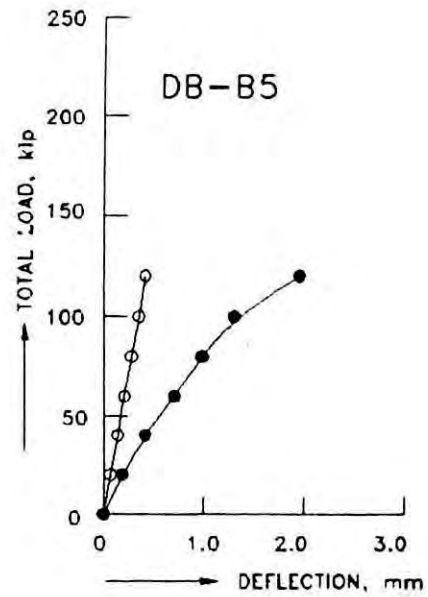
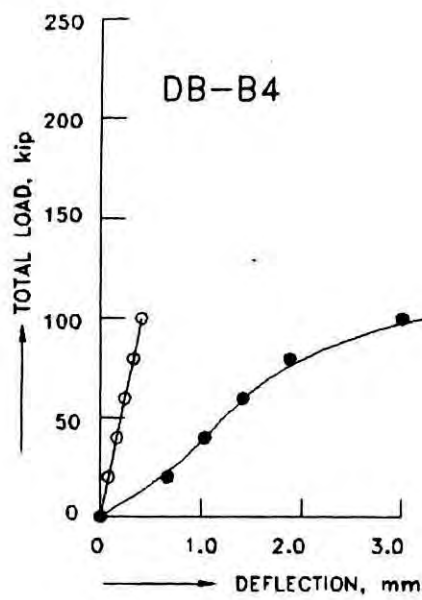
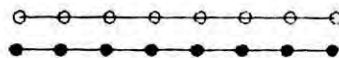


FIG. 5.3 LOAD DEFLECTION CURVES FOR BEAMS DB - B4, B5, C1, C2

Note: Computed Deflection  
Observed Deflection



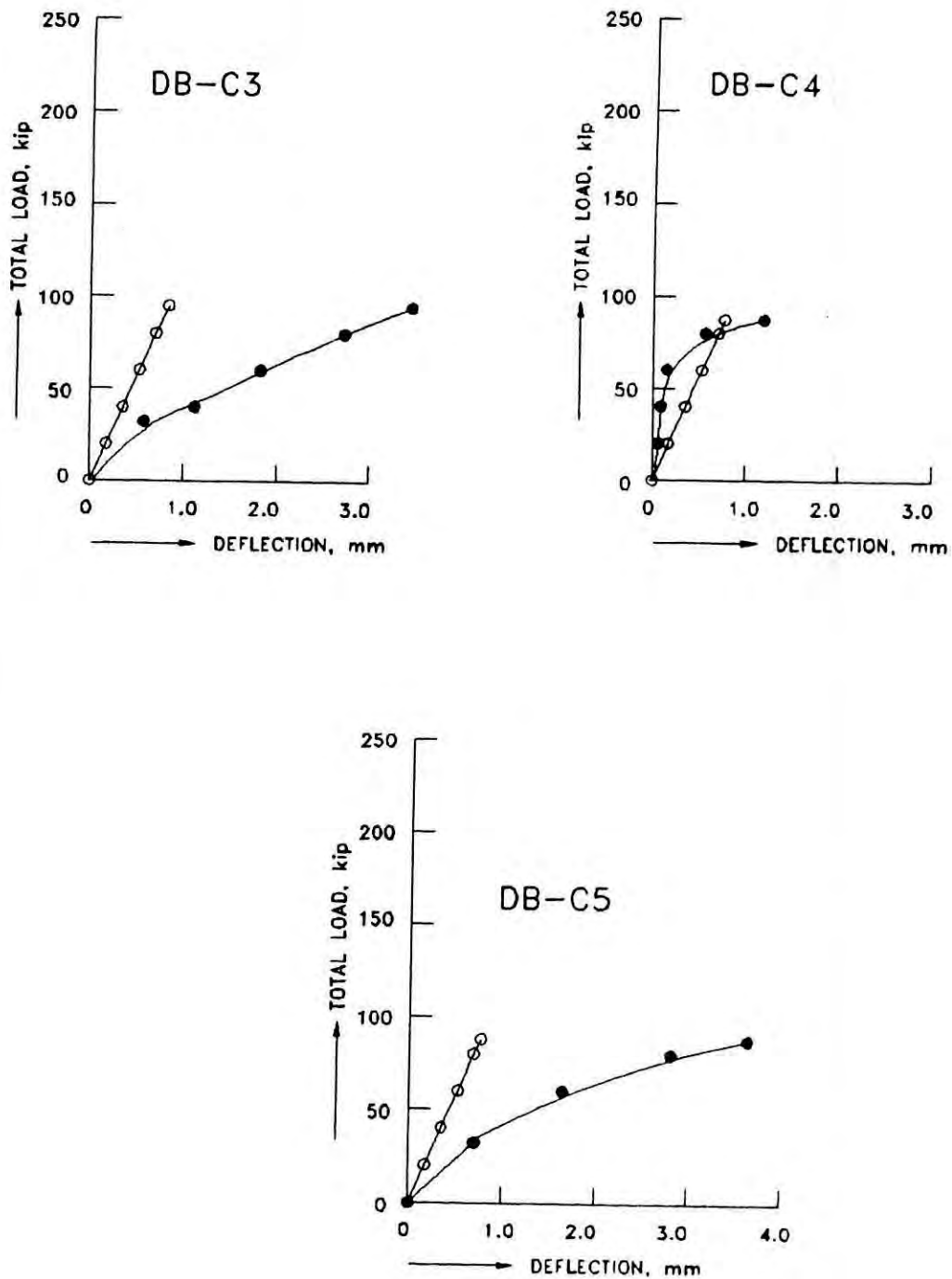
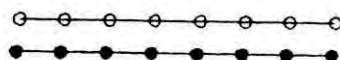


FIG. 5.4 LOAD DEFLECTION CURVES FOR BEAMS DB - C3, C4, C5

Note: Computed Deflection  
Observed Deflection



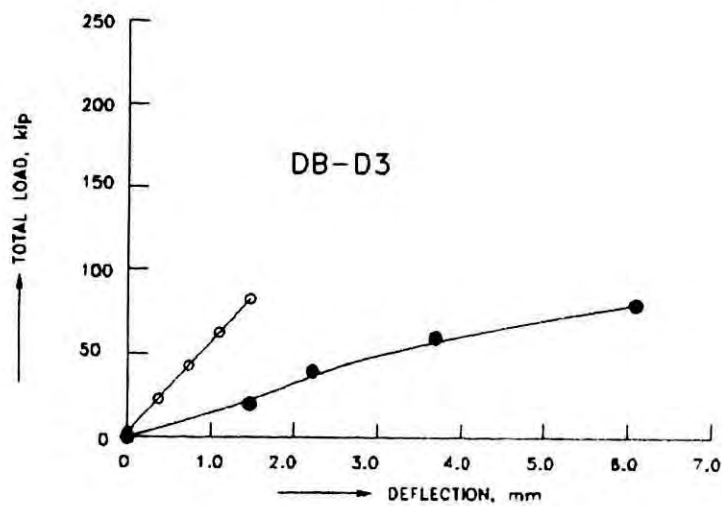
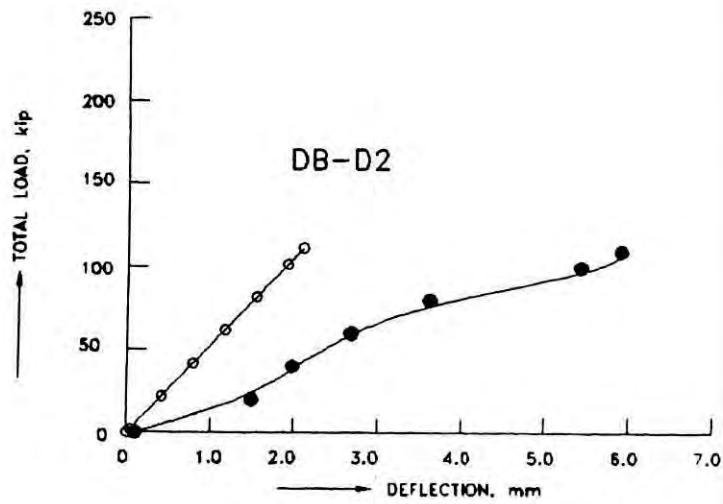
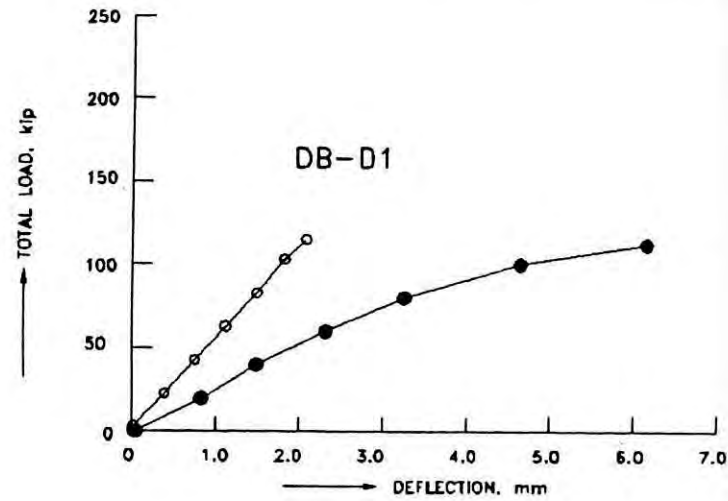
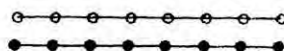


FIG. 5.5 LOAD DEFLECTION CURVES FOR BEAMS DB - D1, D2, D3

Note: Computed Deflection  
Observed Deflection



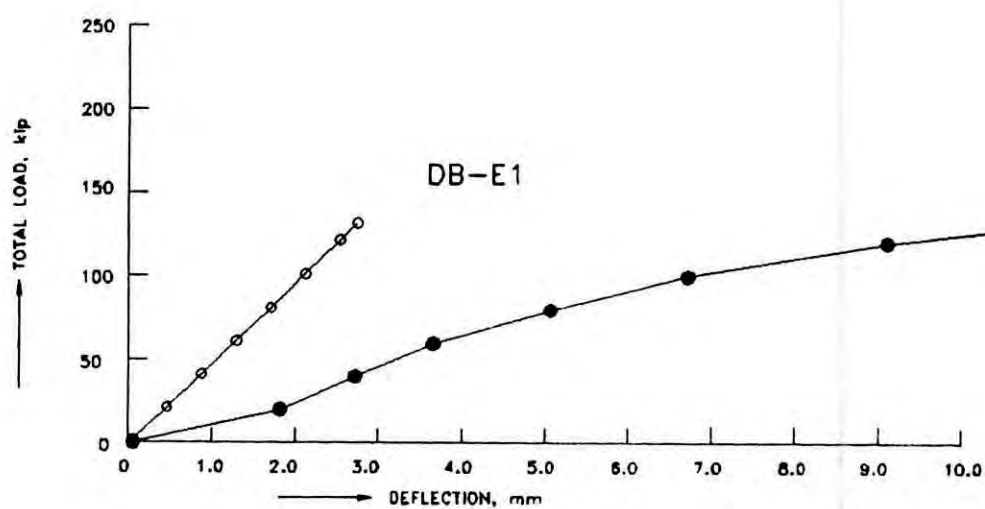
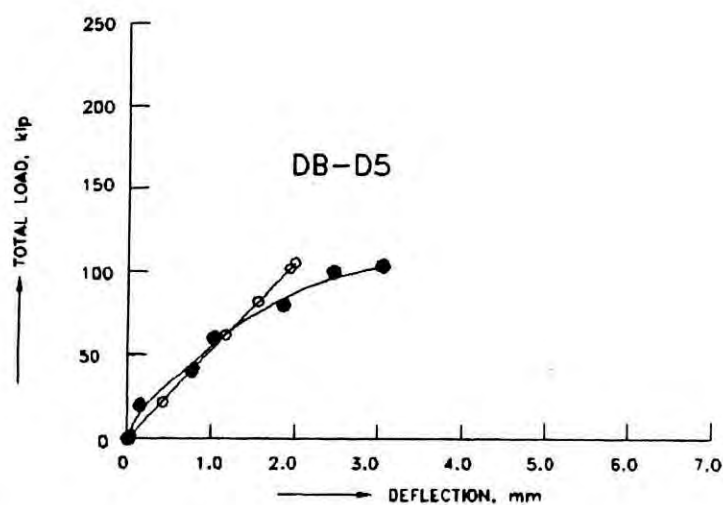
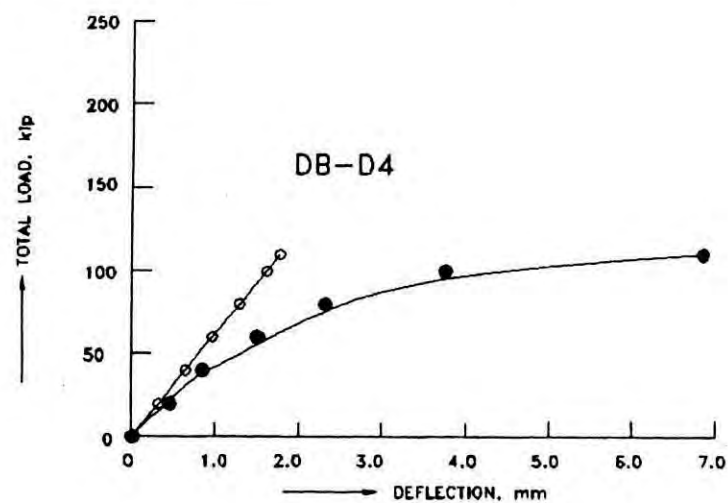
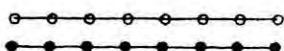


FIG. 5.6 LOAD DEFLECTION CURVES FOR BEAMS DB - D4, D5, E1

Note: Computed Deflection  
 Observed Deflection





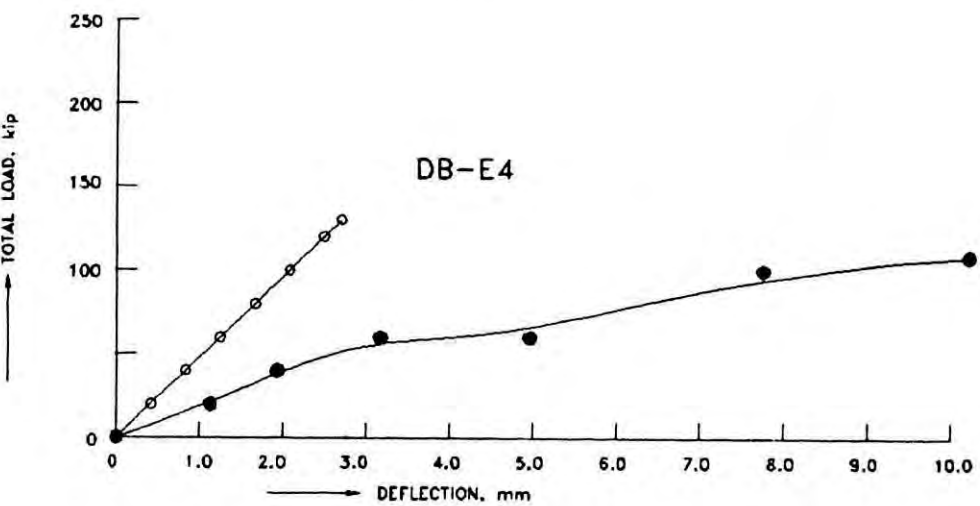
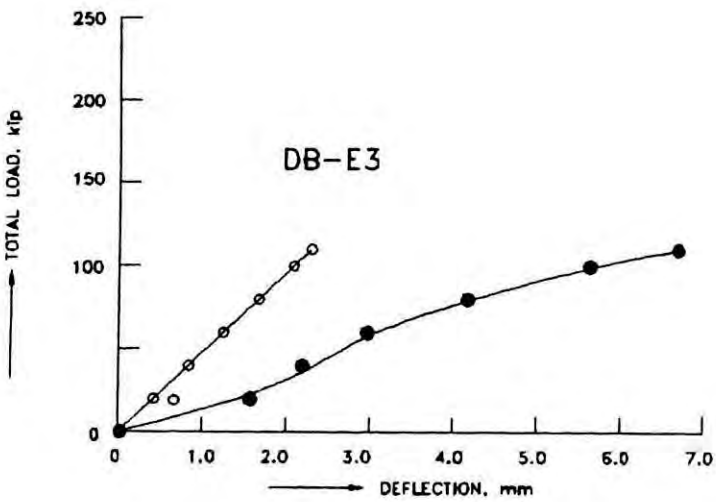
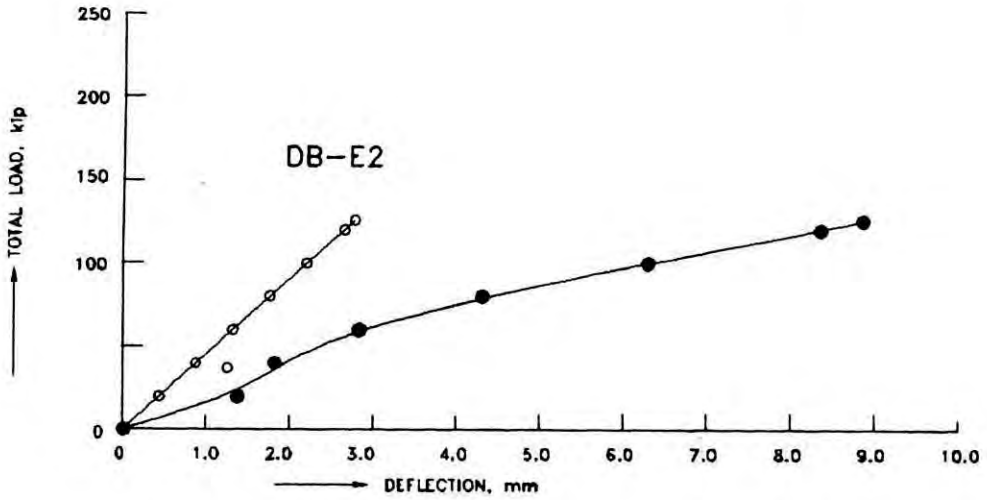
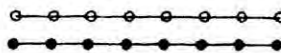


FIG. 5.7 LOAD DEFLECTION CURVES FOR BEAMS DB - E2, E3, E4

Note: Computed Deflection  
Observed Deflection



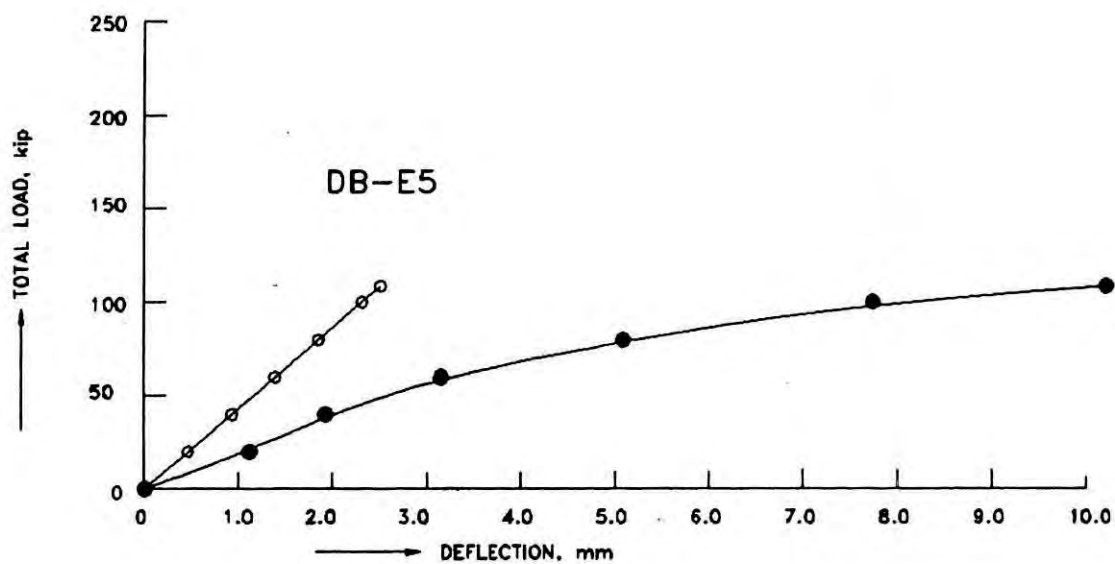
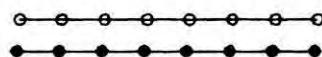


FIG. 5.8 LOAD DEFLECTION CURVES FOR BEAMS DB - E5

Note: Computed Deflection  
Observed Deflection



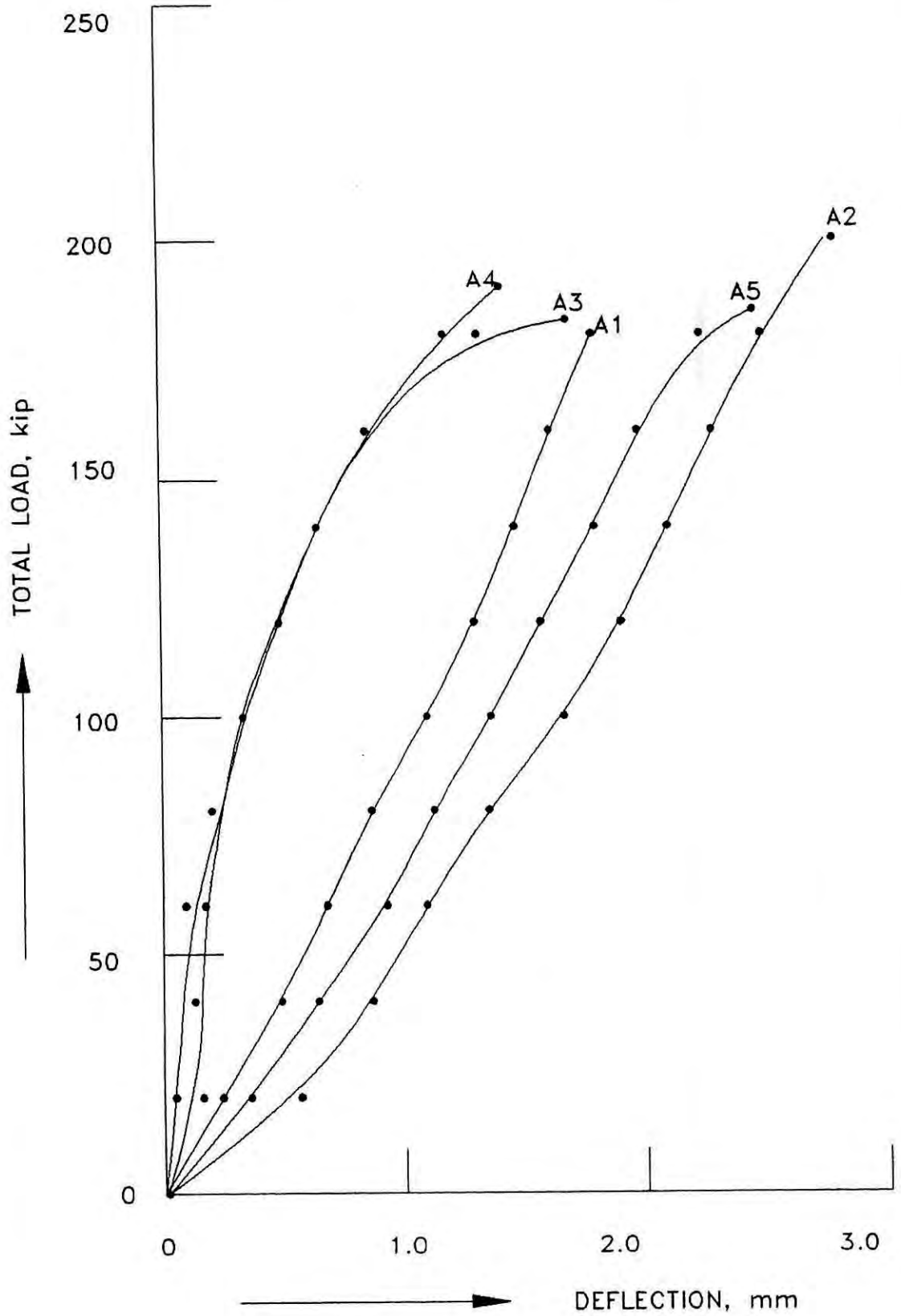


FIG. 5.9 LOAD DEFLECTION CURVES FOR BEAMS DB - A1, A2, A3, A4 A5

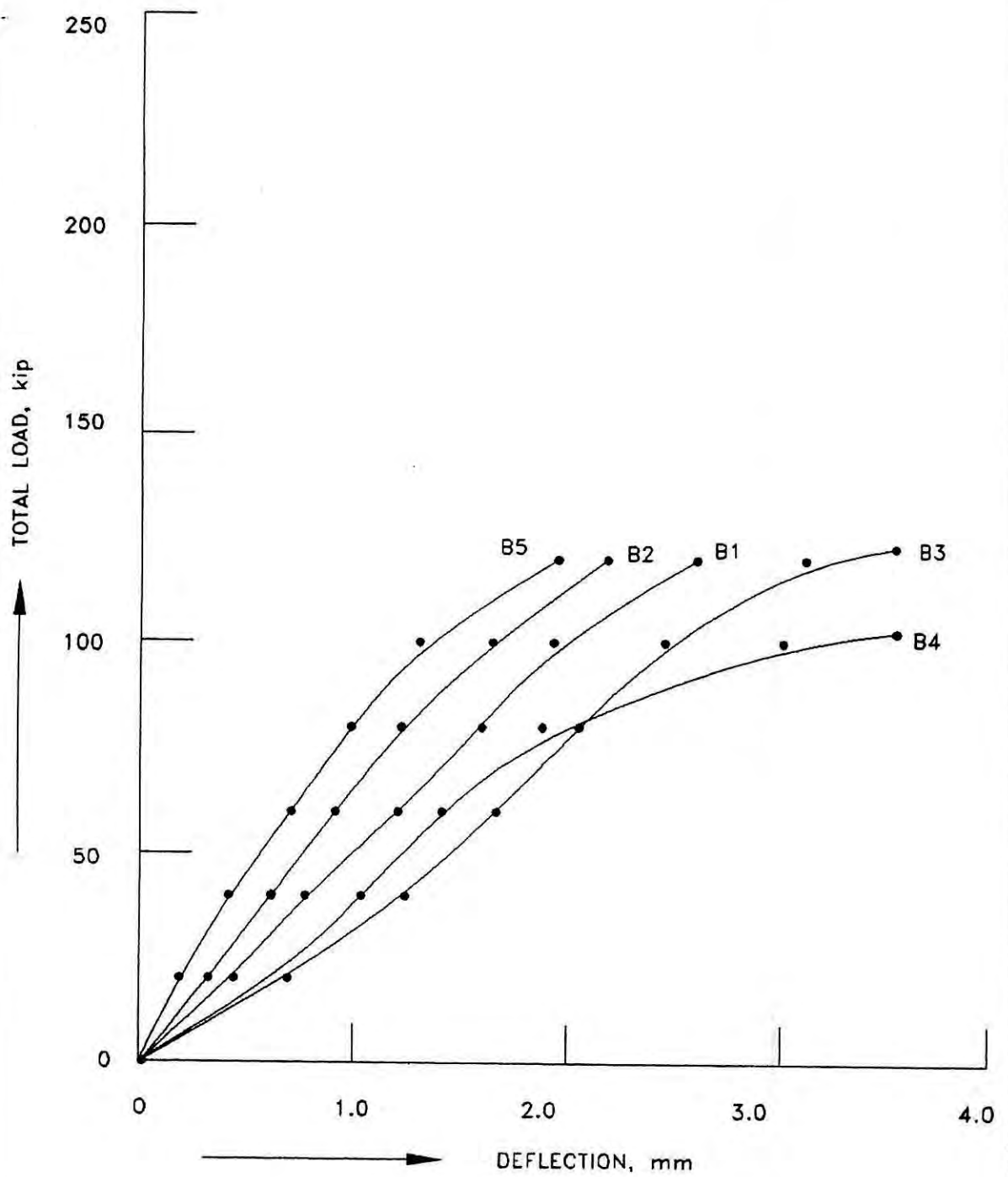


FIG. 5.10 LOAD DEFLECTION CURVES FOR BEAMS DB - B1, B2, B3, B4, B5

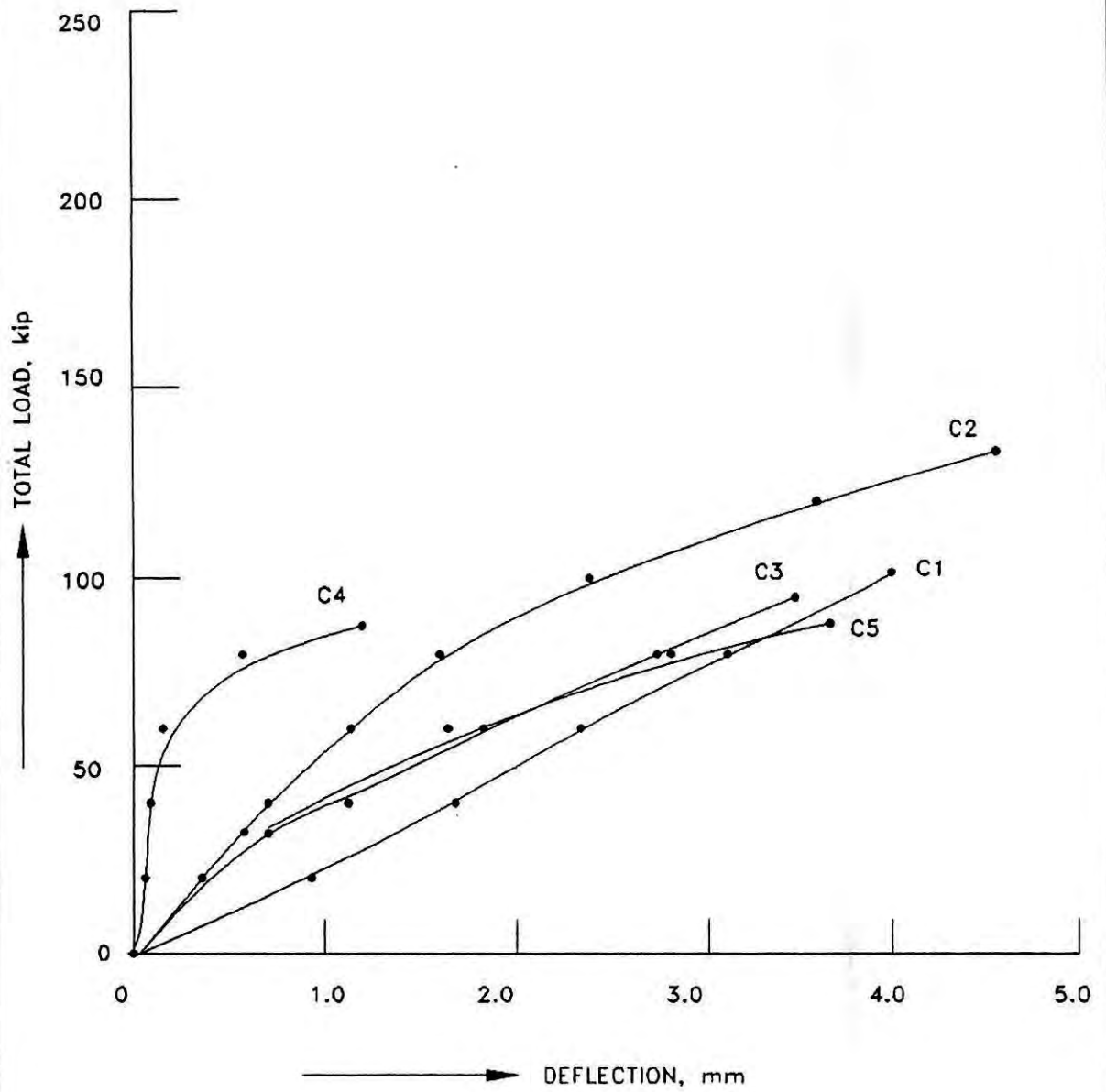


FIG. 5.11 LOAD DEFLECTION CURVES FOR BEAMS DB - C1, C2, C3, C4, C5

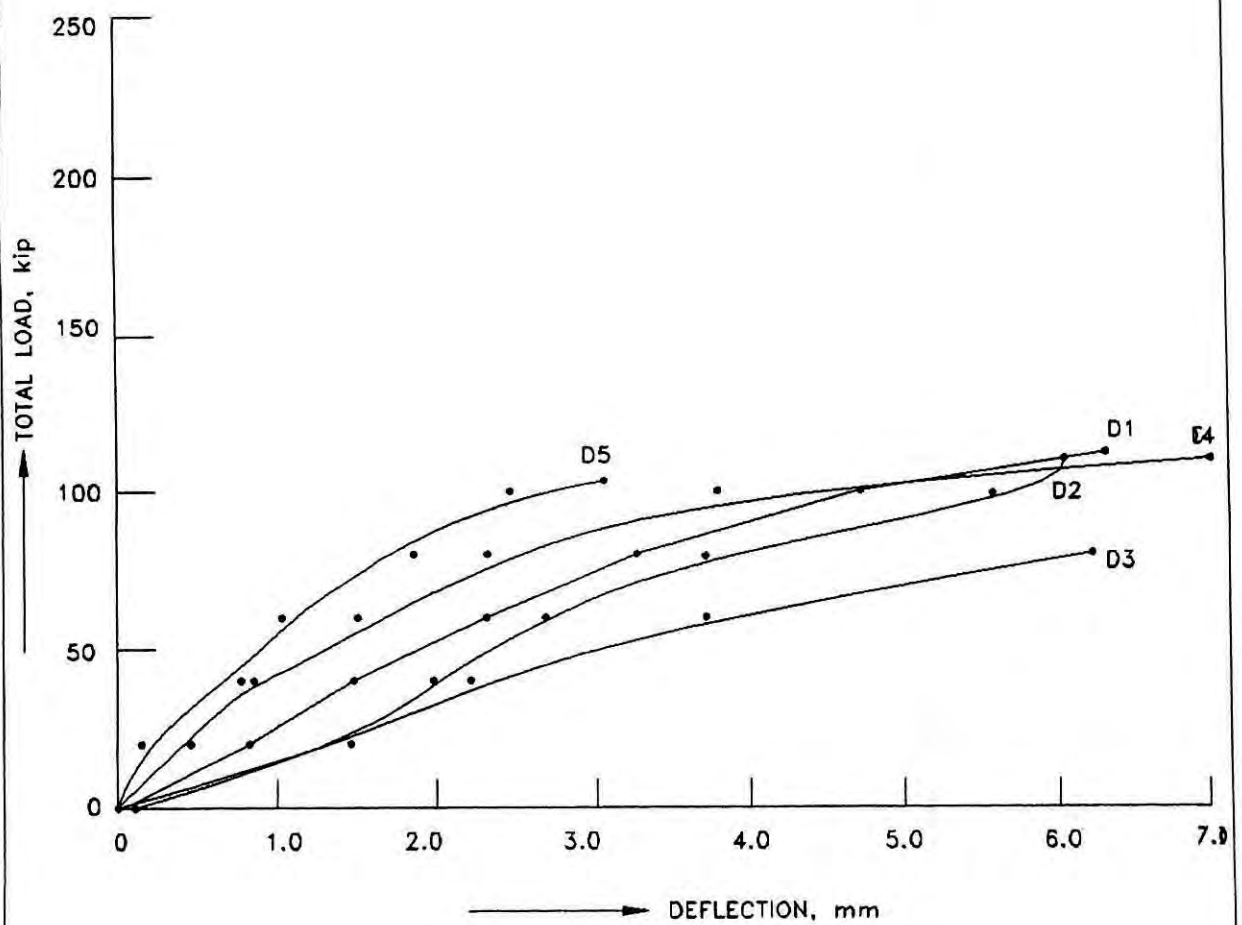


FIG. 5.12 LOAD DEFLECTION CURVES FOR BEAMS D1, D2, D3, D4, D5



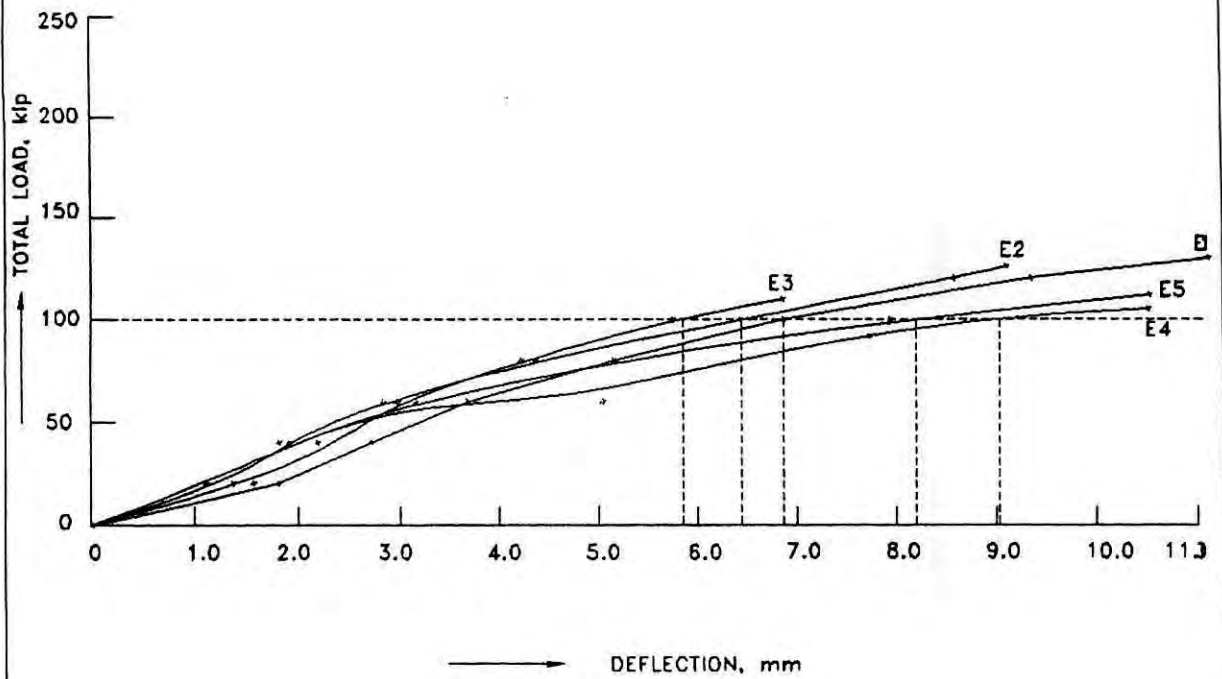


FIG. 5.13 LOAD DEFLECTION CURVES FOR BEAMS DB - E1, E2, E3, E4, E5

## 5.4 GENERAL CRACK PATTERN

In the test programme, the following types of cracks were observed on the surface of the test beams

(i) Flexure cracks, (ii) Shear cracks and (iii) Secondary cracks.

Flexure cracks, caused by the flexural tension along the beam length were usually observed in the zone of maximum bending moments and was accentuated by deflection or by the presence of local weaknesses in the beam section. Flexure cracks were also developed in the shear span usually at a later stage of loading. But in beam DB-C3 the flexural crack in the shear span occurred almost simultaneously with the mid span flexural crack and in beam DB-C1 and DB-D5 the shear span flexural crack appeared prior to the formation of crack in the mid span. This could probably be attributed to the local weaknesses of concrete in the shear span compared to that of mid span section.

For the relatively deeper beam DBA series the flexure crack at shear span occurred at about 26% to 52% (with an average of 37%) higher load than that of the load at which the first flexure crack at mid span appeared. For the DBB series this variation ranged between 0% to 40% with an average of 15%. Similarly for the DBC series (except DB-C1 and DB-C3), this variation range is 0% to 16.67% with an average of 8.83%. For the other two series DBD (except DB-D5) and DBE no flexural crack occurred at shear span. Only the diagonal cracks are found prominently.

The depth of penetration of the flexure crack at mid span for the DBA series ( $L/D = 1$  and steel percentage about 1.00%) were usually found to be below 40% of the overall depth from the bottom face of the beam. On the other hand the depth of penetration of similar cracks in the case of DBB series ( $L/D = 1.75$  and steel percentage about 1.45%) were found to vary from a minimum of about 38% to as high as 60% of the total depth. For the DBC series ( $L/D = 3$  and steel percentage about 4.50%) the depth of the flexural crack at mid span were found to vary from 32% to 72% of the total depth. For the DBD series ( $L/D = 4$  and steel percentage about 5.40%) the depth of the flexural crack at mid span were found to vary from 17% to 45% of the total depth. For the DBE series ( $L/D = 5$  and steel percentage about 4.40) the depth of the flexural crack at mid span were found to vary from 30% to 50% of the total depth. The vertical cracks in the compression zone at higher loads is possible due to the splitting action under arch compression rather than flexural stresses in deep beams. This type of crack has also been observed by Ramkrishnan and Ananthanarayana<sup>(16)</sup> during their tests. The depth of arch compression ribs are smaller in relatively shallower deep beams. Shallower deep beams are, therefore, probably more susceptible to splitting compared to the deeper ones. These cracks may be referred to as secondary cracks.

The shear crack appeared in the shear span as an inclined crack and was usually found to originate at about mid depth of the beam section and was located approximately half way between the support and the loading block for DBA series beam. In the case of DBB series beams these cracks were initially formed at a relatively lower depth (about  $0.3D$  to  $0.5D$ ) from the bottom face and were slightly shifted towards the centre of the beam span. In case of DBC and DBD series the shear crack were initially formed at the bottom face below ( $0.33D$ ) and moderately shifted towards the centre of the beam. But for DBE series these cracks have almost formed at the centre of the beam and below  $0.3D$  of the beams. It is observed that the shear crack pattern become more flatter with the increase of the  $L/D$  ratio from one to four. But in DBE series where the  $L/D$  ratio is five, it is interestingly found that the shear cracks become steeper than that of DBB, DBC and DBD series. Also the shear cracks are shifted almost at the centre of the beams. It may be a reason that when the  $L/D$  ratio become more than four the beams may change its nature from deep to rectangular one. However, the inclination of these shear cracks formed by principal tension in a shear span were approximately parallel to a line joining the inner edge of the support and edge of the loading block for all the series of test beams.

The shear cracks were not always developed simultaneously in both the shear spans of a beam especially in the relatively shallower beams. There was a certain amount of load lag in the development of these two cracks. For DBB series, this variation ranged between 20% to 42% with an average of 26% of the initial load at which the first diagonal crack occurred. For DBC series, this variation ranged between 20% to 65% with an average of 38% of the initial load at which the first diagonal crack occurred. Similarly for DBD series, this variation ranged between 16% to 20% with an average of 18.66% of the initial load at which the first diagonal crack occurred. But for DBE series, no variation was found and shear cracks are simultaneously occurred in both the shear spans of the beams.

The secondary cracks as encountered in the test programme were mainly of splitting type and has been already mentioned in the discussion of the flexural cracks. On an average the number of cracks were found to be directly related to the amount of total web steel and thus fewer well developed cracks were observed in the beams with higher web steel percentage and the vice versa.

The crack patterns as observed on the different beam surfaces have been reproduced in drawing and presented in Fig. 5.14 through 5.38 . Photographs of the beams with the cracks are presented in Figs. 5.39 to Fig. 5.63. The numerical values shown in Fig. 5.14 through 5.38 are in Kips.

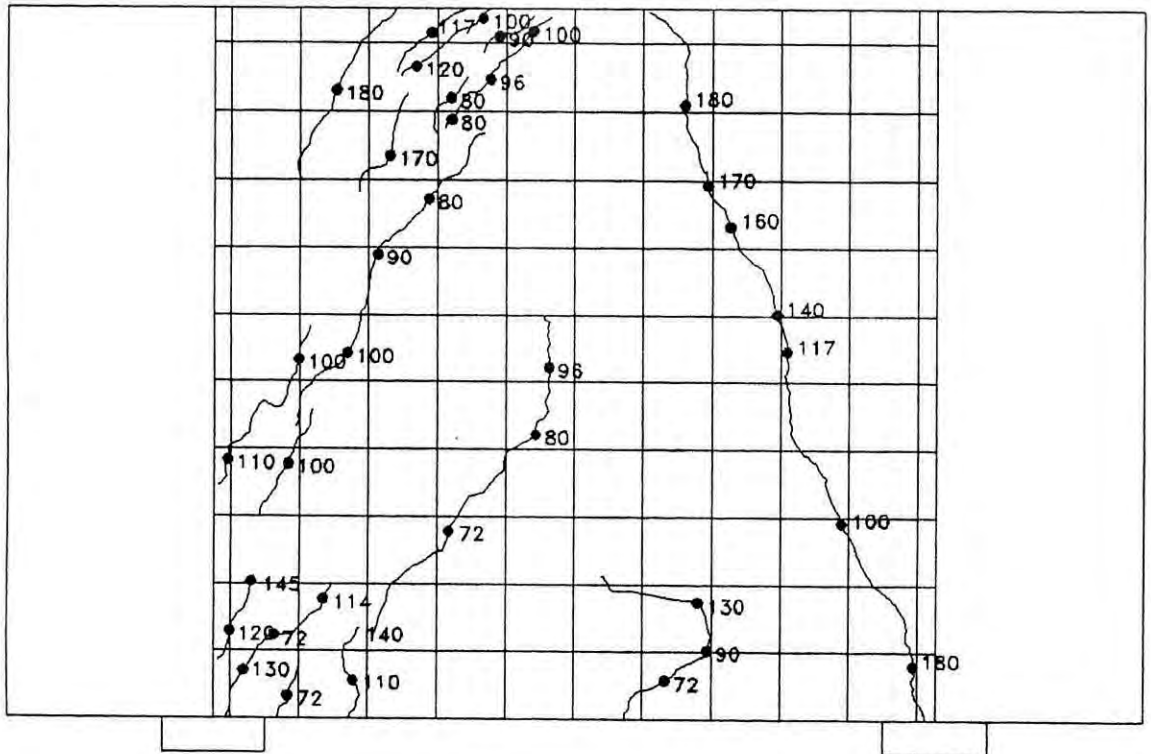


Fig: 5.14 CRACK PATTERN OF : DB-A1

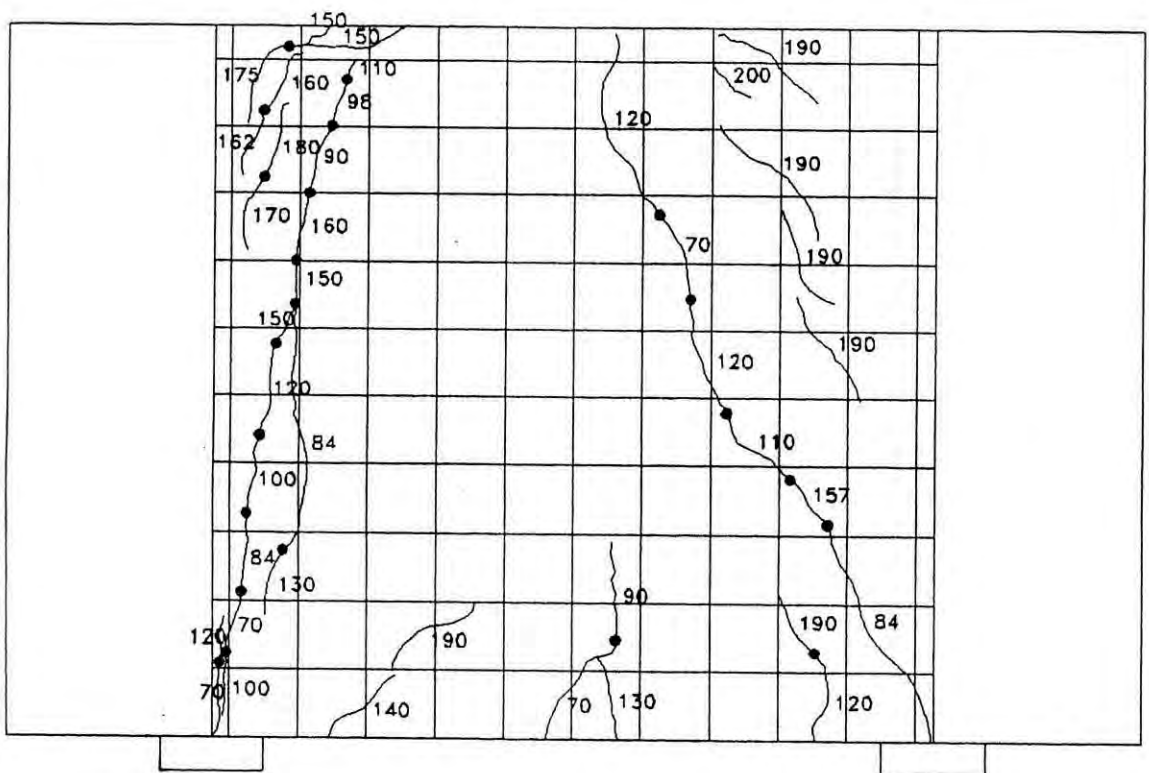


Fig: 5.15 CRACK PATTERN OF : DB-A2

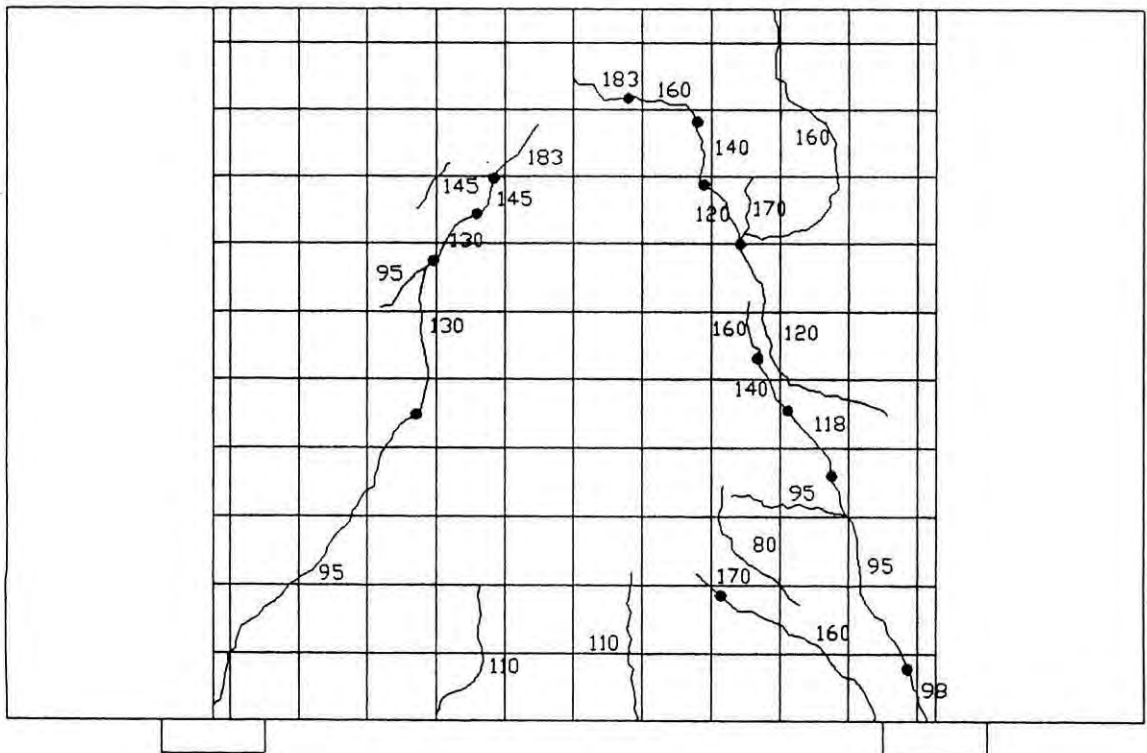


Fig: 5.16 CRACK PATTERN OF : DB-A3

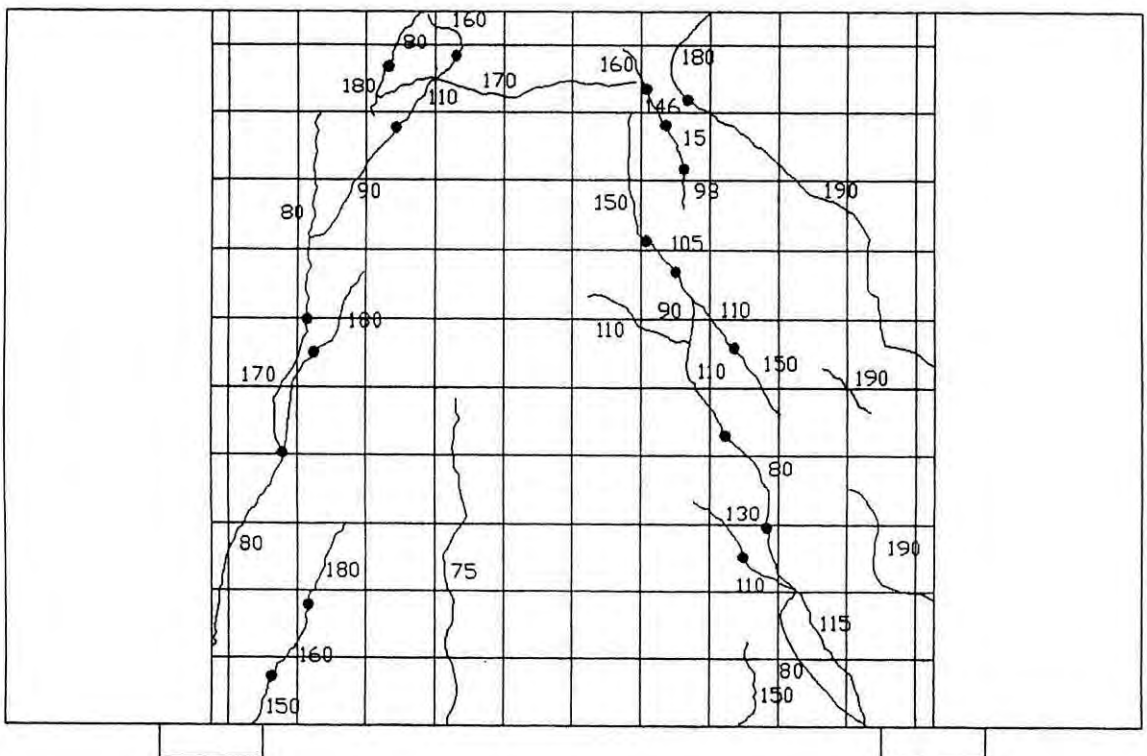


Fig: 5.17 CRACK PATTERN OF : DB-A4

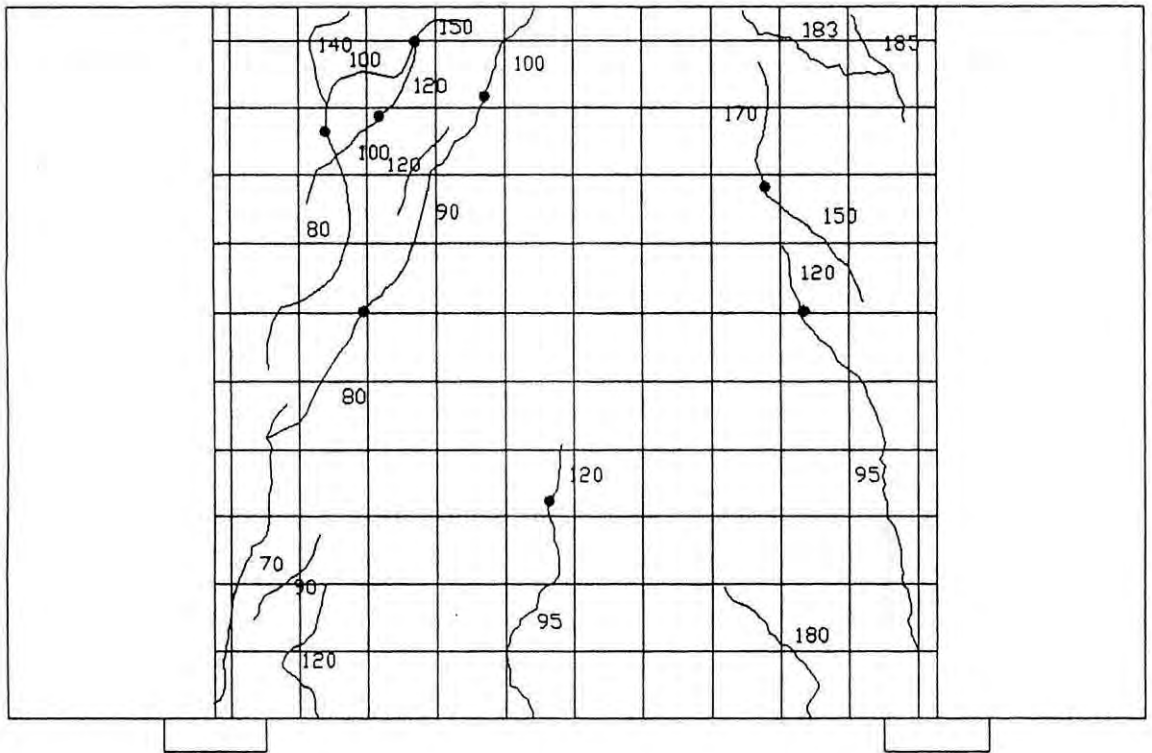


Fig: 5.18 CRACK PATTERN OF : DB-A5

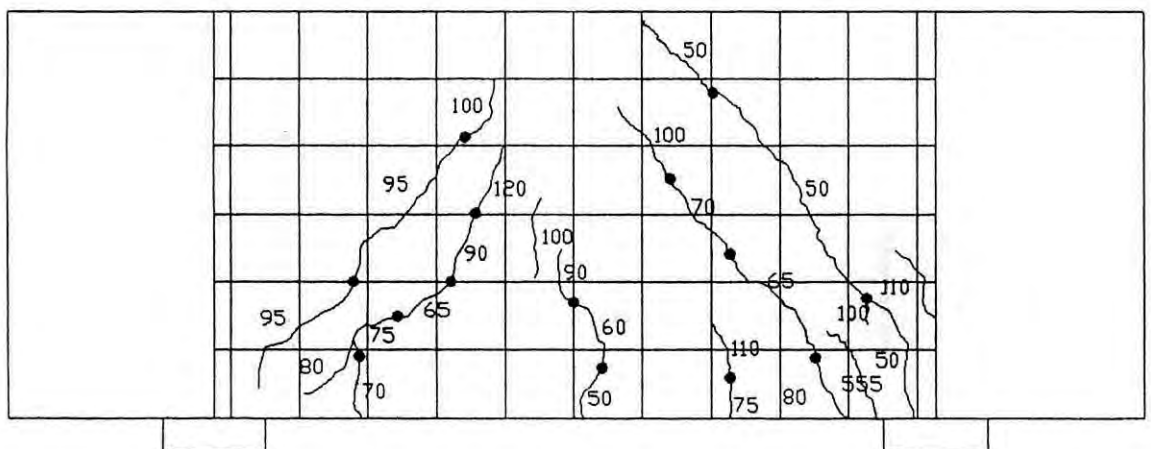


Fig: 5.19 CRACK PATTERN OF : DB-B1



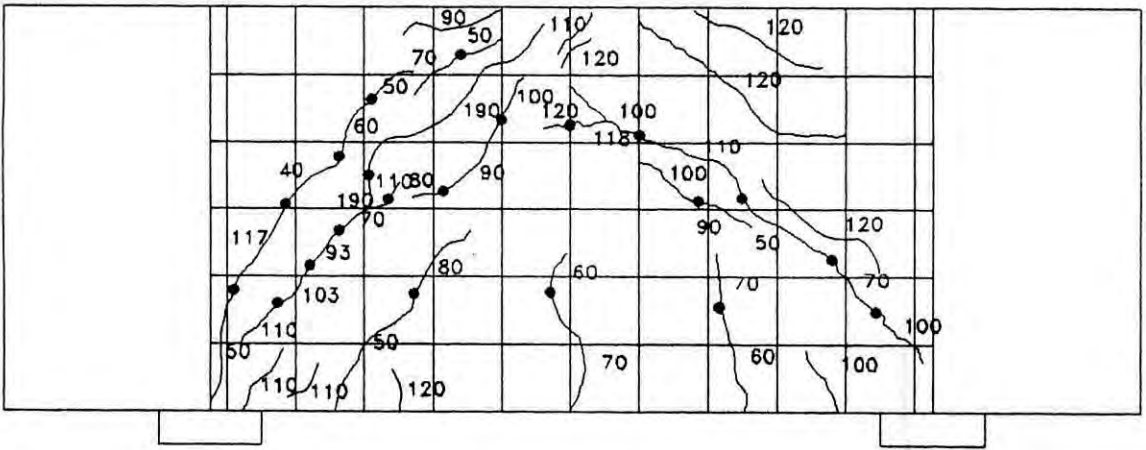


Fig: 5.20 CRACK PATTERN OF : DB-B2

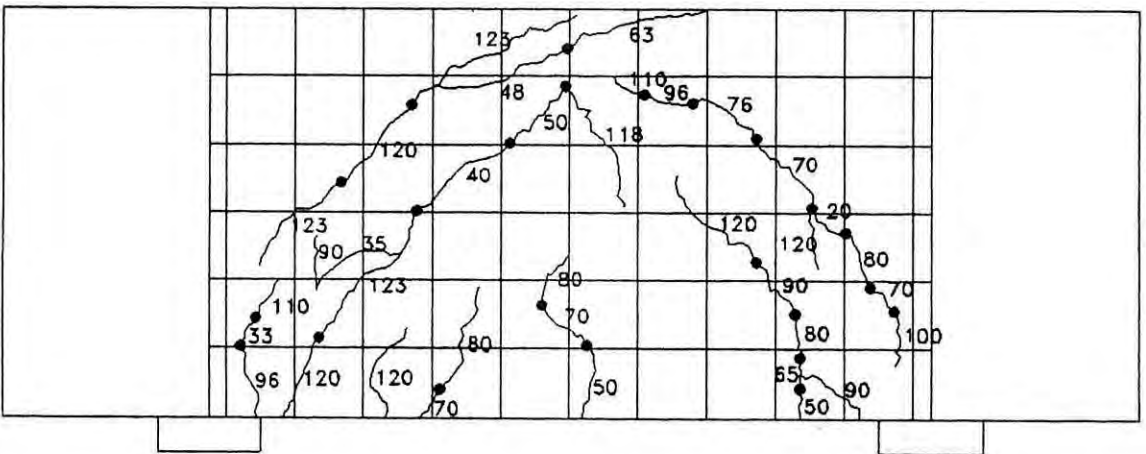


Fig: 5.21 CRACK PATTERN OF : DB-B3

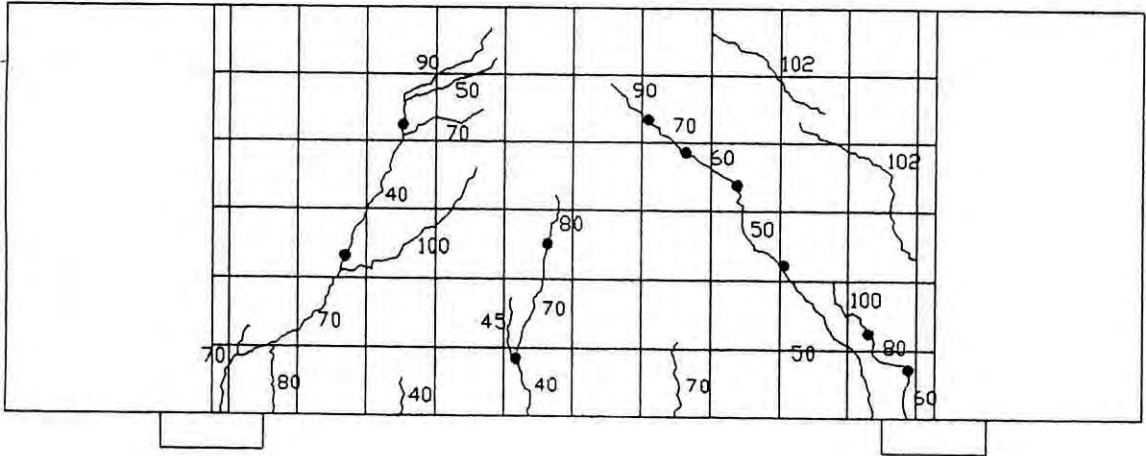


Fig: 5.22 CRACK PATTERN OF : DB-B4

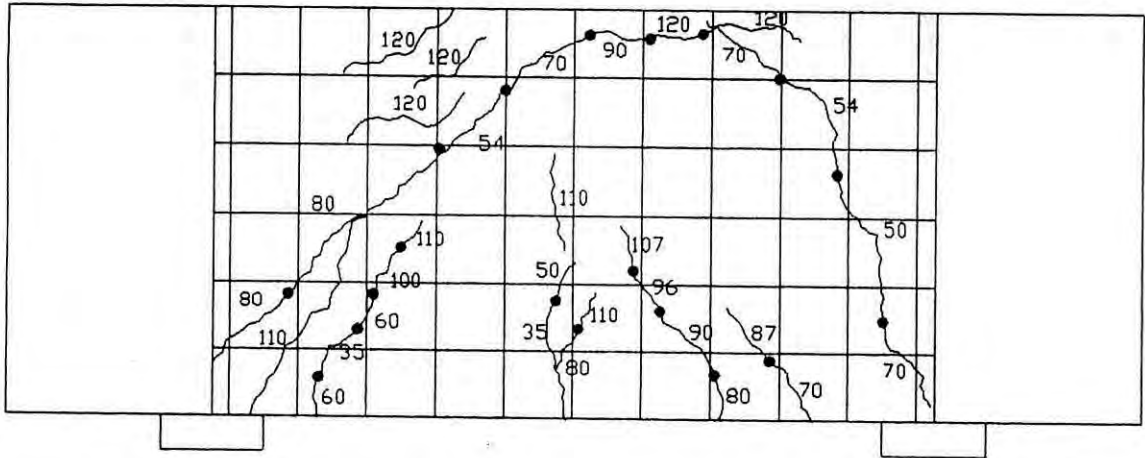


Fig: 5.23 CRACK PATTERN OF : DB-B5

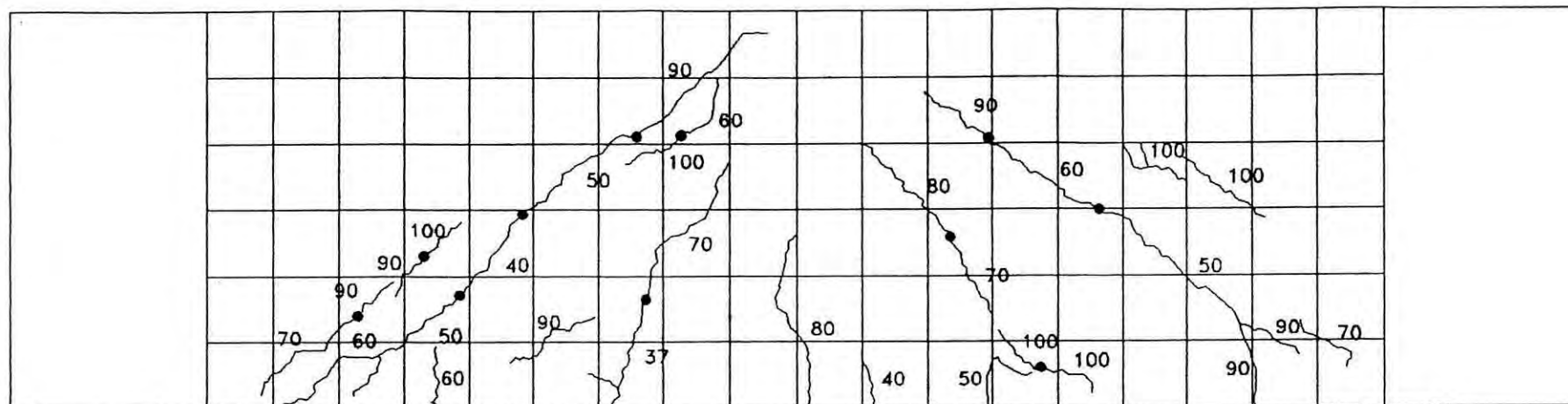


Fig: 5.24 CRACK PATTERN OF : DB-C1

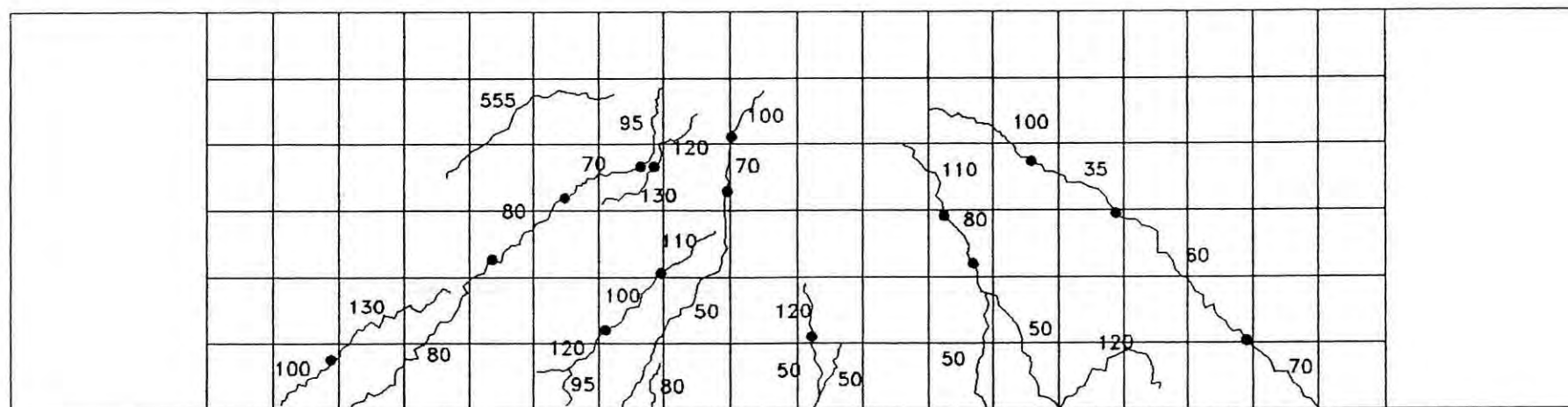


Fig: 5.25 CRACK PATTERN OF : DB-C2

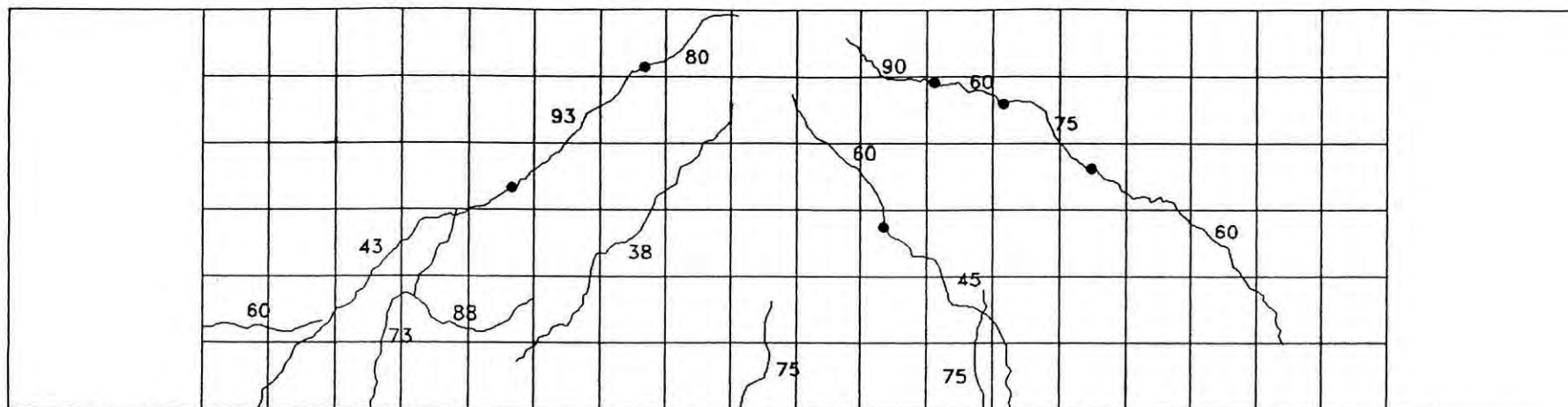


Fig: 5.26 CRACK PATTERN OF : DB-C3

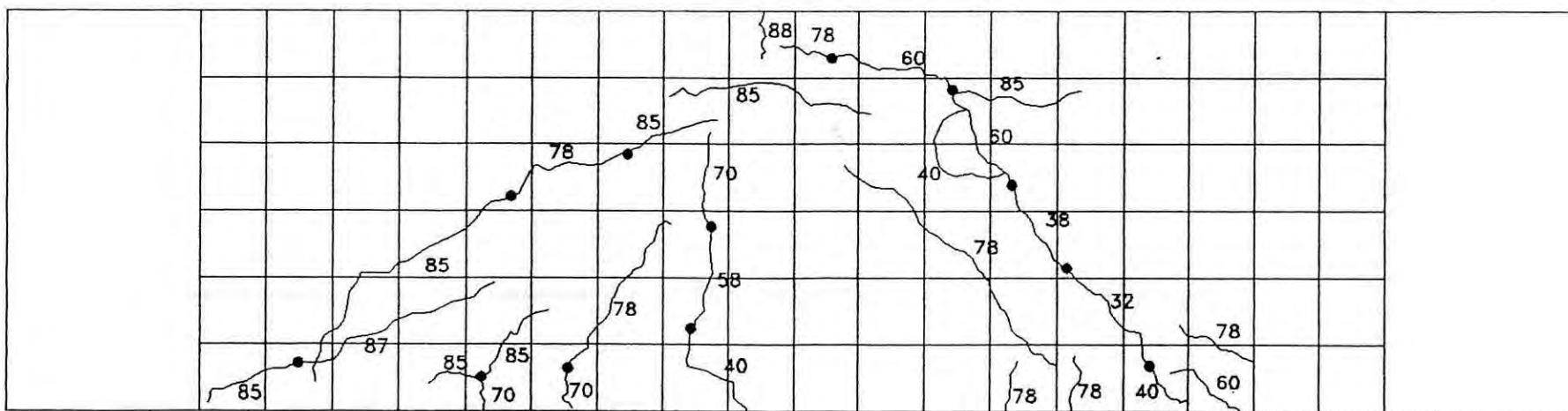
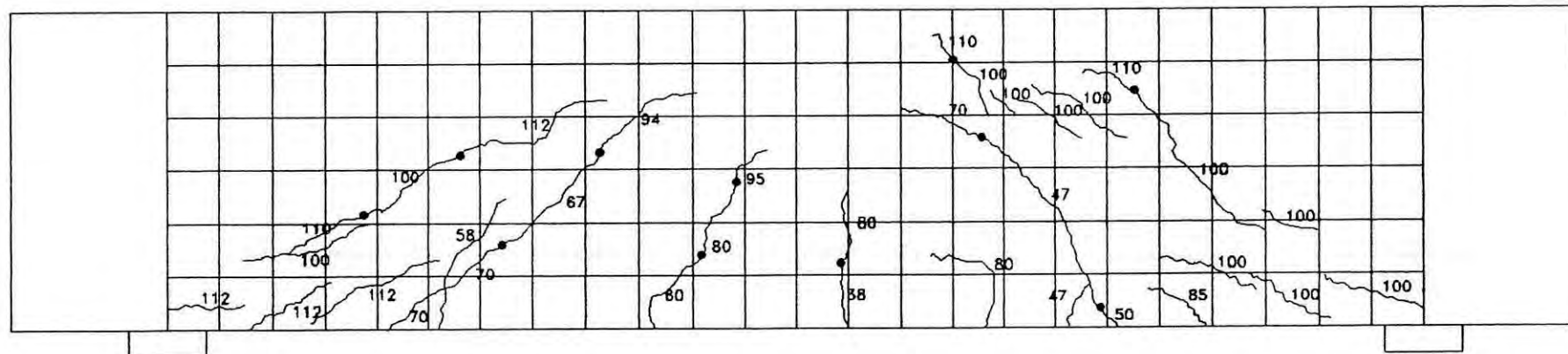
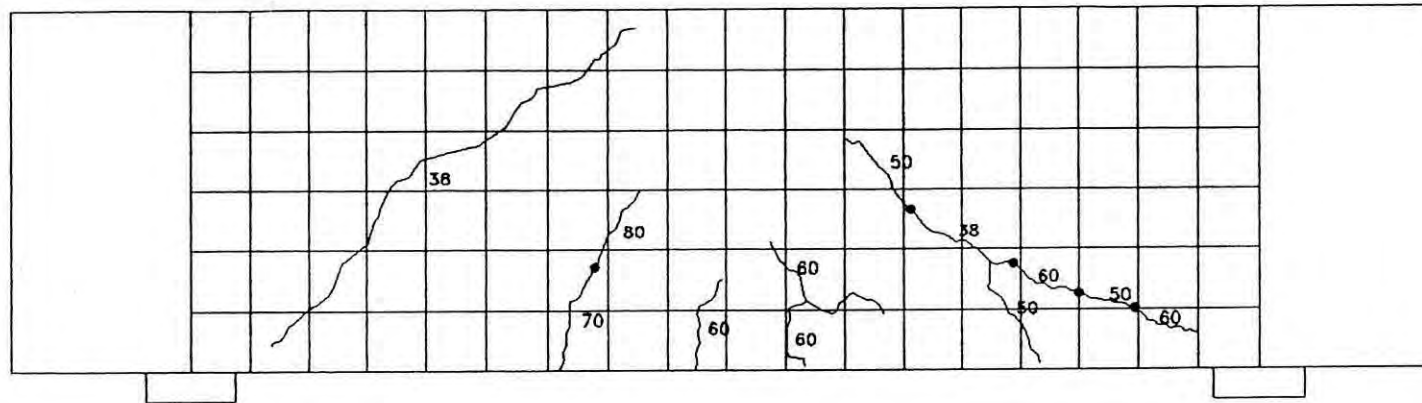


Fig: 5.27 CRACK PATTERN OF : DB-C4



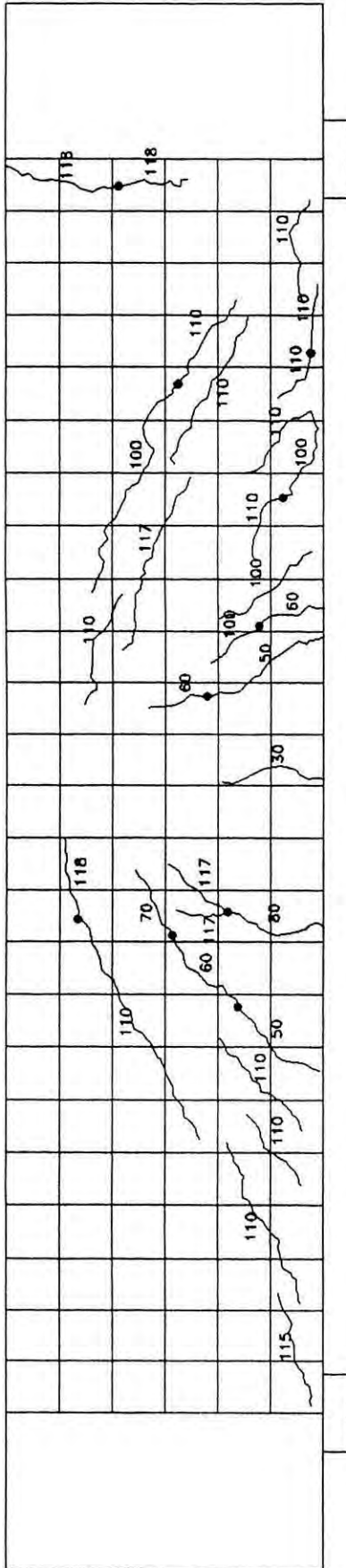


Fig: 5.30 CRACK PATTERN OF : DB-D2

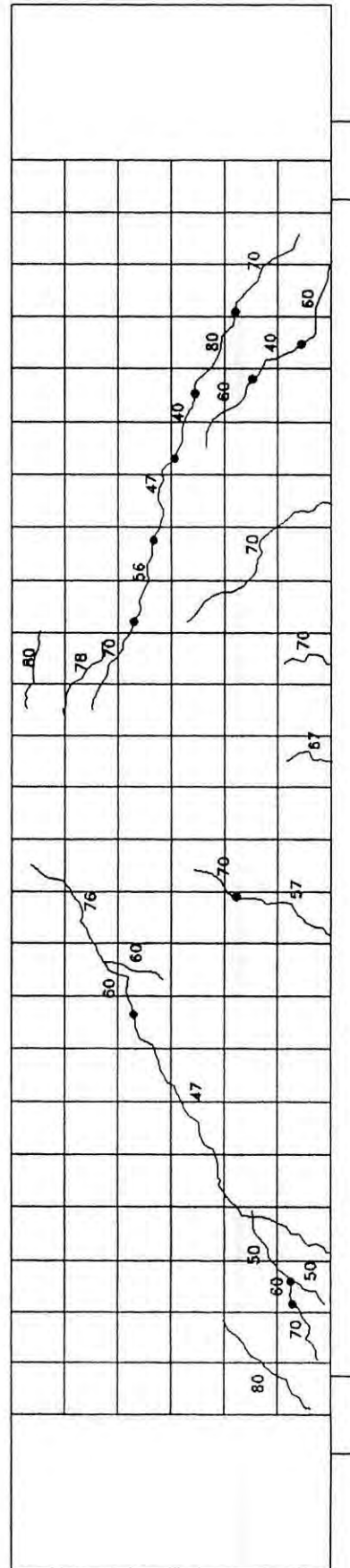


Fig: 5.31 CRACK PATTERN OF : DB-D3





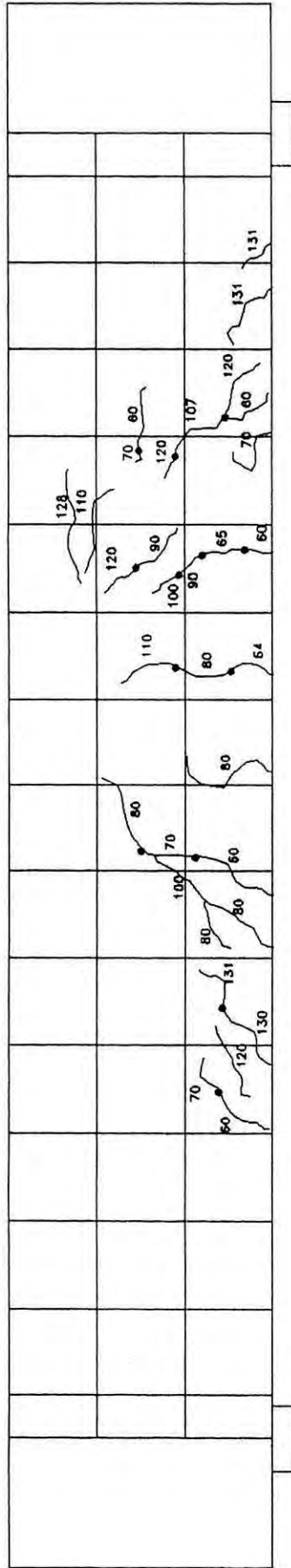


Fig: 5.34 CRACK PATTERN OF : DB-E1

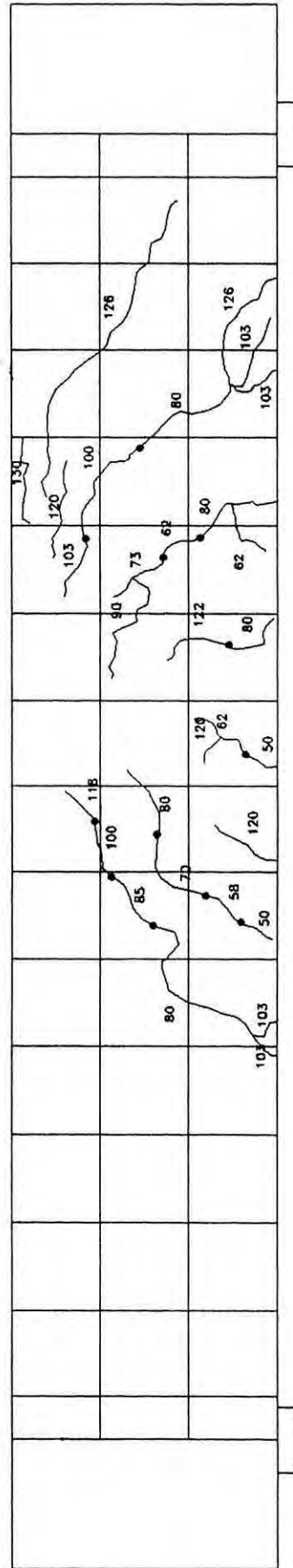


Fig: 5.35 CRACK PATTERN OF : DB-E2



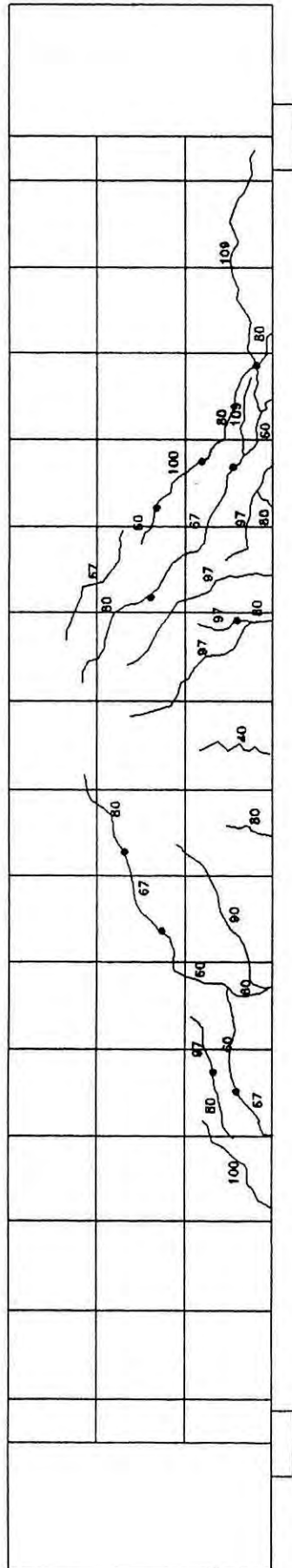


Fig: 5.38 CRACK PATTERN OF : DB-E5

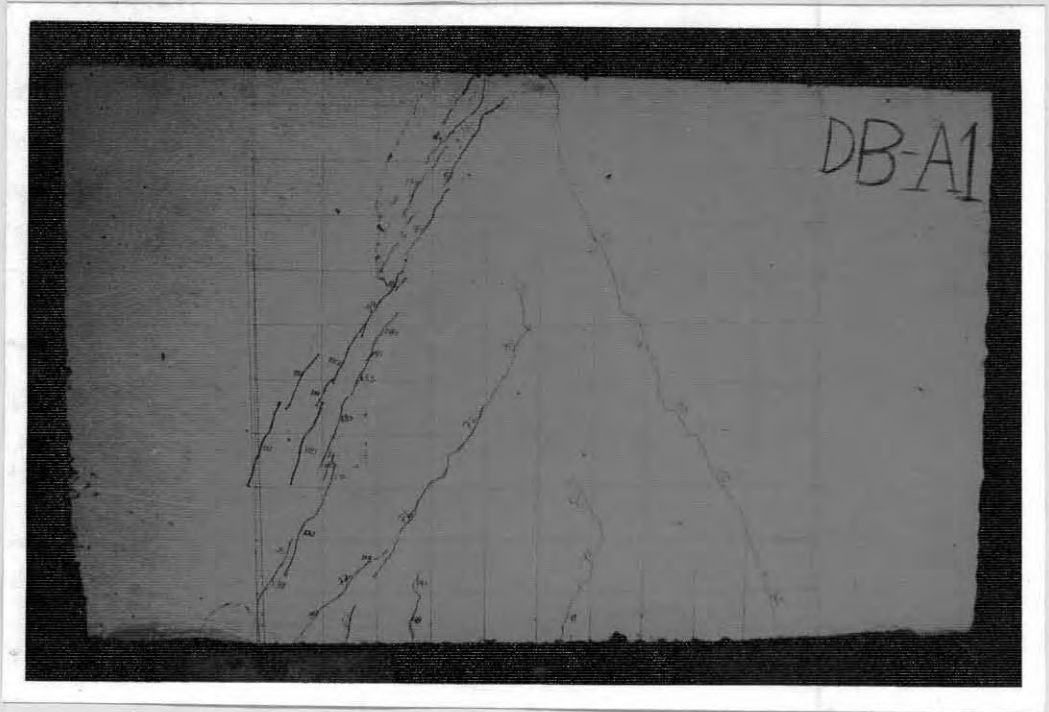


Fig. 5.39 Observed mode of failure and the crack pattern of Beam DB-A1



Fig. 5.40 Observed mode of failure and the crack pattern of Beam DB-A2



Fig. 5.41 Observed mode of failure and the crack pattern of Beam DB-A3

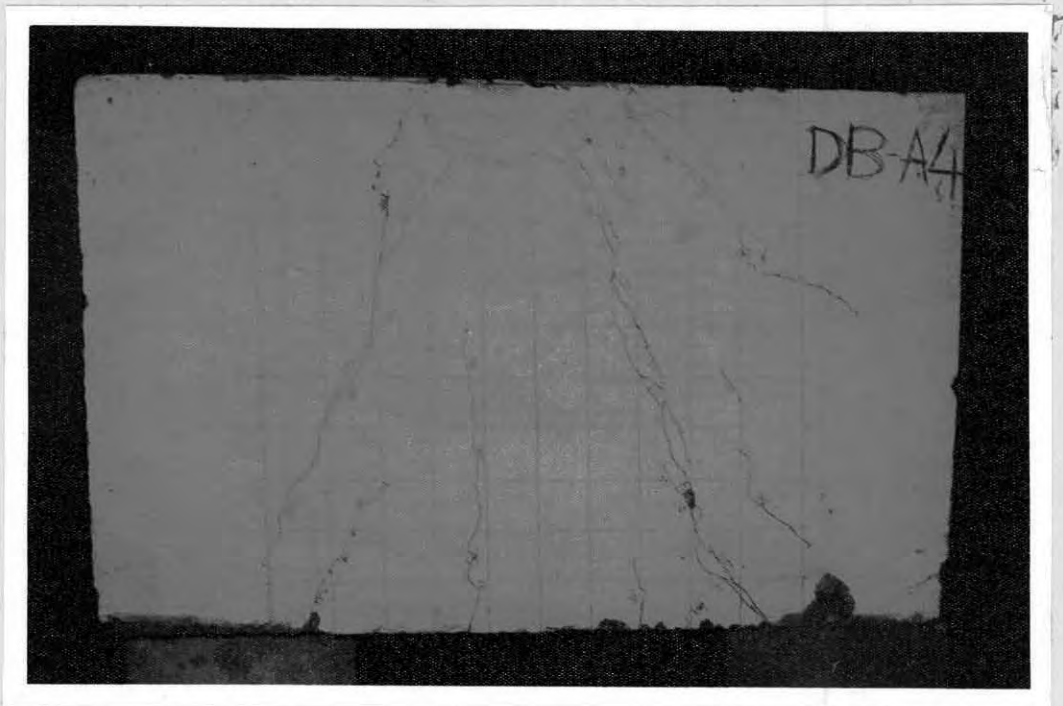


Fig. 5.42 Observed mode of failure and the crack pattern of Beam DB-A4





Fig. 5.43 Observed mode of failure and the crack pattern of Beam DB-A5

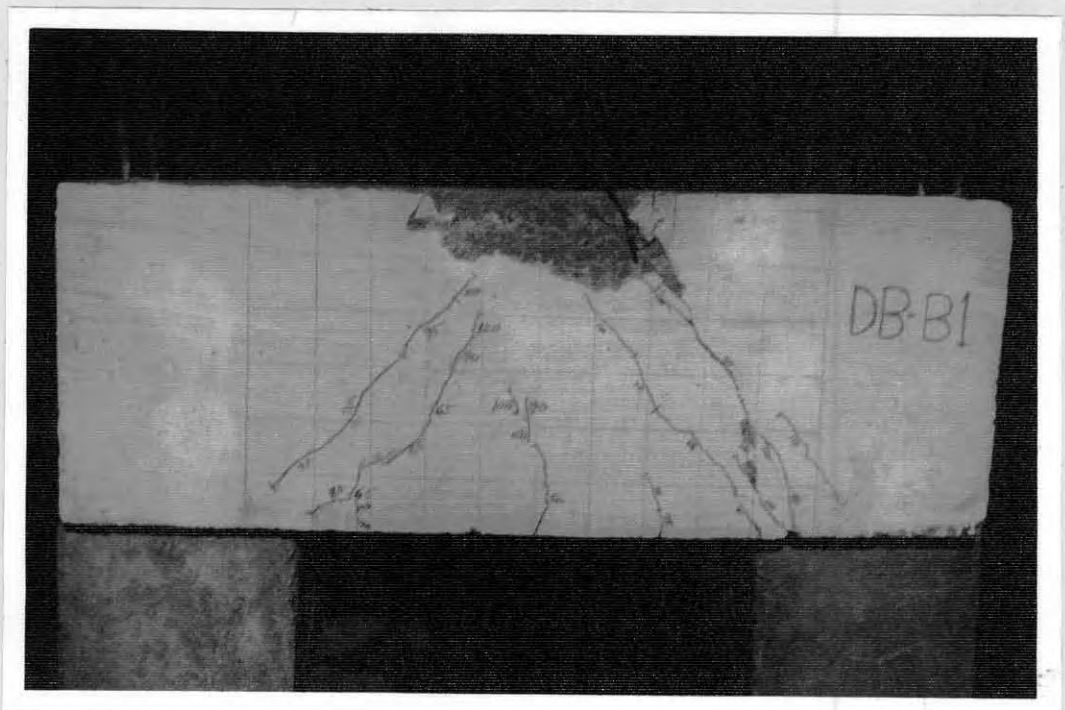


Fig. 5.44 Observed mode of failure and the crack pattern of Beam DB-B1

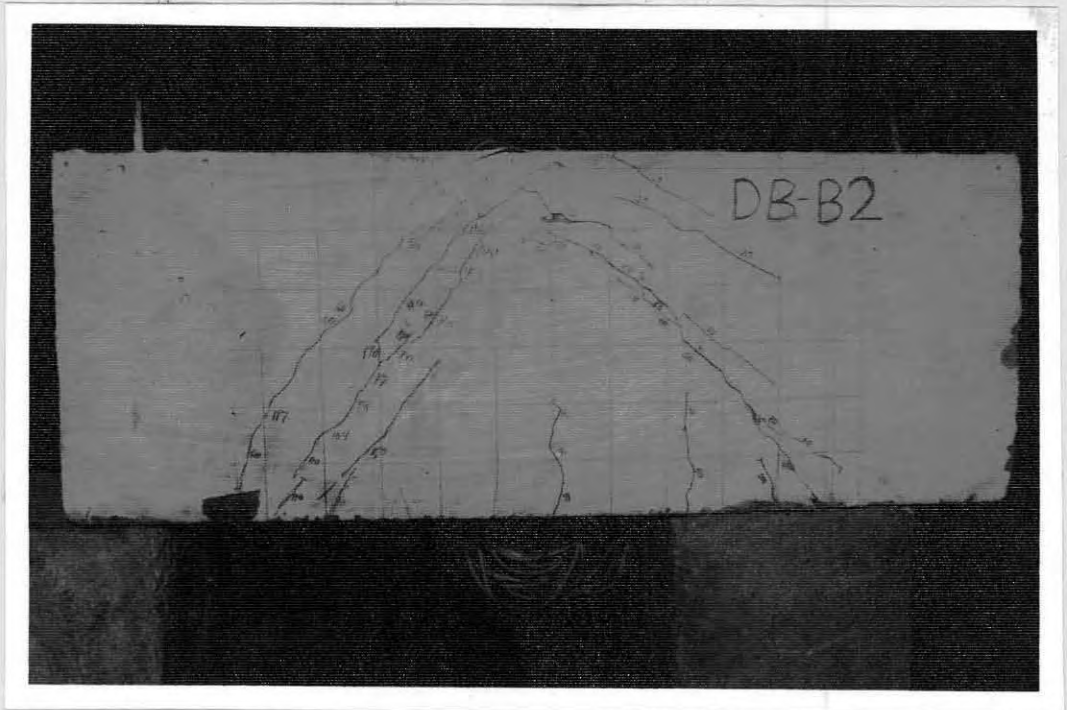


Fig. 5.45 Observed mode of failure and the crack pattern of Beam DB-B2

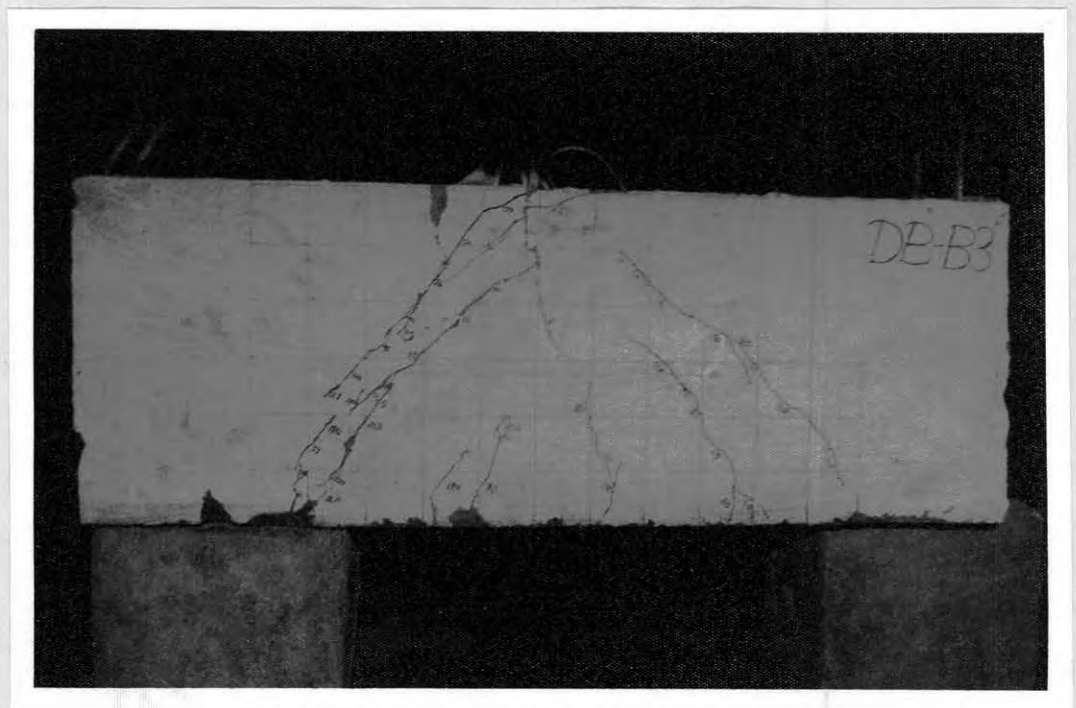


Fig. 5.46 Observed mode of failure and the crack pattern of Beam DB-B3

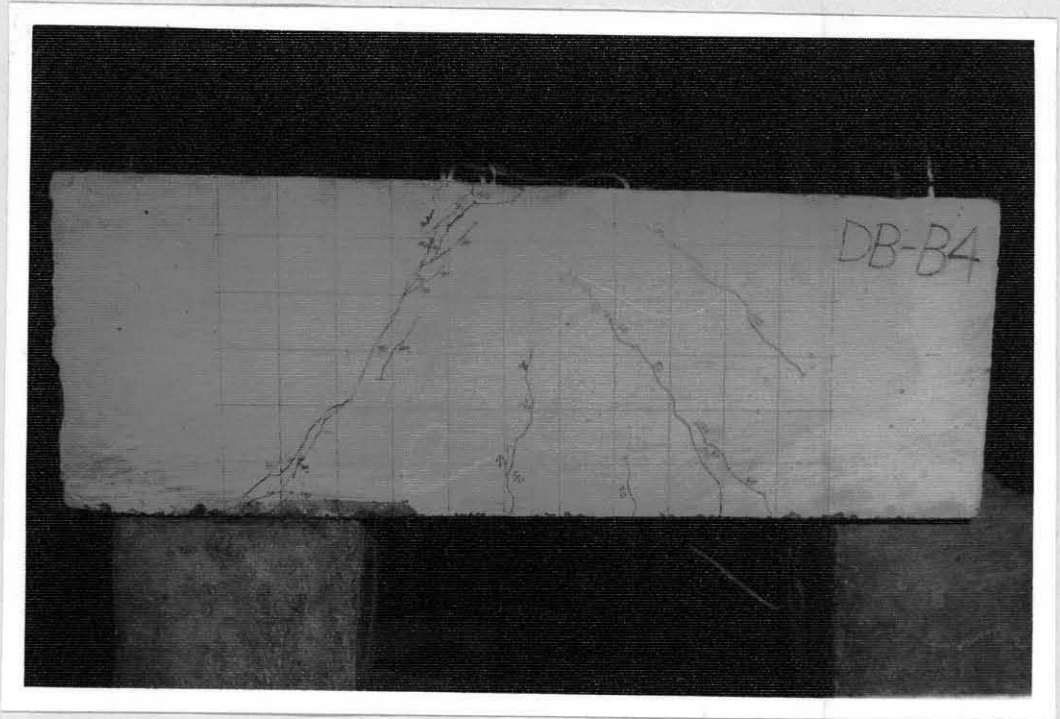


Fig. 5.47 Observed mode of failure and the crack pattern of Beam DB-B4



Fig. 5.48 Observed mode of failure and the crack pattern of Beam DB-B5



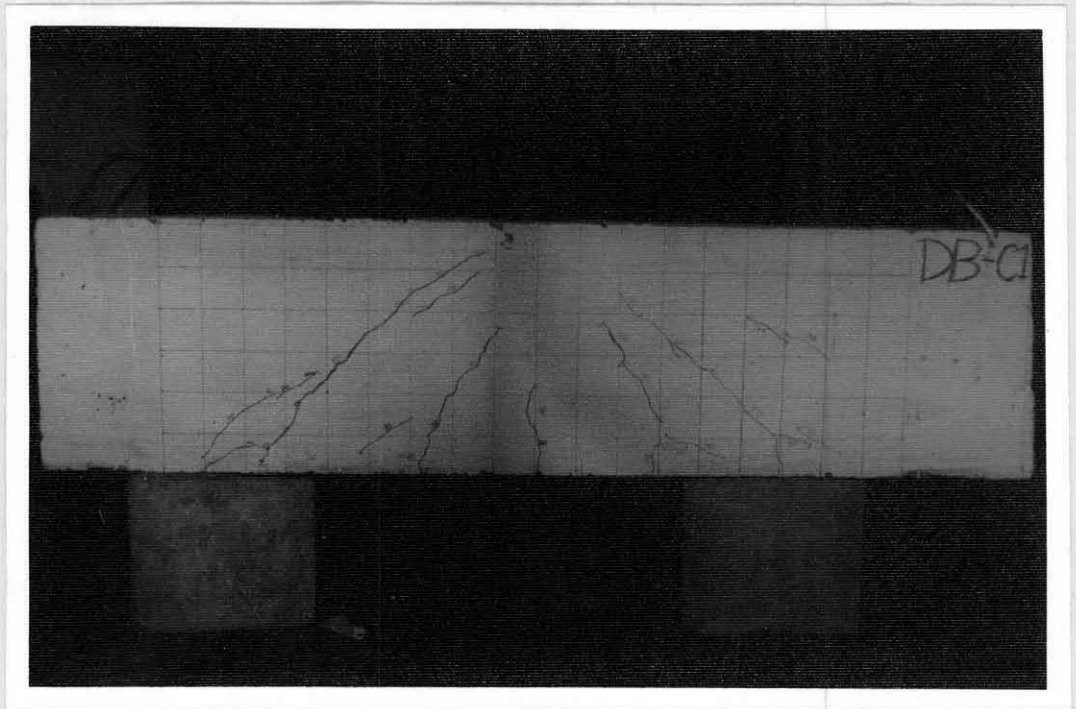


Fig. 5.49 Observed mode of failure and the crack pattern of Beam DB-C1

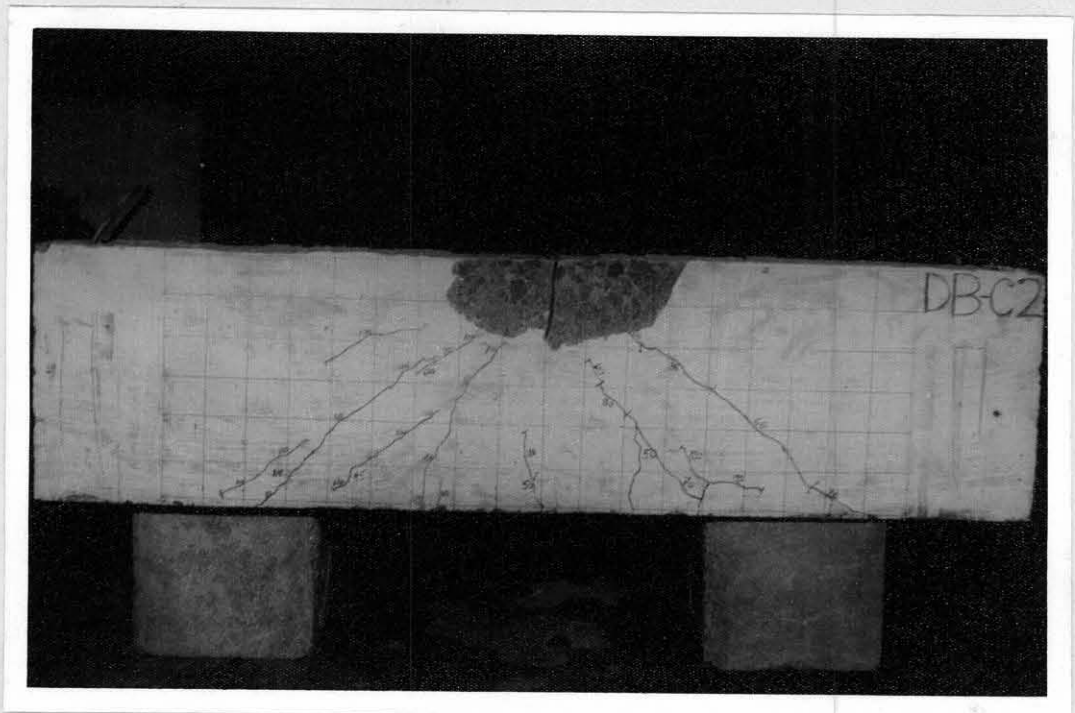


Fig. 5.50 Observed mode of failure and the crack pattern of Beam DB-C2

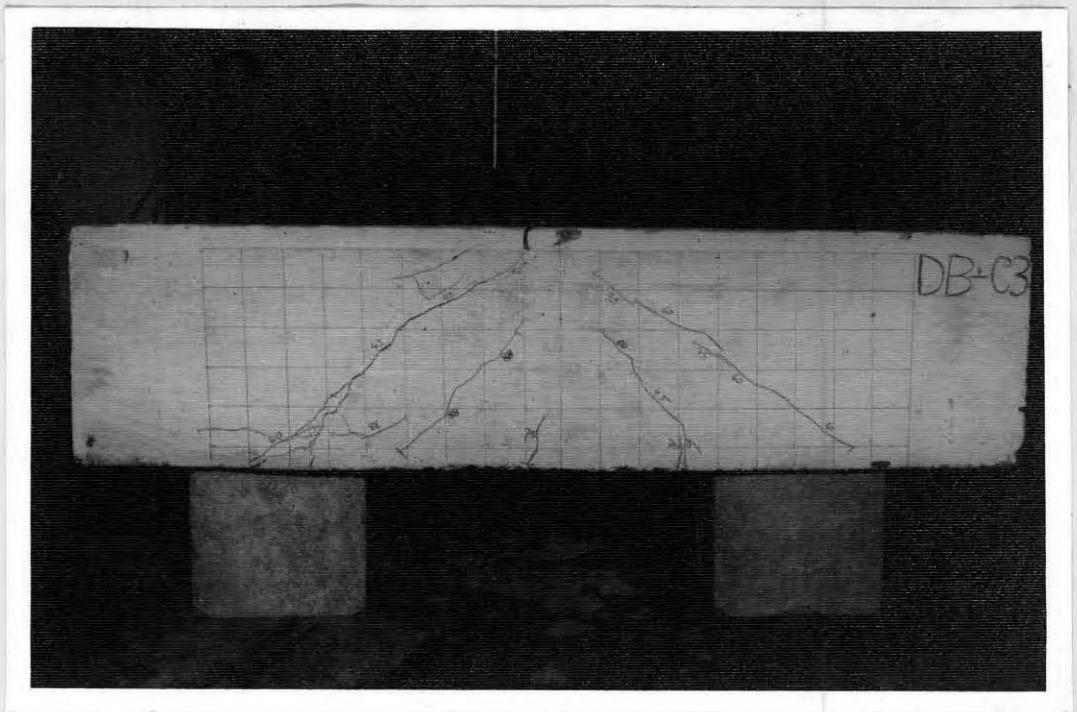


Fig. 5.51 Observed mode of failure and the crack pattern of Beam DB-C3

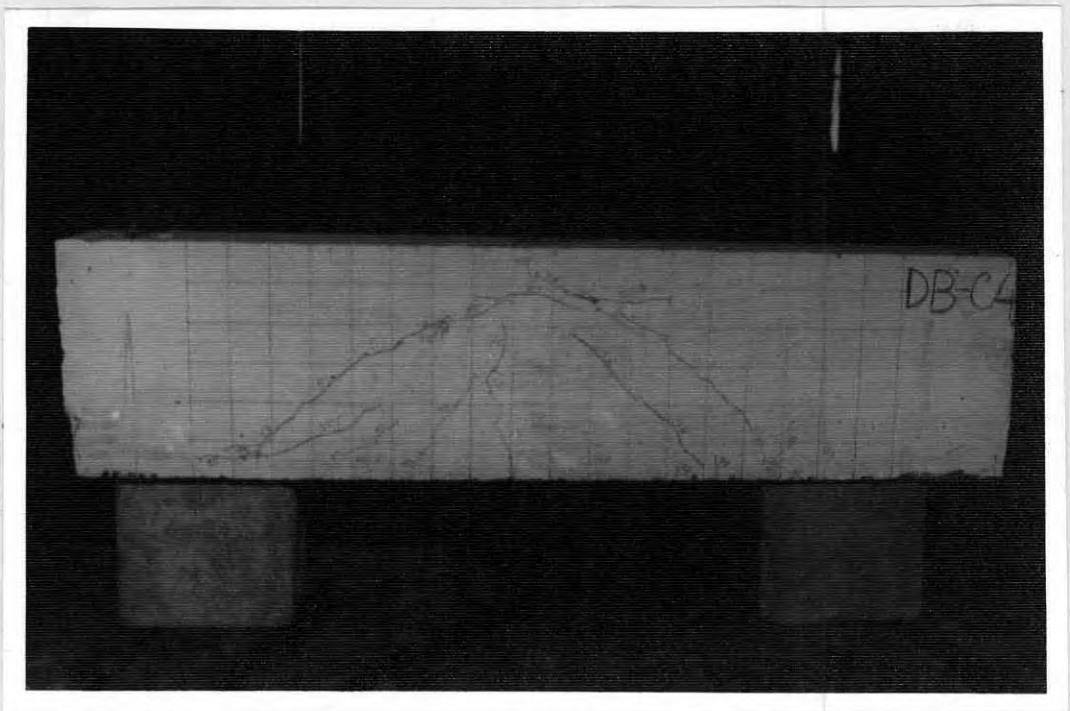


Fig. 5.52 Observed mode of failure and the crack pattern of Beam DB-C4

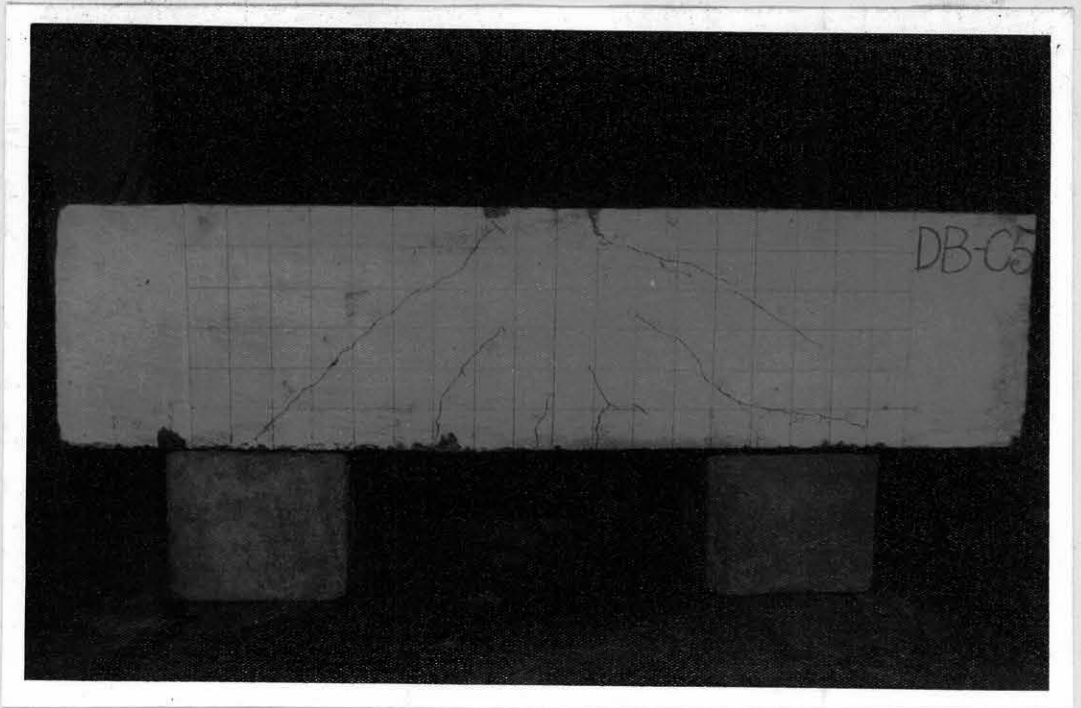


Fig. 5.53 Observed mode of failure and the crack pattern of Beam DB-C5

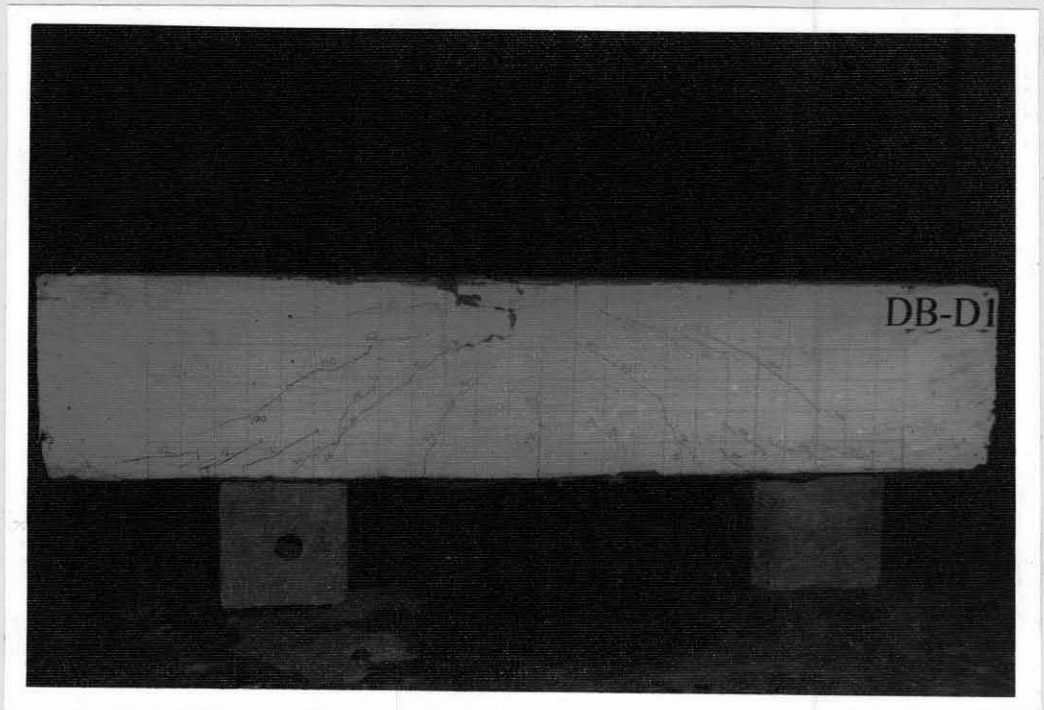


Fig. 5.54 Observed mode of failure and the crack pattern of Beam DB-D1



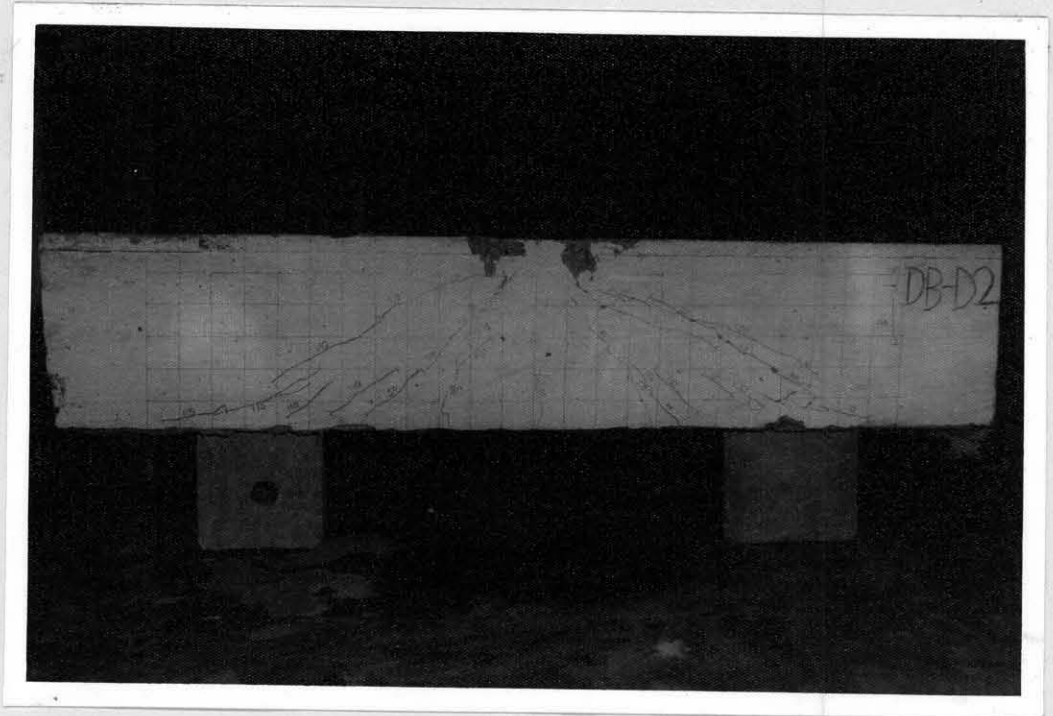


Fig. 5.55 Observed mode of failure and the crack pattern of Beam DB-D2

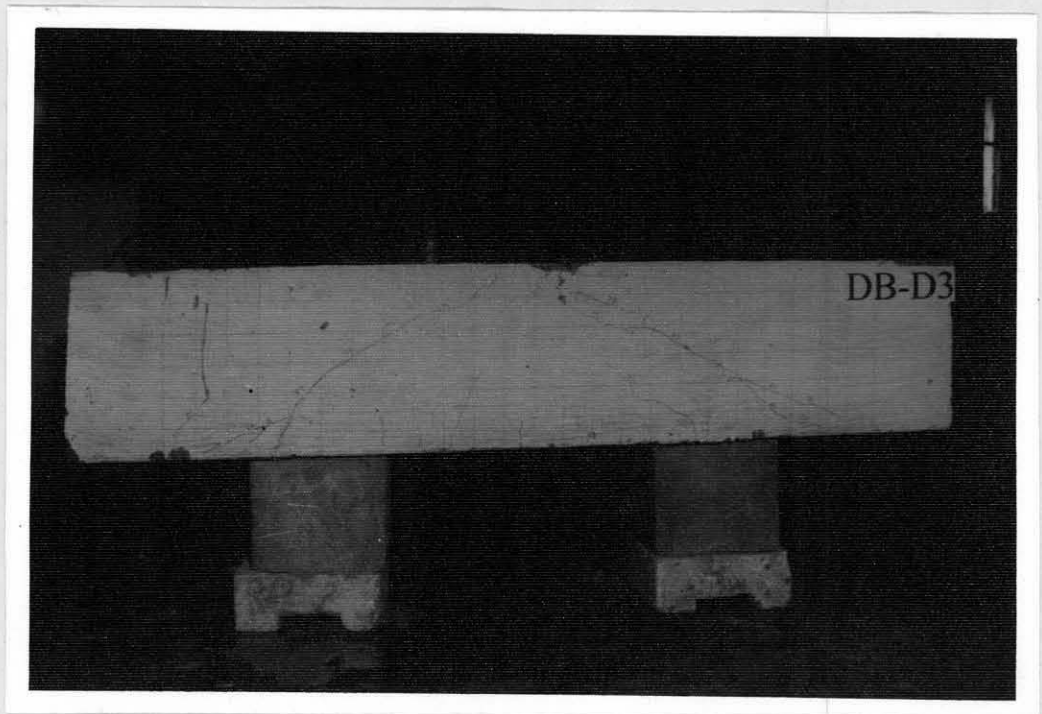


Fig. 5.56 Observed mode of failure and the crack pattern of Beam DB-D3

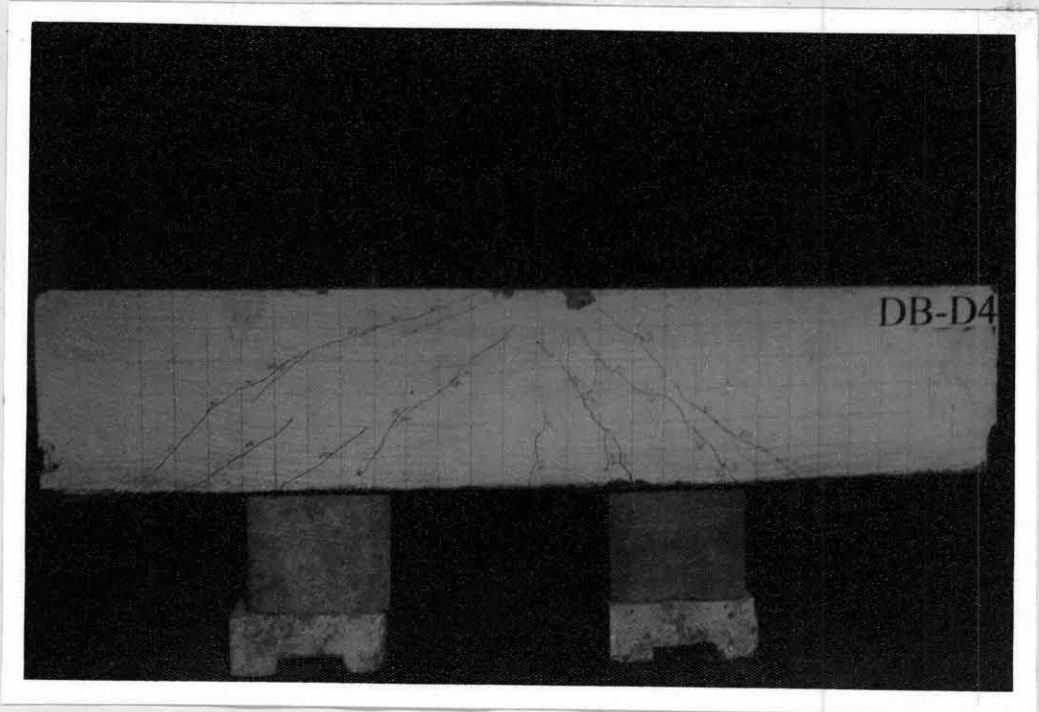


Fig. 5.57 Observed mode of failure and the crack pattern of Beam DB-D4

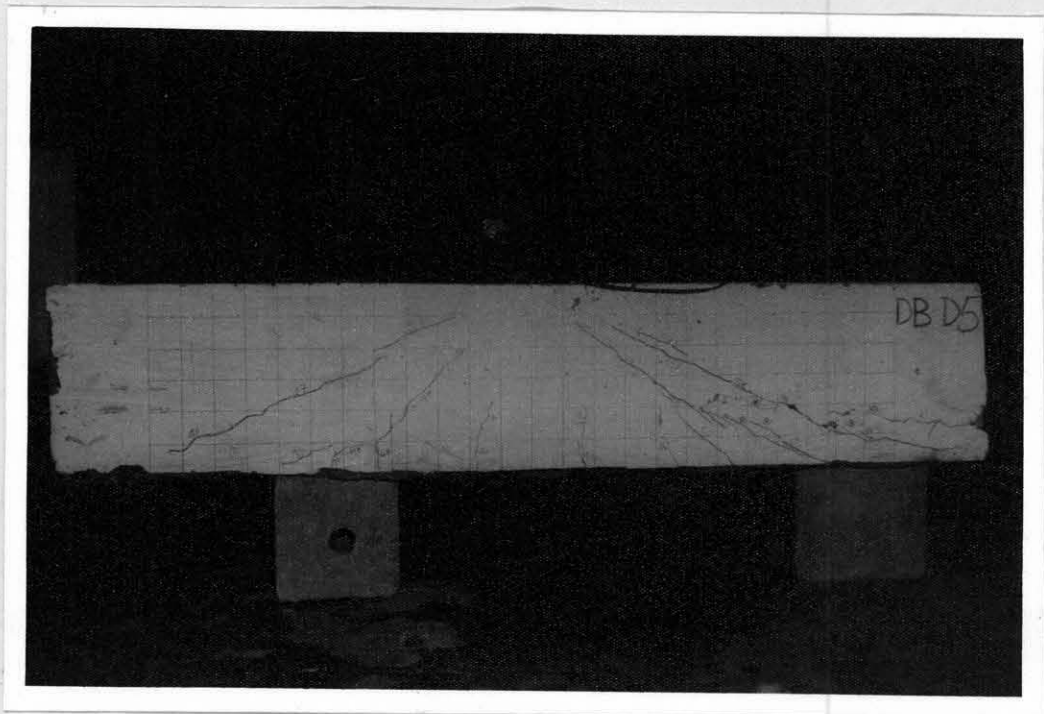


Fig. 5.58 Observed mode of failure and the crack pattern of Beam DB-D5

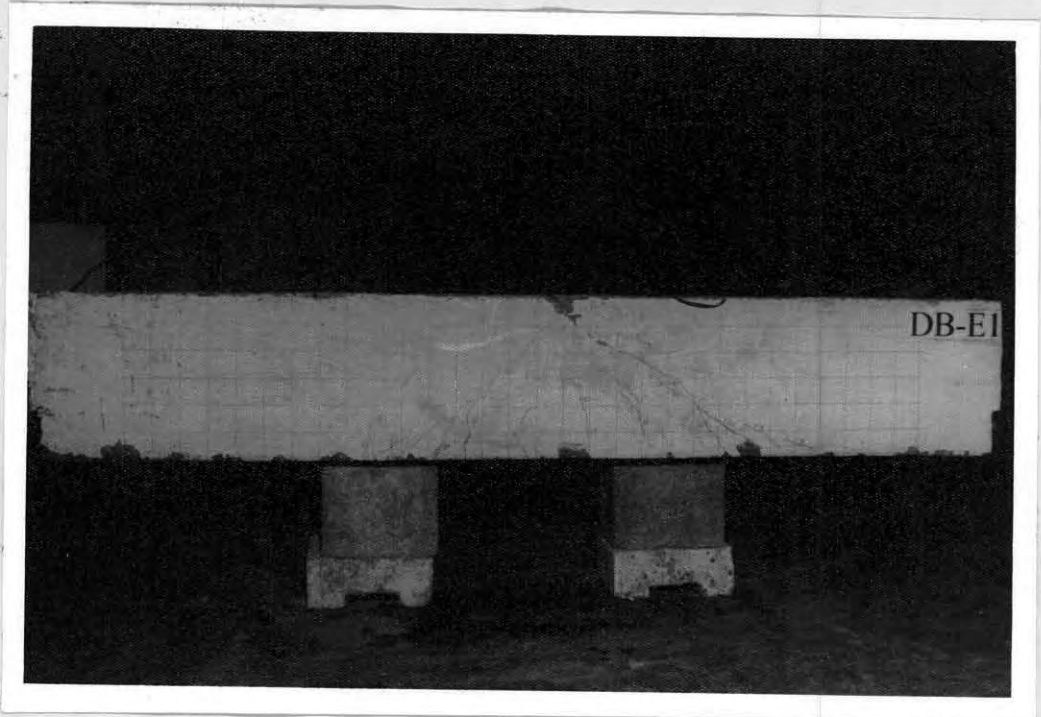


Fig. 5.59 Observed mode of failure and the crack pattern of Beam DB-E1

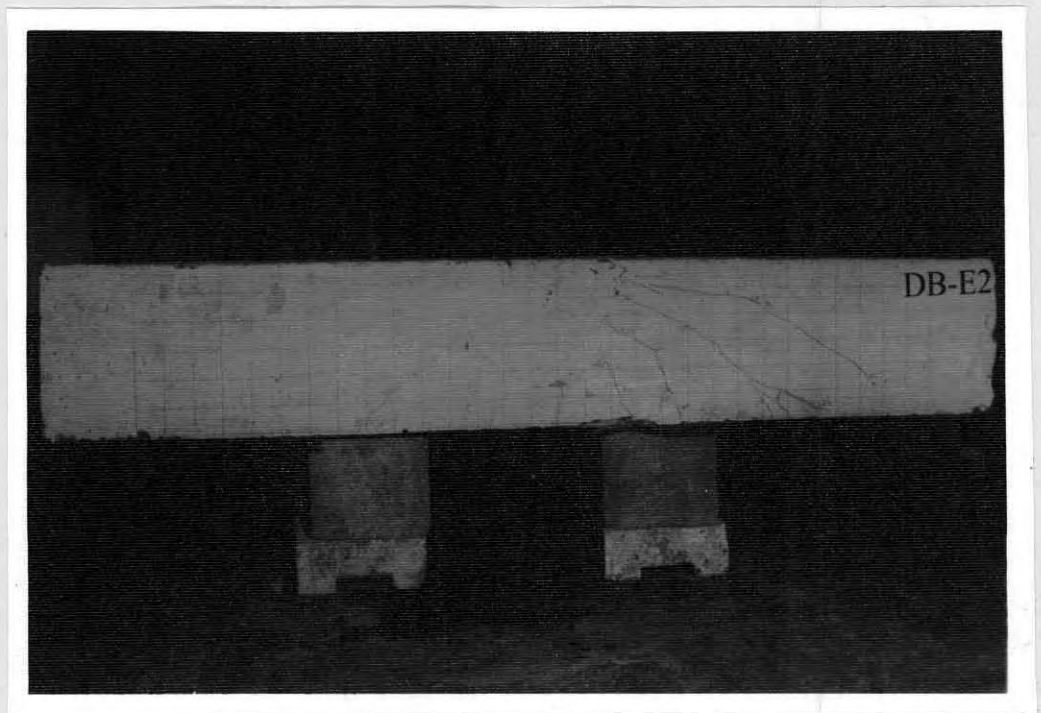


Fig. 5.60 Observed mode of failure and the crack pattern of Beam DB-E2



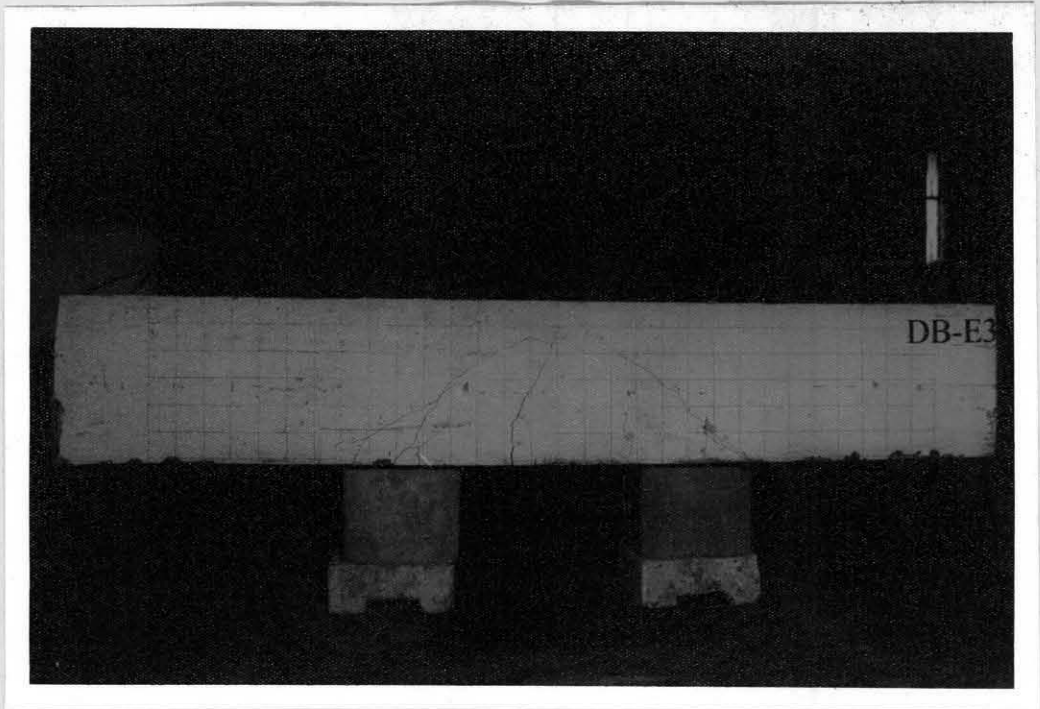


Fig. 5.61 Observed mode of failure and the crack pattern of Beam DB-E3

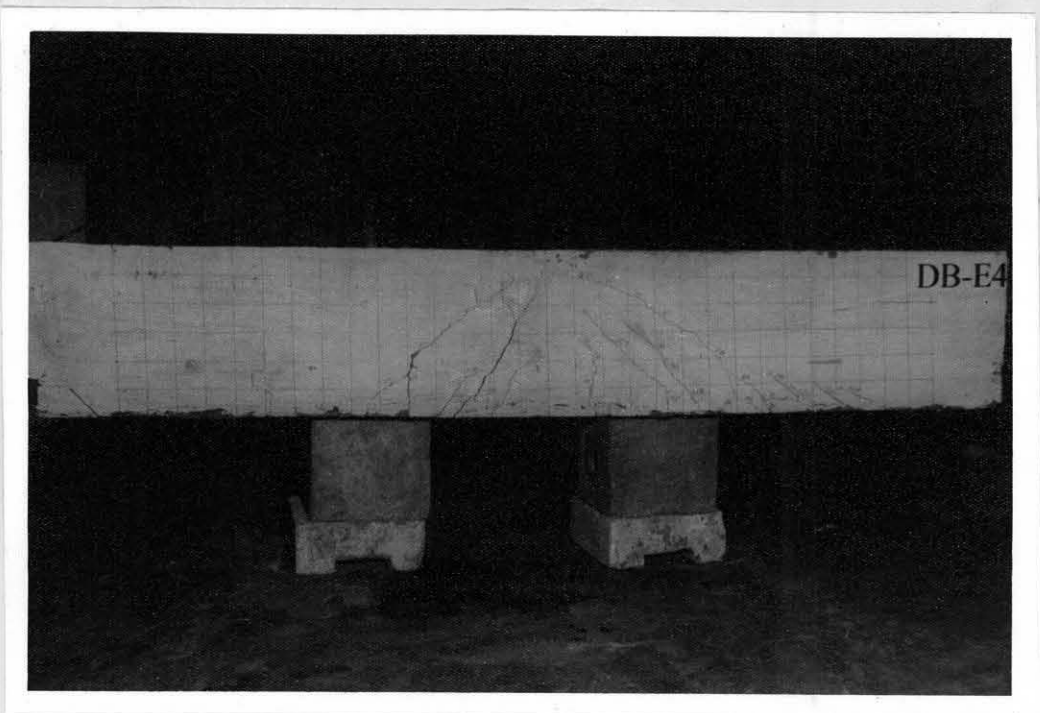


Fig. 5.62 Observed mode of failure and the crack pattern of Beam DB-E4

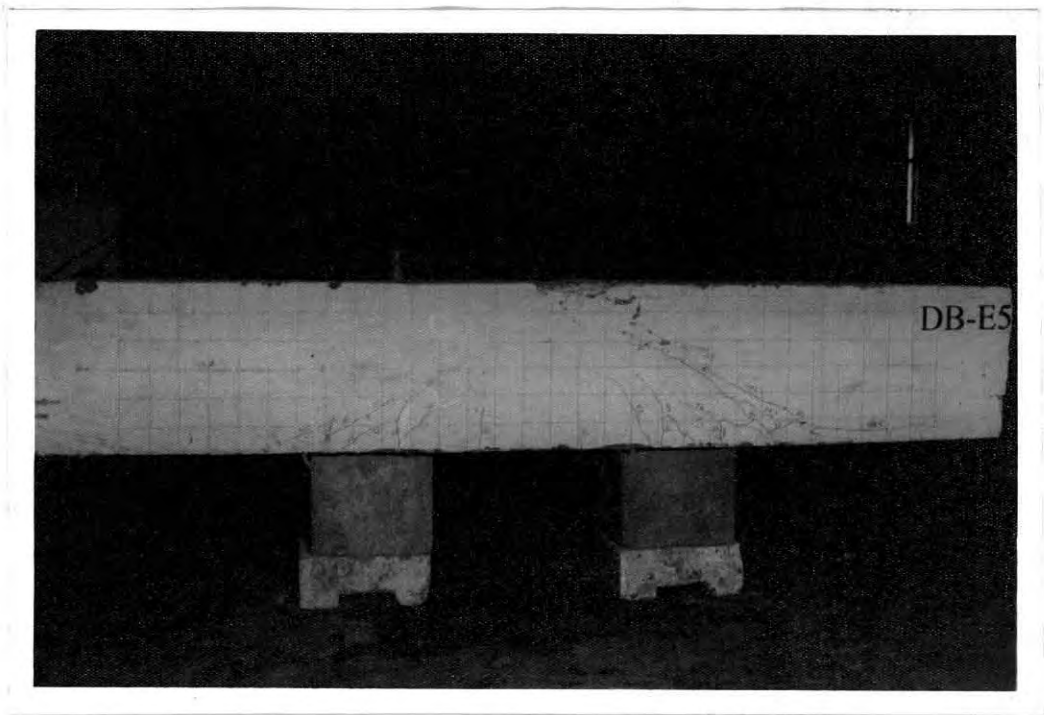


Fig. 5.63 Observed mode of failure and the crack pattern of Beam DB-E5

## CHAPTER 6

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### ANALYSIS AND DISCUSSION OF TEST RESULTS

#### 6.1 GENERAL

The test data presented in the preceding chapter are discussed and analyzed in the following articles.

#### 6.2 SHEAR CHARACTERISTICS OF THE TEST BEAMS

The behavior of test beams at the initiation of shear cracks and at ultimate load condition are as follows:

##### 6.2.1 Nominal Shear Stress at Cracking

The test data illustrating the nominal shearing stress characteristics at cracking and failure loads are presented in Table 6.1 for all the series of test beams. The variation of nominal shearing stress at initial diagonal cracking load for different web reinforcement arrangement has been found to be consistent with the variation of web reinforcement in the beams. In DBA series where the L/D ratio is unity, the nominal shearing stress at initial diagonal cracking load varies from 273.44 psi to 397.82 psi with an average of 306.83 psi which has a wide range of variation but the nominal shear stress at ultimate load varies from 697.72 psi to 782.57 psi with an average of 752.51 psi. The variation of the nominal shearing stress is at the initial diagonal cracking and at ultimate load in series DBD to DBE are also similar with that of DBA. But the variation is found directly dependent on the variation of web reinforcement particularly on the variation of vertical web reinforcement. It is found that beams having wider spacing of vertical web reinforcement had relatively lower value of nominal shear strength at initial diagonal cracking. But the variation of vertical web reinforcement have relatively lower effect on the nominal shearing stress at ultimate load.

After analysing the average nominal shearing stress both at initial diagonal cracking load and at ultimate load, it is found that the stresses are decreasing with the increase of L/D ratio. But it is very interesting that the average nominal shearing stress at initial diagonal cracking for DBE series is just becoming 51.43% of DBA series and similarly the nominal shearing stress at ultimate load for the beams DBE series is only 61% that of DBA series. It is found that the variation of average shearing stress in the first four series are minimum and inversely proportional to the L/D ratio. But the variation of average shear stress in fifth series DBE shows heterogeneity with the other series. Such beams having L/D ratio of 5 may not be deep beams, rather these beams (DBE series) may behave like rectangular beams where the horizontal shear reinforcement may have very less prominent effect on shear strength of the beams.



As reported by de Paiva<sup>(15)</sup> the critical stress at diagonal cracking for ordinary beams may be computed using the equation suggested by Diaz de Cossio. The equation is similar to the one endorsed in ACI Building code 318-89 for similar beams. The de Cossio equation is represented as,

$$v_{cr} = \frac{V_{cr}}{bd} = (2.14 + 4600 \frac{pvd}{M\sqrt{f'_c}}) \sqrt{f'_c} \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (6.1)$$

The cracking loads for the beams of this investigation were computed using equation 6.1 and are tabulated in Table 6.2. The ratio of the measured critical load to the computed one using equation 6.1 is also shown in the same table. It is observed from the table that the actual critical load is about 15 percent higher on an average than that of computed critical load for the test series DBA and about 3 percent higher in the case of DBB, but the ratio becomes less for the other three series of beams and these values are about 17 percent, 30 percent and 40 percent for series DBC, DBD and DBE respectively. Again it is very much distinct that the average ratio of  $v_{cr}/v_{co}$  for DBE series is only 53 percent of the same for DBA series. It also implies that the beams DBE series may not be deep beam rather it is behaving as ordinary rectangular beams.

Attempts were made by Kabir to develop similar expression for the test beams of this investigation correlating critical shear stress  $v_{cr}$  with the major variables like  $p$ ,  $a/D$  ratio and  $f'_c$  which are considered to influence the shear strength of beams. Although the number of test data were not large enough to bring about a definite conclusion yet an apparent trend of linear relationship appeared to exist between the terms

$$\frac{V_{cr}}{bd\sqrt{f'_c}} \quad \text{and} \quad 1000 \frac{pV_{cr}d}{M_{cr}\sqrt{f'_c}}$$

where,  $V_{cr}$  and  $M_{cr}$  are the shear force and bending moment respectively at the critical section of the beam at diagonal cracking.

The numerical values of these two terms for the test beams are presented in Table 6.3. From this table it is clearly seen that the values of both the ratio  $V_{cr}/bd\sqrt{f'_c}$  and  $1000 PV_{cr}d/M_{cr}\sqrt{f'_c}$  are increasing upto  $L/D$  ratio 4.00 but for  $L/D$  ratio 5.00 the values for both the ratio are suddenly decreasing which shows a different behaviour and suggests that the beam having  $L/D$  ratio 5.00 may not be a deep beam rather it behaves like a rectangular beam.

**Table 6.1 Nominal Shear Stress at Cracking and Ultimate Loads.**

| Beam Mark                | Nominal Shear Stress at                         |                             | Ratio $v_u/v_{cr}$ | $\sqrt{f'_c}$ | Ratio $v_u/\sqrt{f'_c}$ |
|--------------------------|-------------------------------------------------|-----------------------------|--------------------|---------------|-------------------------|
|                          | Initial Diagonal Cracking Stress $v_{cr}$ (psi) | Ultimate Stress $v_u$ (psi) |                    |               |                         |
| Series DB-A : L/D = 1.00 |                                                 |                             |                    |               |                         |
| DB-A1                    | 278.31                                          | 697.72                      | 2.51               |               | 9.98                    |
| DB-A2                    | 273.44                                          | 785.16                      | 2.87               |               | 11.23                   |
| DB-A3                    | 397.82                                          | 766.33                      | 1.93               | 69.90         | 10.96                   |
| DB-A4                    | 288.46                                          | 730.77                      | 2.53               |               | 10.46                   |
| DB-A5                    | 296.11                                          | 782.57                      | 2.64               |               | 11.20                   |
| Average: C               | 306.83<br>15.05                                 | 752.51<br>4.46              | 2.50<br>12.49      |               | 10.77<br>4.46           |
| Series DB-B : L/D = 1.75 |                                                 |                             |                    |               |                         |
| DB-B1                    | 370.86                                          | 904.91                      | 2.44               |               | 11.98                   |
| DB-B2                    | 296.69                                          | 890.08                      | 3.00               |               | 11.79                   |
| DB-B3                    | 242.50                                          | 903.88                      | 3.73               | 75.53         | 11.97                   |
| DB-B4                    | 297.62                                          | 762.65                      | 2.56               |               | 10.10                   |
| DB-B5                    | 253.18                                          | 868.06                      | 3.43               |               | 11.49                   |
| Average: C               | 292.17<br>15.48                                 | 865.62<br>6.16              | 3.03<br>16.29      |               | 11.47<br>6.15           |
| Series DB-C : L/D = 3.00 |                                                 |                             |                    |               |                         |
| DB-C1                    | 258.06                                          | 732.32                      | 2.84               |               | 10.77                   |
| DB-C2                    | 350.73                                          | 932.94                      | 2.66               |               | 13.72                   |
| DB-C3                    | 309.13                                          | 682.96                      | 2.21               | 67.98         | 10.05                   |
| DB-C4                    | 231.48                                          | 632.96                      | 2.73               |               | 9.31                    |
| DB-C5                    | 270.66                                          | 626.78                      | 2.32               |               | 9.22                    |
| Average: C               | 284.02<br>14.68                                 | 721.59<br>15.57             | 2.55<br>9.55       |               | 10.61<br>8.42           |
| Series DB-D : L/D = 4.00 |                                                 |                             |                    |               |                         |
| DB-D1                    | 223.40                                          | 658.44                      | 2.95               |               | 10.31                   |
| DB-D2                    | 178.57                                          | 702.38                      | 3.93               |               | 11.00                   |
| DB-D3                    | 238.10                                          | 476.19                      | 2.00               | 63.88         | 7.45                    |
| DB-D4                    | 223.76                                          | 615.35                      | 2.75               |               | 9.63                    |
| DB-D5                    | 238.10                                          | 616.07                      | 2.59               |               | 9.64                    |
| Average: C               | 220.39<br>9.93                                  | 613.69<br>12.36             | 2.84<br>22.10      |               | 9.61<br>12.39           |
| Series DB-E : L/D = 5.00 |                                                 |                             |                    |               |                         |
| DB-E1                    | 146.79                                          | 480.73                      | 3.28               |               | 7.74                    |
| DB-E2                    | 191.75                                          | 483.20                      | 2.52               |               | 7.78                    |
| DB-E3                    | 150.40                                          | 421.12                      | 2.80               | 62.09         | 6.78                    |
| DB-E4                    | 143.94                                          | 492.42                      | 3.42               |               | 7.93                    |
| DB-E5                    | 156.13                                          | 423.50                      | 2.71               |               | 6.82                    |
| Average: C               | 157.80<br>11.06                                 | 460.19<br>6.01              | 2.95<br>11.71      |               | 7.41<br>7.77            |

**Table 6.2 Comparison of Measured and Computed Cracking Stress after de Cossio.**

| Beam Mark                                    | Concrete Strength $f'_c$ (psi) | Measured Diagonal Cracking Stress $V_{cr}$ (psi) | Computed Cracking Stress after De Cossio $V_{co}$ (psi) | Ratio $V_{cr}/V_{co}$ |
|----------------------------------------------|--------------------------------|--------------------------------------------------|---------------------------------------------------------|-----------------------|
| <b>Series DB-A : <math>L/D = 1.00</math></b> |                                |                                                  |                                                         |                       |
| DB-A1                                        |                                | 278.31                                           | 265.11                                                  | 1.05                  |
| DB-A2                                        |                                | 273.44                                           | 260.40                                                  | 1.05                  |
| DB-A3                                        | 4886                           | 397.82                                           | 273.62                                                  | 1.45                  |
| DB-A4                                        |                                | 288.46                                           | 263.57                                                  | 1.09                  |
| DB-A5                                        |                                | 296.11                                           | 271.43                                                  | 1.09                  |
| <b>Average:</b>                              |                                | <b>306.83</b>                                    |                                                         | <b>1.146</b>          |
| <b>C :</b>                                   |                                | <b>15.05</b>                                     |                                                         | <b>13.36</b>          |
| <b>Series DB-B : <math>L/D = 1.75</math></b> |                                |                                                  |                                                         |                       |
| DB-B1                                        |                                | 370.86                                           | 284.73                                                  | 1.30                  |
| DB-B2                                        |                                | 296.69                                           | 284.16                                                  | 1.04                  |
| DB-B3                                        | 5704                           | 242.50                                           | 283.59                                                  | 0.86                  |
| DB-B4                                        |                                | 297.62                                           | 281.13                                                  | 1.06                  |
| DB-B5                                        |                                | 253.18                                           | 283.95                                                  | 0.89                  |
| DB-A5                                        |                                | 296.11                                           | 271.43                                                  | 1.09                  |
| <b>Average:</b>                              |                                | <b>292.17</b>                                    |                                                         | <b>1.03</b>           |
| <b>C :</b>                                   |                                | <b>15.48</b>                                     |                                                         | <b>15.19</b>          |
| <b>Series DB-C : <math>L/D = 3.00</math></b> |                                |                                                  |                                                         |                       |
| DB-C1                                        |                                | 258.06                                           | 340.31                                                  | 0.76                  |
| DB-C2                                        |                                | 350.73                                           | 342.72                                                  | 1.02                  |
| DB-C3                                        | 4621                           | 309.13                                           | 345.20                                                  | 0.90                  |
| DB-C4                                        |                                | 231.48                                           | 347.20                                                  | 0.67                  |
| DB-C5                                        |                                | 270.66                                           | 344.65                                                  | 0.79                  |
| <b>Average:</b>                              |                                | <b>284.01</b>                                    |                                                         | <b>0.83</b>           |
| <b>C :</b>                                   |                                | <b>14.68</b>                                     |                                                         | <b>14.60</b>          |
| <b>Series DB-D : <math>L/D = 4.00</math></b> |                                |                                                  |                                                         |                       |
| DB-D1                                        |                                | 223.40                                           | 314.30                                                  | 0.71                  |
| DB-D2                                        |                                | 178.57                                           | 316.52                                                  | 0.56                  |
| DB-D3                                        | 4080                           | 238.10                                           | 317.62                                                  | 0.75                  |
| DB-D4                                        |                                | 223.76                                           | 313.21                                                  | 0.71                  |
| DB-D5                                        |                                | 238.10                                           | 315.78                                                  | 0.75                  |
| <b>Average:</b>                              |                                | <b>220.39</b>                                    |                                                         | <b>0.696</b>          |
| <b>C :</b>                                   |                                | <b>9.93</b>                                      |                                                         | <b>10.64</b>          |
| <b>Series DB-E : <math>L/D = 5.00</math></b> |                                |                                                  |                                                         |                       |
| DB-E1                                        |                                | 146.79                                           | 256.55                                                  | 0.57                  |
| DB-E2                                        |                                | 191.75                                           | 259.60                                                  | 0.74                  |
| DB-E3                                        | 3856                           | 150.40                                           | 260.22                                                  | 0.58                  |
| DB-E4                                        |                                | 143.94                                           | 259.82                                                  | 0.55                  |
| DB-E5                                        |                                | 156.13                                           | 260.01                                                  | 0.60                  |
| <b>Average:</b>                              |                                | <b>157.80</b>                                    |                                                         | <b>0.608</b>          |
| <b>C :</b>                                   |                                | <b>11.06</b>                                     |                                                         | <b>15.07</b>          |

**Table 6.3 Relationship between  $V_{cr}/bd\sqrt{f'_c}$  and  $1000 pV_{cr}d/M_{cr}\sqrt{f'_c}$**

| Beam Mark                       | $\sqrt{f'_c}$ | Critical Shear Stress, $v_{cr}$ (psi) | Ratio $V_{cr}/bd \sqrt{f'_c}$ | Ratio $1000 PV_{cr}d/ M_{cr}\sqrt{f'_c}$ |
|---------------------------------|---------------|---------------------------------------|-------------------------------|------------------------------------------|
| <b>Series DB-B : L/D = 1.00</b> |               |                                       |                               |                                          |
| DB-A1                           | 69.90         | 278.31                                | 3.98                          | 0.36                                     |
| DB-A2                           |               | 273.44                                | 3.91                          | 0.34                                     |
| DB-A3                           |               | 397.82                                | 5.69                          | 0.39                                     |
| DB-A4                           |               | 288.46                                | 4.13                          | 0.35                                     |
| DB-A5                           |               | 296.11                                | 4.24                          | 0.38                                     |
|                                 |               |                                       | <b>Average:</b>               | <b>0.364</b>                             |
|                                 |               |                                       | <b>C :</b>                    | <b>5.09</b>                              |
| <b>Series DB-B : L/D = 1.75</b> |               |                                       |                               |                                          |
| DB-B1                           | 75.53         | 370.86                                | 4.91                          | 0.35                                     |
| DB-B2                           |               | 296.69                                | 3.93                          | 0.35                                     |
| DB-B3                           |               | 242.50                                | 3.21                          | 0.35                                     |
| DB-B4                           |               | 297.62                                | 3.94                          | 0.34                                     |
| DB-B5                           |               | 253.18                                | 3.35                          | 0.35                                     |
|                                 |               |                                       | <b>Average:</b>               | <b>0.348</b>                             |
|                                 |               |                                       | <b>C :</b>                    | <b>1.15</b>                              |
| <b>Series DB-C : L/D = 3.00</b> |               |                                       |                               |                                          |
| DB-C1                           | 67.98         | 258.06                                | 3.80                          | 0.62                                     |
| DB-C2                           |               | 350.73                                | 5.16                          | 0.63                                     |
| DB-C3                           |               | 309.13                                | 4.55                          | 0.64                                     |
| DB-C4                           |               | 231.48                                | 3.41                          | 0.65                                     |
| DB-C5                           |               | 270.66                                | 3.98                          | 0.64                                     |
|                                 |               |                                       | <b>Average:</b>               | <b>0.636</b>                             |
|                                 |               |                                       | <b>C :</b>                    | <b>1.60</b>                              |
| <b>Series DB-D : L/D = 4.00</b> |               |                                       |                               |                                          |
| DB-D1                           | 63.88         | 223.40                                | 3.50                          | 0.60                                     |
| DB-D2                           |               | 178.57                                | 2.80                          | 0.61                                     |
| DB-D3                           |               | 238.10                                | 3.73                          | 0.62                                     |
| DB-D4                           |               | 223.76                                | 3.50                          | 0.60                                     |
| DB-D5                           |               | 238.10                                | 3.73                          | 0.61                                     |
|                                 |               |                                       | <b>Average:</b>               | <b>0.608</b>                             |
|                                 |               |                                       | <b>C :</b>                    | <b>1.23</b>                              |
| <b>Series DB-E : L/D = 5.00</b> |               |                                       |                               |                                          |
| DB-E1                           | 62.09         | 146.79                                | 2.36                          | 0.43                                     |
| DB-E2                           |               | 191.75                                | 3.09                          | 0.44                                     |
| DB-E3                           |               | 150.40                                | 2.42                          | 0.45                                     |
| DB-E4                           |               | 143.94                                | 2.32                          | 0.44                                     |
| DB-E5                           |               | 156.13                                | 2.51                          | 0.45                                     |
|                                 |               |                                       | <b>Average:</b>               | <b>0.442</b>                             |
|                                 |               |                                       | <b>C :</b>                    | <b>1.79</b>                              |

The linear relationship between the two terms  $\frac{V_{cr}}{bd\sqrt{f'_c}}$  and  $1000 \frac{pV_{cr}d}{M_{cr}\sqrt{f'_c}}$  may be stated by Kabir as,

$$v_{cr} = \frac{V_{cr}}{bd} = (-2.18 + 15500 \frac{pV_{cr}d}{M_{cr}\sqrt{f'_c}}) \sqrt{f'_c} \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (6.2)$$

where,  $v_{cr}$  is the shear stress at the critical section located not further than 'd' from support.

A comparison of the estimate of diagonal cracking load using the proposed equation by eq<sup>n</sup>.6.2 and the test values for the same are furnished in Table 6.4 for both the series of beams. A fair agreement appears to exist between them considering the well known variability of concrete.

### 6.2.2 Nominal Shear Stress at Initial Diagonal Cracking Load and Ultimate Load

From table 6.1, the nominal shear stresses at initial diagonal cracking Load are found to vary between 273.44 psi and 397.82 psi with an average of 306.83 psi for the test beams of DBA series, 242.50 psi and 370.86 psi with an average of 292.17 psi for the test beams of DBB series, 231.48 psi and 350.73 psi with an average of 284.012 psi for the test beams of DBC series, 178.57 psi and 238.10 psi with an average of 220.386 psi for the test beams of DBD series and 143.94 psi and 191.75 psi with an average of 157.802 psi for the test beams of DBE series. The overall average value of initial diagonal cracking stresses for the whole set of twenty five beams is 212.64 psi.

Again from the table 6.1, the nominal shear stresses at ultimate load are found to vary between 697.72 psi and 785.16 psi with an average of 752.51 psi for the test beams of DBA series, 762.65 psi and 904.91 psi with an average of 865.916 psi for the test beams of DBB series, 626.78 psi and 932.94 psi with an average of 721.592 psi for the test beams of DBC series, 615.35 psi and 702.38 psi with an average of 613.686 psi for the test beams of DBD series and 421.12 psi and 492.42 psi with an average of 460.194 psi for the test beams of DBE series. The overall average value of ultimate shearing stresses for the whole set of twenty five beams is 682.78 psi.

This shows again that the nominal shear stress at ultimate load for the beams DBA to DBD are similar but for DBE the stress is just 61% of the DBA series which again shows heterogeneous with the other four series of deep beams.



**Table 6.4 Comparison of Measured and Computed Cracking Stress after Kabir.**

| Beam Mark                       | Concrete Strength<br>$f'_c$<br>(psi) | Measured Diagonal Cracking Stress<br>$v_{cr}$<br>(psi) | Computed Cracking Stress after Kabir $v_{kb}$<br>(psi) | Ratio<br>$v_{cr}/v_{kb}$ |
|---------------------------------|--------------------------------------|--------------------------------------------------------|--------------------------------------------------------|--------------------------|
| <b>Series DB-A : L/D = 1.00</b> |                                      |                                                        |                                                        |                          |
| DB-A1                           |                                      | 278.31                                                 | 236.93                                                 | 1.17                     |
| DB-A2                           |                                      | 273.44                                                 | 221.05                                                 | 1.24                     |
| DB-A3                           | 4886                                 | 397.82                                                 | 265.59                                                 | 1.50                     |
| DB-A4                           |                                      | 288.46                                                 | 231.72                                                 | 1.24                     |
| DB-A5                           |                                      | 296.11                                                 | 258.23                                                 | 1.15                     |
|                                 |                                      |                                                        | <b>Average:</b>                                        | <b>1.26</b>              |
|                                 |                                      |                                                        | <b>C :</b>                                             | <b>9.95</b>              |
| <b>Series DB-B : L/D = 1.75</b> |                                      |                                                        |                                                        |                          |
| DB-B1                           |                                      | 370.86                                                 | 250.16                                                 | 1.48                     |
| DB-B2                           |                                      | 296.69                                                 | 248.23                                                 | 1.20                     |
| DB-B3                           | 5704                                 | 242.50                                                 | 246.32                                                 | 0.98                     |
| DB-B4                           |                                      | 297.62                                                 | 238.03                                                 | 1.25                     |
| DB-B5                           |                                      | 253.18                                                 | 247.53                                                 | 1.02                     |
|                                 |                                      |                                                        | <b>Average:</b>                                        | <b>1.186</b>             |
|                                 |                                      |                                                        | <b>C :</b>                                             | <b>15.114</b>            |
| <b>Series DB-C : L/D = 3.00</b> |                                      |                                                        |                                                        |                          |
| DB-C1                           |                                      | 258.06                                                 | 508.30                                                 | 0.51                     |
| DB-C2                           |                                      | 350.73                                                 | 516.40                                                 | 0.68                     |
| DB-C3                           | 4621                                 | 309.13                                                 | 524.76                                                 | 0.59                     |
| DB-C4                           |                                      | 231.48                                                 | 531.52                                                 | 0.44                     |
| DB-C5                           |                                      | 270.66                                                 | 522.91                                                 | 0.52                     |
|                                 |                                      |                                                        | <b>Average:</b>                                        | <b>0.548</b>             |
|                                 |                                      |                                                        | <b>C :</b>                                             | <b>14.84</b>             |
| <b>Series DB-D : L/D = 4.00</b> |                                      |                                                        |                                                        |                          |
| DB-D1                           |                                      | 223.40                                                 | 459.19                                                 | 0.49                     |
| DB-D2                           |                                      | 178.57                                                 | 466.67                                                 | 0.38                     |
| DB-D3                           | 4080                                 | 238.10                                                 | 470.41                                                 | 0.51                     |
| DB-D4                           |                                      | 223.76                                                 | 455.54                                                 | 0.49                     |
| DB-D5                           |                                      | 238.10                                                 | 464.21                                                 | 0.51                     |
|                                 |                                      |                                                        | <b>Average:</b>                                        | <b>0.476</b>             |
|                                 |                                      |                                                        | <b>C :</b>                                             | <b>10.26</b>             |
| <b>Series DB-E : L/D = 5.00</b> |                                      |                                                        |                                                        |                          |
| DB-E1                           |                                      | 146.79                                                 | 281.34                                                 | 0.52                     |
| DB-E2                           |                                      | 191.75                                                 | 291.63                                                 | 0.66                     |
| DB-E3                           | 3856                                 | 150.40                                                 | 293.71                                                 | 0.51                     |
| DB-E4                           |                                      | 143.94                                                 | 292.37                                                 | 0.49                     |
| DB-E5                           |                                      | 156.13                                                 | 293.00                                                 | 0.53                     |
|                                 |                                      |                                                        | <b>Average:</b>                                        | <b>0.542</b>             |
|                                 |                                      |                                                        | <b>C :</b>                                             | <b>11.56</b>             |



**Table 6.5 Comparison of Measured and Computed Cracking Stress by ACI Method**

| Beam Mark                       | Concrete Strength<br>$\sqrt{f'_c}$<br>(psi) | Measured Diagonal Cracking Stress<br>$v_{cr}$<br>(psi) | Computed Cracking Stress after ACI<br>$v_{ACI}$ (psi) | Ratio<br>$v_{cr}/v_{ACI}$ |
|---------------------------------|---------------------------------------------|--------------------------------------------------------|-------------------------------------------------------|---------------------------|
| <b>Series DB-A : L/D = 1.00</b> |                                             |                                                        |                                                       |                           |
| DB-A1                           |                                             | 278.31                                                 | 244.64                                                | 1.42                      |
| DB-A2                           |                                             | 273.44                                                 | 244.64                                                | 1.05                      |
| DB-A3                           | 4886                                        | 397.82                                                 | 244.64                                                | 1.45                      |
| DB-A4                           |                                             | 288.46                                                 | 244.64                                                | 1.09                      |
| DB-A5                           |                                             | 296.11                                                 | 244.64                                                | 1.09                      |
|                                 |                                             |                                                        | <b>Average:</b>                                       | <b>1.22</b>               |
|                                 |                                             |                                                        | <b>C :</b>                                            | <b>14.46</b>              |
| <b>Series DB-B : L/D = 1.75</b> |                                             |                                                        |                                                       |                           |
| DB-B1                           |                                             | 370.86                                                 | 264.34                                                | 1.30                      |
| DB-B2                           |                                             | 296.69                                                 | 264.34                                                | 1.04                      |
| DB-B3                           | 5704                                        | 242.50                                                 | 264.34                                                | 0.86                      |
| DB-B4                           |                                             | 297.62                                                 | 264.34                                                | 1.06                      |
| DB-B5                           |                                             | 253.18                                                 | 264.34                                                | 0.89                      |
|                                 |                                             |                                                        | <b>Average:</b>                                       | <b>1.03</b>               |
|                                 |                                             |                                                        | <b>C :</b>                                            | <b>15.19</b>              |
| <b>Series DB-C : L/D = 3.00</b> |                                             |                                                        |                                                       |                           |
| DB-C1                           |                                             | 258.06                                                 | 237.93                                                | 0.76                      |
| DB-C2                           |                                             | 350.73                                                 | 237.93                                                | 1.02                      |
| DB-C3                           | 4621                                        | 309.13                                                 | 237.93                                                | 0.90                      |
| DB-C4                           |                                             | 231.48                                                 | 237.93                                                | 0.67                      |
| DB-C5                           |                                             | 270.66                                                 | 237.93                                                | 0.79                      |
|                                 |                                             |                                                        | <b>Average:</b>                                       | <b>0.828</b>              |
|                                 |                                             |                                                        | <b>C :</b>                                            | <b>14.6</b>               |
| <b>Series DB-D : L/D = 4.00</b> |                                             |                                                        |                                                       |                           |
| DB-D1                           |                                             | 223.40                                                 | 223.56                                                | 0.71                      |
| DB-D2                           |                                             | 178.57                                                 | 223.56                                                | 0.56                      |
| DB-D3                           | 4080                                        | 238.10                                                 | 223.56                                                | 0.75                      |
| DB-D4                           |                                             | 223.76                                                 | 223.56                                                | 0.71                      |
| DB-D5                           |                                             | 238.10                                                 | 223.56                                                | 0.75                      |
|                                 |                                             |                                                        | <b>Average:</b>                                       | <b>0.696</b>              |
|                                 |                                             |                                                        | <b>C :</b>                                            | <b>10.102</b>             |
| <b>Series DB-E : L/D = 5.00</b> |                                             |                                                        |                                                       |                           |
| DB-E1                           |                                             | 146.79                                                 | 217.33                                                | 0.57                      |
| DB-E2                           |                                             | 191.75                                                 | 217.33                                                | 0.74                      |
| DB-E3                           | 3856                                        | 150.40                                                 | 217.33                                                | 0.58                      |
| DB-E4                           |                                             | 143.94                                                 | 217.33                                                | 0.55                      |
| DB-E5                           |                                             | 156.13                                                 | 217.33                                                | 0.60                      |
|                                 |                                             |                                                        | <b>Average:</b>                                       | <b>0.608</b>              |
|                                 |                                             |                                                        | <b>C :</b>                                            | <b>10.96</b>              |

**Table 6.6 Comparison of Measured and Computed Cracking Stress by ACI Method, de Cossio, Kabir**

| Beam Mark                         | Concrete Strength $f'_c$ (psi) | Measured Diagonal Cracking Stress $v_{cr}$ (psi) | Computed Cracking Stress after ACI $v_{ACI}$ (psi) | Computed Cracking Stress after de Cossio $v_{co}$ (psi) | Computed Cracking Stress after Kabir $v_{kb}$ (psi) |
|-----------------------------------|--------------------------------|--------------------------------------------------|----------------------------------------------------|---------------------------------------------------------|-----------------------------------------------------|
| <b>Series DB - A : L/D = 1.00</b> |                                |                                                  |                                                    |                                                         |                                                     |
| DB-A1                             |                                | 278.31                                           | 244.64                                             | 265.11                                                  | 236.93                                              |
| DB-A2                             |                                | 273.44                                           | 244.64                                             | 260.40                                                  | 221.05                                              |
| DB-A3                             | 4886                           | 397.82                                           | 244.64                                             | 273.62                                                  | 265.59                                              |
| DB-A4                             |                                | 288.46                                           | 244.64                                             | 263.57                                                  | 231.72                                              |
| DB-A5                             |                                | 296.11                                           | 244.64                                             | 271.43                                                  | 258.23                                              |
| <b>Series DB - B : L/D = 1.75</b> |                                |                                                  |                                                    |                                                         |                                                     |
| DB-B1                             |                                | 370.86                                           | 264.34                                             | 284.73                                                  | 250.16                                              |
| DB-B2                             |                                | 296.69                                           | 264.34                                             | 284.16                                                  | 248.23                                              |
| DB-B3                             | 5704                           | 242.50                                           | 264.34                                             | 283.59                                                  | 246.32                                              |
| DB-B4                             |                                | 297.62                                           | 264.34                                             | 281.13                                                  | 238.03                                              |
| DB-B5                             |                                | 253.18                                           | 264.34                                             | 283.95                                                  | 247.53                                              |
| <b>Series DB - C : L/D = 3.00</b> |                                |                                                  |                                                    |                                                         |                                                     |
| DB-C1                             |                                | 258.06                                           | 237.93                                             | 340.31                                                  | 508.30                                              |
| DB-C2                             |                                | 350.73                                           | 237.93                                             | 342.72                                                  | 516.40                                              |
| DB-C3                             | 4621                           | 309.13                                           | 237.93                                             | 345.20                                                  | 524.76                                              |
| DB-C4                             |                                | 231.48                                           | 237.93                                             | 347.20                                                  | 531.52                                              |
| DB-C5                             |                                | 270.66                                           | 237.93                                             | 344.65                                                  | 522.91                                              |
| <b>Series DB - D : L/D = 4.00</b> |                                |                                                  |                                                    |                                                         |                                                     |
| DB-D1                             |                                | 223.40                                           | 223.56                                             | 314.30                                                  | 459.19                                              |
| DB-D2                             |                                | 178.57                                           | 223.56                                             | 316.52                                                  | 466.67                                              |
| DB-D3                             | 4080                           | 238.10                                           | 223.56                                             | 317.62                                                  | 470.41                                              |
| DB-D4                             |                                | 223.76                                           | 223.56                                             | 313.21                                                  | 455.54                                              |
| DB-D5                             |                                | 238.10                                           | 223.56                                             | 315.78                                                  | 464.21                                              |
| <b>Series DB - E : L/D = 5.00</b> |                                |                                                  |                                                    |                                                         |                                                     |
| DB-E1                             |                                | 146.79                                           | 217.33                                             | 256.55                                                  | 281.34                                              |
| DB-E2                             |                                | 191.75                                           | 217.33                                             | 259.60                                                  | 291.63                                              |
| DB-E3                             | 3856                           | 150.40                                           | 217.33                                             | 260.22                                                  | 293.71                                              |
| DB-E4                             |                                | 143.94                                           | 217.33                                             | 259.82                                                  | 292.37                                              |
| DB-E5                             |                                | 156.13                                           | 217.33                                             | 260.01                                                  | 293.00                                              |

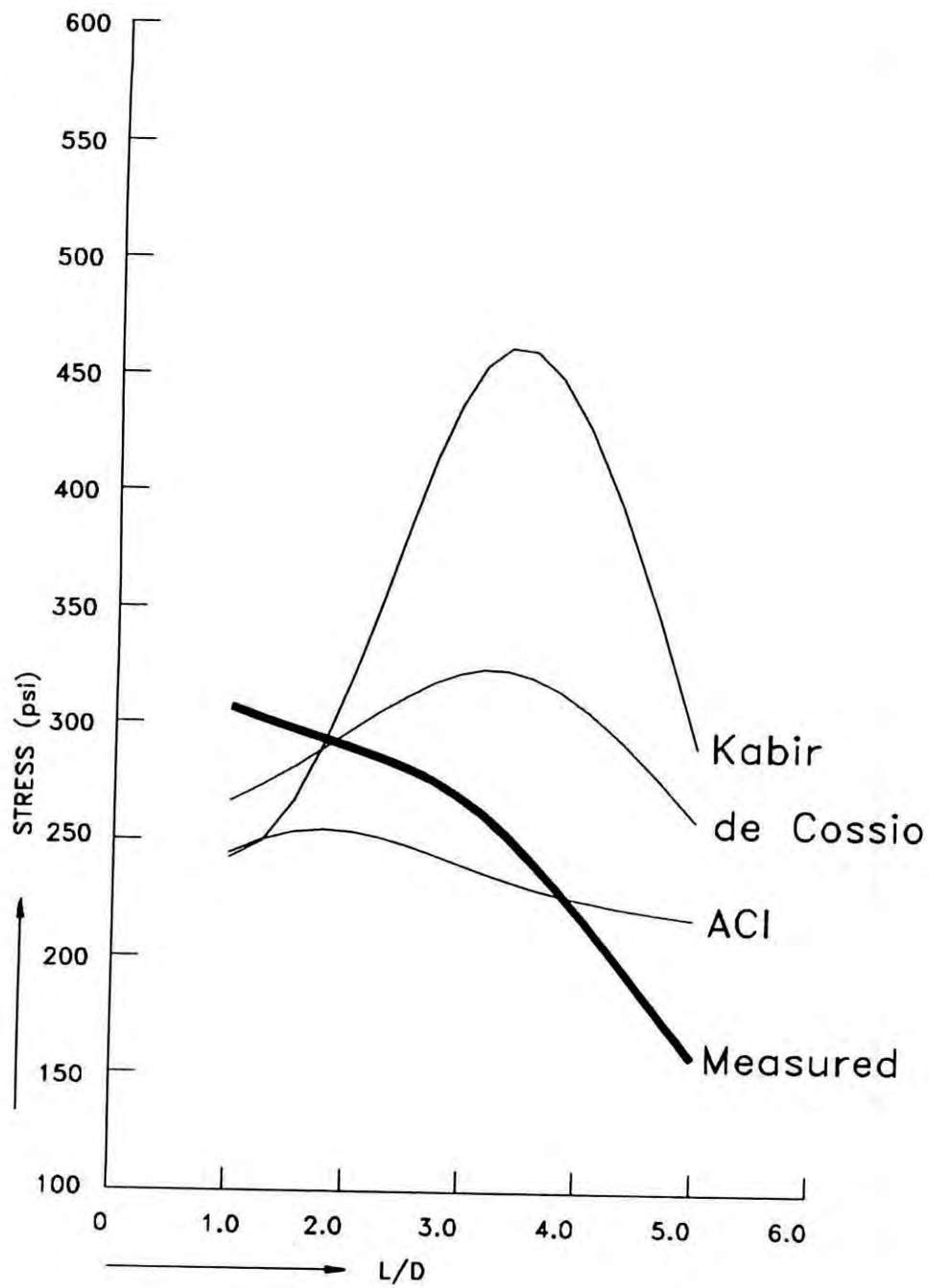


FIG. 6.1 COMPARISON OF MEASURED AND COMPUTED CRACKING STRESS BY ACI METHOD, DE COSSIO & KABIR

**Table 6.7a Ultimate Shear Computation by Various Method**

**Series DB-A:  $L/D = 1.00$**

| Beam Mark | Component of Ultimate Shear Carried by |               |                  |                    |                                | Computed Ultimate Shear |
|-----------|----------------------------------------|---------------|------------------|--------------------|--------------------------------|-------------------------|
|           | Concrete                               | Tension Steel | Vertical Stirrup | Horizontal Stirrup | Web Steel Total<br>(6)=(4)+(5) |                         |
| (1)       | (2)                                    | (3)           | (4)              | (5)                |                                | (7)                     |

**ACI Method**

|       |        |   |      |       |       |        |
|-------|--------|---|------|-------|-------|--------|
| DB-A1 | 108.50 | - | 6.34 | 16.23 | 22.56 | 131.06 |
| DB-A2 | 107.37 | - | 4.38 | 21.62 | 25.99 | 133.36 |
| DB-A3 | 100.15 | - | 8.49 | 13.90 | 22.39 | 122.54 |
| DB-A4 | 109.04 | - | 6.40 | 16.29 | 22.69 | 131.74 |
| DB-A5 | 99.15  | - | 3.20 | 16.00 | 19.20 | 118.35 |

**S.P. Ray and C.S. Reddy Method**

|       |       |       |      |      |       |        |
|-------|-------|-------|------|------|-------|--------|
| DB-A1 | 82.78 | 37.98 | 4.39 | 4.59 | 8.98  | 129.75 |
| DB-A2 | 80.39 | 36.95 | 3.29 | 6.70 | 9.99  | 127.33 |
| DB-A3 | 76.18 | 37.81 | 5.69 | 4.57 | 10.26 | 124.25 |
| DB-A4 | 82.91 | 37.80 | 4.43 | 4.57 | 9.00  | 129.71 |
| DB-A5 | 74.76 | 37.30 | 1.94 | 4.51 | 6.45  | 118.52 |

**Ramkrishnan and Ananthanarayan Method**

|       |        |   |   |   |   |        |
|-------|--------|---|---|---|---|--------|
| DB-A1 | 193.81 | - | - | - | - | 193.81 |
| DB-A2 | 191.72 | - | - | - | - | 191.72 |
| DB-A3 | 178.90 | - | - | - | - | 178.90 |
| DB-A4 | 194.71 | - | - | - | - | 194.71 |
| DB-A5 | 177.23 | - | - | - | - | 177.23 |

**Series DB-B:  $L/D = 1.75$**

**ACI Method**

|       |       |   |      |       |       |       |
|-------|-------|---|------|-------|-------|-------|
| DB-B1 | 61.09 | - | 7.09 | 13.83 | 20.92 | 82.01 |
| DB-B2 | 61.09 | - | 9.49 | 10.74 | 20.23 | 81.32 |
| DB-B3 | 61.66 | - | 2.87 | 19.53 | 22.40 | 84.06 |
| DB-B4 | 60.90 | - | 4.74 | 7.86  | 12.61 | 73.51 |
| DB-B5 | 62.64 | - | 3.53 | 14.01 | 17.54 | 80.18 |

**S.P. Ray and C.S. Reddy Method**

|       |       |       |       |      |       |       |
|-------|-------|-------|-------|------|-------|-------|
| DB-B1 | 34.08 | 34.84 | 12.71 | 4.21 | 16.93 | 85.84 |
| DB-B2 | 33.99 | 34.70 | 17.01 | 2.10 | 19.11 | 87.81 |
| DB-B3 | 34.33 | 34.77 | 5.31  | 6.31 | 11.61 | 80.72 |
| DB-B4 | 33.50 | 34.04 | 8.65  | 2.06 | 10.71 | 78.25 |
| DB-B5 | 35.23 | 35.30 | 6.28  | 6.40 | 12.68 | 83.21 |

**Ramkrishnan and Ananthanarayan Method**

|       |       |   |   |   |   |       |
|-------|-------|---|---|---|---|-------|
| DB-B1 | 89.35 | - | - | - | - | 89.35 |
| DB-B2 | 89.35 | - | - | - | - | 89.35 |
| DB-B3 | 90.09 | - | - | - | - | 90.09 |
| DB-B4 | 89.28 | - | - | - | - | 89.28 |
| DB-B5 | 91.52 | - | - | - | - | 91.52 |

**Table 6.7b Ultimate Shear Computation by Various Method**

**Series DB-C:  $L/D = 3.00$**

**ACI Method**

|       |       |   |       |       |       |       |
|-------|-------|---|-------|-------|-------|-------|
| DB-C1 | 58.48 | - | 10.65 | 11.79 | 22.44 | 80.92 |
| DB-C2 | 58.15 | - | 14.26 | 9.28  | 23.54 | 81.69 |
| DB-C3 | 56.73 | - | 4.28  | 16.47 | 20.75 | 77.49 |
| DB-C4 | 56.38 | - | 7.18  | 6.94  | 14.12 | 70.50 |
| DB-C5 | 57.26 | - | 5.37  | 11.91 | 17.28 | 74.54 |

**S.P. Ray and C.S. Reddy Method**

|       |       |       |       |      |       |        |
|-------|-------|-------|-------|------|-------|--------|
| DB-C1 | 23.93 | 49.70 | 25.21 | 2.08 | 27.29 | 100.92 |
| DB-C2 | 23.87 | 50.08 | 32.12 | 1.05 | 33.17 | 107.12 |
| DB-C3 | 23.11 | 49.26 | 9.83  | 3.09 | 12.93 | 85.30  |
| DB-C4 | 22.99 | 49.42 | 16.84 | 1.03 | 17.87 | 90.28  |
| DB-C5 | 23.40 | 49.64 | 12.61 | 3.12 | 15.73 | 88.77  |

**Ramkrishnan and Ananthanarayan Method**

|       |       |   |   |   |   |       |
|-------|-------|---|---|---|---|-------|
| DB-C1 | 91.18 | - | - | - | - | 91.18 |
| DB-C2 | 90.56 | - | - | - | - | 90.56 |
| DB-C3 | 88.46 | - | - | - | - | 88.46 |
| DB-C4 | 87.81 | - | - | - | - | 87.81 |
| DB-C5 | 89.19 | - | - | - | - | 89.19 |

**Series DB-D:  $L/D = 4.00$**

**ACI Method**

|       |       |   |       |       |       |       |
|-------|-------|---|-------|-------|-------|-------|
| DB-D1 | 65.19 | - | 13.77 | 9.68  | 23.45 | 88.64 |
| DB-D2 | 64.39 | - | 18.36 | 7.53  | 25.88 | 90.27 |
| DB-D3 | 64.39 | - | 5.48  | 13.61 | 19.08 | 83.47 |
| DB-D4 | 68.51 | - | 9.19  | 6.03  | 15.22 | 83.73 |
| DB-D5 | 64.39 | - | 6.91  | 9.65  | 16.56 | 80.94 |

**S.P. Ray and C.S. Reddy Method**

|       |       |       |       |      |       |       |
|-------|-------|-------|-------|------|-------|-------|
| DB-D1 | 21.60 | 19.18 | 35.27 | 0.54 | 35.81 | 76.59 |
| DB-D2 | 21.33 | 19.18 | 47.54 | 0.27 | 47.81 | 88.32 |
| DB-D3 | 21.55 | 19.87 | 12.23 | 0.83 | 13.06 | 54.48 |
| DB-D4 | 24.03 | 23.34 | 22.57 | 0.33 | 22.90 | 70.27 |
| DB-D5 | 21.19 | 18.72 | 16.90 | 0.78 | 17.69 | 57.60 |

**Ramkrishnan and Ananthanarayan Method**

|       |        |   |   |   |   |        |
|-------|--------|---|---|---|---|--------|
| DB-D1 | 124.10 | - | - | - | - | 124.10 |
| DB-D2 | 122.57 | - | - | - | - | 122.57 |
| DB-D3 | 122.57 | - | - | - | - | 122.57 |
| DB-D4 | 129.83 | - | - | - | - | 129.83 |
| DB-D5 | 122.57 | - | - | - | - | 122.57 |

**Table 6.7c Ultimate Shear Computation by Various Method**

**Series DB-D:  $L/D = 5.00$**

**ACI Method**

|       |        |   |       |       |       |        |
|-------|--------|---|-------|-------|-------|--------|
| DB-E1 | 101.53 | - | 16.74 | 8.65  | 25.39 | 126.92 |
| DB-E2 | 97.15  | - | 22.06 | 6.42  | 28.48 | 125.64 |
| DB-E3 | 99.09  | - | 6.67  | 12.16 | 18.83 | 117.92 |
| DB-E4 | 98.36  | - | 11.32 | 5.06  | 16.38 | 114.74 |
| DB-E5 | 95.46  | - | 8.30  | 8.06  | 16.36 | 111.81 |

**S.P. Ray and C.S. Reddy Method**

|       |       |       |       |      |       |       |
|-------|-------|-------|-------|------|-------|-------|
| DB-E1 | 17.07 | 16.91 | 49.60 | 0.35 | 49.95 | 83.93 |
| DB-E2 | 15.33 | 14.72 | 69.52 | 0.15 | 69.67 | 99.72 |
| DB-E3 | 16.98 | 17.63 | 19.45 | 0.55 | 20.00 | 54.61 |
| DB-E4 | 16.09 | 15.88 | 33.76 | 0.17 | 33.92 | 65.89 |
| DB-E5 | 14.20 | 12.85 | 25.09 | 0.40 | 25.49 | 52.54 |

**Ramkrishnan and Ananthanarayan Method**

|       |        |   |   |   |   |        |
|-------|--------|---|---|---|---|--------|
| DB-E1 | 151.38 | - | - | - | - | 151.38 |
| DB-E2 | 145.35 | - | - | - | - | 145.35 |
| DB-E3 | 147.75 | - | - | - | - | 147.75 |
| DB-E4 | 146.50 | - | - | - | - | 146.50 |
| DB-E5 | 142.98 | - | - | - | - | 142.98 |



The ratio of nominal ultimate shear stress to critical shear stress is also presented in Table 6.1. This ratio attains an average value of 2.50 for DBA series, 3.03 for DBB series, 2.55 for DBC series, 2.84 for DBD series and 2.95 for DBE of beams. Conversely as shown in Table 5.4 the average critical load was found to be about 40.79 percent for DBA series, 33.87 percent for DBB series, 39.57 percent for DB C series, 36.88 percent for DBD series and 40.79 percent for DBE series of the ultimate load.

Relation between ultimate shear stresses and the square root of concrete cylinder ultimate strength is presented in Table 6.1 It is presented that the ratio  $v_u/\sqrt{f'_c}$  has a mean of 10.466 for DBA series, 11.466 for DBB series, 10.614 for DBC series, 9.606 for DBD series and 7.41 for DBE of beams. The average value of this ratio comprising of all the twenty five test beams is found to be 9.97. The test results of this investigation recommends a higher value of  $10\sqrt{f'_c}$  instead of  $8\sqrt{f'_c}$ .

In table 6.6 and Fig. 6.1 the measured diagonal cracking stress is compared with that of ACI Method, de Cossio and Kabir and it is observed that the measured diagonal cracking stress is very close to the computed cracking stress obtained by other three methods upto L/D ratio 2. But for L/D ratio 3 to 5 the measured diagonal cracking stress is found to be close with that of ACI Method only.

### 6.2.3 Estimation of Ultimate Load

Three of the several available formulas were used to determine the ultimate load of deep beams of the test series. The ACI 318-89 code recommendations were used as the basis of design of the test beams to ensure failure by shear. After casting of beams and testing of control cylinder specimens, the actual values of the materials and dimension of the cast beams were used to compute the ultimate load of the beams following ACI 318-89 code provisions, Ray and Reddy's<sup>(22)</sup> method and Ramkrishna and Ananthanarayana's<sup>(16)</sup> method. Computation of ultimate load by these methods with its component share of concrete, tension steel and web steel respectively are shown in Table 6.7 for the five series of beams tested. It is to be noted that the direct contribution of flexural reinforcement to ultimate shear strength is ignored by ACI Code recommendation while Ramkrishnan and Ananthanarayana disregard the contribution of both longitudinal and web steel to ultimate shear resistance.

From the Table 6.7a, Table 6.7b and Table 6.7c (columns 2,4,5 and 6) it is evident that concrete provides the major bulk of shear resistance in deep beams. Thus, the change in ultimate shear due to variation of web steel arrangement had much been offset by the unintentional change in concrete strength. For example, in a beam (DB-D1) with a total computed ultimate load of 88.64 kips the horizontal web steel ratio was reduced by 41.67 percent to get the beam DB-D4. This reduction in web steel decreased the contribution of horizontal reinforcement from  $9.68^k$  to  $6.03^k$ . The total decrease is only  $3.65^k$ . But the unintentional increase in concrete strength has increased the concrete contribution by about 3.32 kips which is only 3.7 percent of the total. Therefore, it is apparent that the variation of web steel arrangement could not bring about a significant change in the ultimate load capacity of the test beams.

A comparison of the ultimate loads estimated by these three methods and the measured ultimate load is presented in Table 6.8 It is seen from the table that on an average, ACI 318-89 code provisions underestimate the ultimate load varies from 10.36 percent to 32.16 percent for the five test series and the equation suggested by Ramkrishnan and Ananthanarayana underestimates the ultimate load varies from 0.3 percent to 10 percent for the first three series overestimates the ultimate load varies from 20.87percent to 21.46 percent for the last two series (DBD and DBE ). On the contrary, the Ray and Reddy formula underestimates the ultimate load varies from 28.57 percent to 58.30 percent for the first test series of beams. The co-efficient of variation for all the three methods of estimate is found to be relatively small considering the wide variability of concrete test results. It seems quite indicative that all these methods can be modified to predict the ultimate load of deep beams with brick aggregate concrete.

The ACI method being most conservative has disregarded the effect of flexural steel in the form of dowel action to the resistance of ultimate shear while the Ray and Reddy method has no upper limit for the dowel stress even if it is found to exceed the yield stress of main steel. A careful examination of test results reveals that if the dowel force estimated by Ray and Reddy method be limited to a maximum value of  $(A_s f_y)/4$  the predicted values become more realistic. Similar provision due to dowel action of tensile reinforcement is suggested to be included in ACI Code. Considering the simplicity of ACI 318-89 equations, it is recommended that the dowel shear be computed by

$$V_d = \frac{D-X}{D} A_s f_y \leq \frac{1}{4} A_s f_y \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (6.3)$$

where, D = overall depth  
X = clear shear span  
 $A_s$  = area of tension steel  
 $f_y$  = yield stress of tension steel.

The ACI building code recommends that ultimate shear stress of concrete alone be computed by the equation 3.9 i.e

$$V_c = (3.5 - 2.5 \frac{M_u}{V_u d}) (1.9 \sqrt{f'_c} + 2500 p \frac{V_u d}{M_u}) \leq 6 \sqrt{f'_c} \quad \dots \quad \dots \quad \dots \quad \dots \quad (6.4)$$

where, the second term represents the shear stress at initial diagonal cracking and the first term represents the increase in shear due to arch action over that causing initial diagonal cracking. For the test beams (L/D= 1 , 1.75 , 3.00, 4.00 and 5.00), the value of the first term of Eq<sup>n</sup> 6.4 is found to be more than 2. The least value of  $V_{cr}/bd\sqrt{f'_c}$  as seen from column 4 of Table 6.3 is found to be more than 2. The least value of  $v_{cr}$  as seen from column 4 of Table 6.3 is  $2.32\sqrt{f'_c}$ . As the upper limit for  $v_{cr}$  suggested by ACI Code is  $3.5\sqrt{f'_c}$ , so the maximum limit of concrete shear stress  $v_c$  remains same ( $6\sqrt{f'_c}$ ) for brick aggregate deep beams and the ultimate shear intensity  $v_u$  be considered  $10\sqrt{f'_c}$  instead of  $8\sqrt{f'_c}$  with adequate web steel in the beam.

**Table 6.8 Comparison of Measured and Computed Ultimate Loads by Various Method**

| Beam Mark | Measured Ultimate Load, $P_u$ | Computed Ultimate Load by Various Method |              |                                        |              |                                                          |              |
|-----------|-------------------------------|------------------------------------------|--------------|----------------------------------------|--------------|----------------------------------------------------------|--------------|
|           |                               | Ultimate Load by ACI, $P_{u1}$           | $P_{u1}/P_u$ | Ultimate Load by Ray & Reddy, $P_{u2}$ | $P_{u2}/P_u$ | Ultimate Load by Ramkrishnan & Ananthanarayana, $P_{u3}$ | $P_{u3}/P_u$ |

Series DB-A:  $L/D = 1.00$

|                 |        |        |               |        |               |        |                |
|-----------------|--------|--------|---------------|--------|---------------|--------|----------------|
| DB-A1           | 180.50 | 131.06 | 0.7261        | 129.75 | 0.7188        | 193.81 | 1.0737         |
| DB-A2           | 201.00 | 133.36 | 0.6635        | 127.33 | 0.6335        | 191.72 | 0.9538         |
| DB-A3           | 183.00 | 122.53 | 0.6696        | 124.25 | 0.6789        | 178.90 | 0.9776         |
| DB-A4           | 190.00 | 131.73 | 0.6933        | 129.71 | 0.6827        | 194.71 | 1.0248         |
| DB-A5           | 185.00 | 118.34 | 0.6397        | 118.52 | 0.6406        | 177.23 | 0.9580         |
| <b>Average:</b> |        |        | <b>0.6784</b> |        | <b>0.6709</b> |        | <b>0.99758</b> |
| <b>C :</b>      |        |        | <b>4.32</b>   |        | <b>4.63</b>   |        | <b>4.12</b>    |

Series DB-A:  $L/D = 1.75$

|                 |        |       |               |       |             |       |               |
|-----------------|--------|-------|---------------|-------|-------------|-------|---------------|
| DB-B1           | 122.00 | 82.00 | 0.6721        | 85.84 | 0.7036      | 89.35 | 0.7324        |
| DB-B2           | 120.00 | 81.31 | 0.6776        | 87.81 | 0.7317      | 89.35 | 0.7446        |
| DB-B3           | 123.00 | 84.05 | 0.6833        | 80.72 | 0.6563      | 90.09 | 0.7324        |
| DB-B4           | 102.50 | 73.50 | 0.7171        | 78.25 | 0.7634      | 89.28 | 0.8711        |
| DB-B5           | 120.00 | 80.17 | 0.6681        | 83.21 | 0.6935      | 91.52 | 0.7626        |
| <b>Average:</b> |        |       | <b>0.6836</b> |       | <b>0.71</b> |       | <b>0.7686</b> |
| <b>C :</b>      |        |       | <b>2.56</b>   |       | <b>5.09</b> |       | <b>6.82</b>   |

Series DB-A:  $L/D = 3.00$

|                 |        |       |               |        |             |       |                |
|-----------------|--------|-------|---------------|--------|-------------|-------|----------------|
| DB-C1           | 105.00 | 80.91 | 0.7706        | 100.92 | 0.9611      | 91.18 | 0.8684         |
| DB-C2           | 133.00 | 81.68 | 0.6141        | 107.12 | 0.8054      | 90.56 | 0.6809         |
| DB-C3           | 95.00  | 77.47 | 0.8155        | 85.30  | 0.8979      | 88.46 | 0.9312         |
| DB-C4           | 87.50  | 70.49 | 0.8056        | 90.28  | 1.0318      | 87.81 | 1.0036         |
| DB-C5           | 88.00  | 74.53 | 0.8469        | 88.77  | 1.0087      | 89.19 | 1.0135         |
| <b>Average:</b> |        |       | <b>0.7705</b> |        | <b>0.94</b> |       | <b>0.89952</b> |
| <b>C :</b>      |        |       | <b>10.63</b>  |        | <b>8.69</b> |       | <b>13.49</b>   |

Series DB-A:  $L/D = 4.00$

|                 |        |       |               |       |             |        |                |
|-----------------|--------|-------|---------------|-------|-------------|--------|----------------|
| DB-D1           | 112.00 | 88.62 | 0.7913        | 76.59 | 0.6838      | 124.10 | 1.1081         |
| DB-D2           | 118.00 | 90.25 | 0.7648        | 88.32 | 0.7485      | 122.57 | 1.0388         |
| DB-D3           | 80.00  | 83.45 | 1.0431        | 54.48 | 0.6811      | 122.57 | 1.5322         |
| DB-D4           | 110.00 | 83.71 | 0.7610        | 70.27 | 0.6388      | 129.83 | 1.1802         |
| DB-D5           | 103.50 | 80.92 | 0.7818        | 57.60 | 0.5565      | 122.57 | 1.1843         |
| <b>Average:</b> |        |       | <b>0.8284</b> |       | <b>0.66</b> |        | <b>1.20872</b> |
| <b>C :</b>      |        |       | <b>13.03</b>  |       | <b>9.53</b> |        | <b>14.09</b>   |

Series DB-A:  $L/D = 5.00$

|                 |        |        |               |       |              |        |                |
|-----------------|--------|--------|---------------|-------|--------------|--------|----------------|
| DB-E1           | 131.00 | 126.90 | 0.9687        | 83.93 | 0.6407       | 151.38 | 1.1556         |
| DB-E2           | 126.00 | 125.63 | 0.9971        | 99.72 | 0.7914       | 145.35 | 1.1536         |
| DB-E3           | 112.00 | 117.91 | 1.0528        | 54.61 | 0.4876       | 147.75 | 1.3192         |
| DB-E4           | 130.00 | 114.74 | 0.8826        | 65.89 | 0.5069       | 146.50 | 1.1269         |
| DB-E5           | 108.50 | 111.86 | 1.0310        | 52.54 | 0.4843       | 142.98 | 1.3178         |
| <b>Average:</b> |        |        | <b>0.8964</b> |       | <b>0.58</b>  |        | <b>1.21462</b> |
| <b>C :</b>      |        |        | <b>12.02</b>  |       | <b>20.53</b> |        | <b>7.03</b>    |

Ramkrishnan and Ananthanarayana's method is probably one of the simplest method of computing ultimate loads of deep beams and is expressed as,

$$P_u = \beta k f'_{sp} bD$$

where  $\beta$  = a co-efficient for shear span and loading condition effect.

K = splitting co-efficient which is 1.57 for cylinder splitting and 1.12 suggested by them for deep beams.

For deep beam under concentrated load at mid span, it is reduced to

$$P_u = 2.24 f'_{sp} bD$$

### 6.3 MOMENT CHARACTERISTIC OF THE TEST BEAMS

The relevant test data illustrating the moment characteristics of the test beams are presented in Table 6.9. These include the maximum moment at initial diagonal cracking load designated as the maximum critical moment  $M_{cm}$ , the maximum moment at ultimate load  $M_u$  and the flexural moment capacity  $M_{ur}$  of the test beams. The flexural moment capacities of the test beams  $M_{ur}$  were calculated according to the 1989 ACI code recommendation for ultimate strength design of gravel aggregate concrete. The ratios of critical moment to flexural capacity  $M_{cr}/M_{ur}$  and ultimate moment to flexural capacity  $M_u/M_{ur}$  are also included in this table.

The ratio  $M_{cm}/M_{ur}$  is found to attain a mean value of about 0.45, 0.41, 0.25, 0.21 and 0.21 for the series DBA to DBE and the ratio  $M_u/M_{ur}$  is found to attain a mean value of about 1.16 for the first two test series and a mean value of about 0.6 for the last three test series of beams. The relative scatter of this ratio for the beams of DBC and DBD series is significant as evidenced by a higher co-efficient of variation of 16.23 and 12.68 as against only 5.59, 5.25, and 7.30 for the beams of DBA, DBB and DBE series. However it is perhaps suggestive to assume the maximum moment at initial diagonal cracking load to be about 45 percent of the flexural capacity for the beams of similar L/D ratios and subjected to mid span concentrated loading.

It is interesting to note from Table. 6.9 that the full flexural capacity,  $M_{ur}$  has been attained by DBA and DBB series but the beams of DBC, and DBE series are attaining only 60 percent flexural capacity. The L/D ratios of the beams are 1.00, 1.75, 3.00, 4.00 and 5.00 respectively. So the flexural capacity,  $M_{ur}$  decreased with the increase of L/D ratio except L/D = 5.00. Similar results have also been reported by Kani <sup>(31)</sup> for ordinary reinforced concrete beams with values of a/D ratio bellow 1.5. In deep beams, the a/d ratios are usually low and hence it can possibly be recommended that a conservative estimate of the ultimate load capacity of a deep beam may be made on the assumption that it will reach its maximum flexural capacity at failure.



## 6.4 LOAD DEFLECTION CHARACTERISTICS

The maximum deflection at mid span for concentrated load could be computed for simply supported beam by

$$v_{\max} = PL^3/48E_C I$$

Where,

- $v_{\max}$  = Maximum deflection at Mid span
- P = Mid span load
- L = Overall length of beam
- $E_C$  = Modulus of Elasticity of Concrete
- I = Moment of Inertia of beam section.

The computed deflections using the above formula and the observed deflections are shown in Table 6.12. It is seen that the computed deflection are significantly lower than the actual deflections observed during the test. The computed and observed load-deflection curves of the 25 test beams are presented graphically in Figs. 5.1 through 5.8. The deflection recorded represents the mid span deflection with appropriate compensation made for support settlement. The usual load deflection relationship is found to be absent even in the lower range of loading prior to cracking. The load-deflection curves for both the computed and observed deflections show a specific relationship with the L/D ratio i.e. the curves exhibit the flatter nature with increase of L/D ratio. It is also found that the observed deflections for higher L/D ratio is significantly larger than that of the deflection of lower L/D ratios.

The shearing stresses, being considerably high in deep beams, appear to have significant effect on deflection of such beams. This can further be appreciated when the deviations of the observed deflections from the computed deflections are found to be more pronounced in case of relatively deeper beams (L/D = 1.0,) compared to the other set having L/D = 1.75, 3.00, 4.00 and 5.00.

In Figs. 5.9 to 5.13 the load - deflection curves for five set of beams under each series are compared and found that the beams imposed under a particular load shows different values of deflection due to change of shear reinforcement in the beams. For example, in Fig. 5.13 for 100<sup>k</sup> of loading the deflection are 7.00mm, 6.5mm, 6.00mm, 9.5mm and 8.5mm for DB-E1, DB-E2, DB-E3, DB-E4 and DB-E5 respectively. It is seen that the deflections are inversely proportional to the increment in shear reinforcement as shown in Table 4.5.

## 6.5 MODE OF FAILURE AND CRACK PATTERN

Figs. 5.14 through 5.38 show the cracks at failure of the beams together with the loads at which each crack was first observed and the extent of the crack at that load. The cracks which were believed to have caused immediate failure are marked boldly.

**Table 6.9 Moment Characteristics of Test Beams**

| Beam Mark                                    | Maximum Moment at                               |                                   | Computed Flexural Capacity, $M_{uf}$ kip-inch | Ratio $M_{cm}/M_{uf}$ | Ratio $M_u/M_{uf}$ |
|----------------------------------------------|-------------------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------|--------------------|
|                                              | Daigonal Cracking Capacity, $M_{cm}$ , kip-inch | Ultimate Capacity, $M_u$ kip-inch |                                               |                       |                    |
| <b>Series DB - A : <math>L/D=1.00</math></b> |                                                 |                                   |                                               |                       |                    |
| DB-A1                                        | 397.8                                           | 997.3                             | 962.2                                         | 0.4134                | 1.0364             |
| DB-A2                                        | 409.5                                           | 1175.9                            | 967.1                                         | 0.4235                | 1.2159             |
| DB-A3                                        | 529.6                                           | 1020.2                            | 962.2                                         | 0.5504                | 1.0603             |
| DB-A4                                        | 420.0                                           | 1064.0                            | 967.1                                         | 0.4343                | 1.1003             |
| DB-A5                                        | 397.3                                           | 1049.9                            | 952.5                                         | 0.4170                | 1.1022             |
|                                              |                                                 |                                   | <b>Average:</b>                               | <b>0.4477</b>         | <b>1.103</b>       |
|                                              |                                                 |                                   | <b>C :</b>                                    | <b>11.58</b>          | <b>5.59</b>        |
| <b>Series DB - B : <math>L/D=1.75</math></b> |                                                 |                                   |                                               |                       |                    |
| DB-B1                                        | 267.5                                           | 652.7                             | 517.4                                         | 0.5171                | 1.2616             |
| DB-B2                                        | 215.0                                           | 645.0                             | 517.4                                         | 0.4156                | 1.2467             |
| DB-B3                                        | 178.2                                           | 664.2                             | 522.2                                         | 0.3413                | 1.2719             |
| DB-B4                                        | 217.0                                           | 556.1                             | 507.7                                         | 0.4274                | 1.0953             |
| DB-B5                                        | 185.5                                           | 636.0                             | 522.2                                         | 0.3552                | 1.2179             |
|                                              |                                                 |                                   | <b>Average:</b>                               | <b>0.4113</b>         | <b>1.2187</b>      |
|                                              |                                                 |                                   | <b>C :</b>                                    | <b>15.03</b>          | <b>5.25</b>        |
| <b>Series DB - C : <math>L/D=3.00</math></b> |                                                 |                                   |                                               |                       |                    |
| DB-C1                                        | 333.0                                           | 945.0                             | 1494.5                                        | 0.2228                | 0.6323             |
| DB-C2                                        | 451.3                                           | 1200.3                            | 1508.4                                        | 0.2992                | 0.7957             |
| DB-C3                                        | 389.2                                           | 859.8                             | 1494.4                                        | 0.2604                | 0.5753             |
| DB-C4                                        | 391.2                                           | 796.3                             | 1508.4                                        | 0.2593                | 0.5279             |
| DB-C5                                        | 344.9                                           | 798.6                             | 1508.4                                        | 0.2286                | 0.5294             |
|                                              |                                                 |                                   | <b>Average:</b>                               | <b>0.25406</b>        | <b>0.61212</b>     |
|                                              |                                                 |                                   | <b>C :</b>                                    | <b>10.75</b>          | <b>16.23</b>       |
| <b>Series DB - D : <math>L/D=4.00</math></b> |                                                 |                                   |                                               |                       |                    |
| DB-D1                                        | 465.5                                           | 1372.0                            | 2199.6                                        | 0.2116                | 0.6238             |
| DB-D2                                        | 367.5                                           | 1445.5                            | 2199.5                                        | 0.1671                | 0.6572             |
| DB-D3                                        | 487.0                                           | 974.0                             | 2199.5                                        | 0.2214                | 0.4428             |
| DB-D4                                        | 487.0                                           | 1339.3                            | 2283.4                                        | 0.2133                | 0.5865             |
| DB-D5                                        | 492.0                                           | 1273.1                            | 2199.5                                        | 0.2237                | 0.5788             |
|                                              |                                                 |                                   | <b>Average:</b>                               | <b>0.2074</b>         | <b>0.57782</b>     |
|                                              |                                                 |                                   | <b>C :</b>                                    | <b>9.97</b>           | <b>12.68</b>       |
| <b>Series DB - E : <math>L/D=5.00</math></b> |                                                 |                                   |                                               |                       |                    |
| DB-E1                                        | 608.0                                           | 1991.2                            | 3044.6                                        | 0.1997                | 0.6540             |
| DB-E2                                        | 753.8                                           | 1899.5                            | 2960.8                                        | 0.2546                | 0.6415             |
| DB-E3                                        | 605.0                                           | 1694.0                            | 3044.6                                        | 0.1987                | 0.5564             |
| DB-E4                                        | 586.2                                           | 2005.3                            | 3072.5                                        | 0.1908                | 0.6526             |
| DB-E5                                        | 2932.8                                          | 1643.8                            | 606.0                                         | 0.2066                | 0.5605             |
|                                              |                                                 |                                   | <b>Average:</b>                               | <b>0.21008</b>        | <b>0.613</b>       |
|                                              |                                                 |                                   | <b>C :</b>                                    | <b>10.86</b>          | <b>7.30</b>        |

\* C represents co-efficient of variation in per cent.



**Table 6.10 Comparison of Shear Capacity of Rectangular and Deep Beam**

| Beam Mark                        | Ultimate Stress of Concrete, $f_c'$ (psi) | Yield Stress of Web Steel, $f_y$ (psi) | Area of Web Steel, $A_s$ (sq.in) | Width of Beam, $b$ (in) | Effective Depth of Beam, $d$ (in) | Spacing of Web Steel, $s$ (in) | Shear Capacity of Concrete (kip) | Shear Capacity of Steel (kip) | Total Shear Capacity of Rectangular Beam (kip) | Observed initial Cracking Load of Deep Beam (kip) |
|----------------------------------|-------------------------------------------|----------------------------------------|----------------------------------|-------------------------|-----------------------------------|--------------------------------|----------------------------------|-------------------------------|------------------------------------------------|---------------------------------------------------|
| <b>Series DB -A : L/D = 1.00</b> |                                           |                                        |                                  |                         |                                   |                                |                                  |                               |                                                |                                                   |
| DB-A1                            | 4886                                      | 51300                                  | 0.057                            | 6.500                   | 19.900                            | 3.000                          | 18.080                           | 38.790                        | 56.880                                         | 72.000                                            |
| DB-A2                            | 4886                                      | 51300                                  | 0.057                            | 6.400                   | 20.000                            | 4.500                          | 17.890                           | 25.990                        | 43.890                                         | 70.000                                            |
| DB-A3                            | 4886                                      | 51300                                  | 0.057                            | 6.000                   | 19.900                            | 2.250                          | 16.690                           | 51.720                        | 68.420                                         | 95.000                                            |
| DB-A4                            | 4886                                      | 51300                                  | 0.057                            | 6.500                   | 20.000                            | 3.000                          | 18.170                           | 38.990                        | 57.160                                         | 75.000                                            |
| DB-A5                            | 4886                                      | 51300                                  | 0.057                            | 6.000                   | 19.700                            | 6.000                          | 16.520                           | 19.200                        | 35.730                                         | 70.000                                            |
| <b>Average:</b>                  |                                           |                                        |                                  |                         |                                   |                                |                                  |                               | <b>52.420</b>                                  | <b>76.400</b>                                     |
| <b>Series DB -B : L/D = 1.75</b> |                                           |                                        |                                  |                         |                                   |                                |                                  |                               |                                                |                                                   |
| DB-B1                            | 5704                                      | 51300                                  | 0.057                            | 6.300                   | 10.700                            | 2.000                          | 10.180                           | 31.290                        | 41.470                                         | 50.000                                            |
| DB-B2                            | 5704                                      | 51300                                  | 0.057                            | 6.300                   | 10.700                            | 1.500                          | 10.180                           | 41.720                        | 51.900                                         | 40.000                                            |
| DB-B3                            | 5704                                      | 51300                                  | 0.057                            | 6.300                   | 10.800                            | 5.000                          | 10.280                           | 12.630                        | 22.910                                         | 33.000                                            |
| DB-B4                            | 5704                                      | 51300                                  | 0.057                            | 6.400                   | 10.500                            | 3.000                          | 10.150                           | 20.470                        | 30.620                                         | 40.000                                            |
| DB-B5                            | 5704                                      | 51300                                  | 0.057                            | 6.400                   | 10.800                            | 4.000                          | 10.440                           | 15.790                        | 26.230                                         | 35.000                                            |
| <b>Average:</b>                  |                                           |                                        |                                  |                         |                                   |                                |                                  |                               | <b>34.630</b>                                  | <b>39.600</b>                                     |
| <b>Series DB -C : L/D = 3.00</b> |                                           |                                        |                                  |                         |                                   |                                |                                  |                               |                                                |                                                   |
| DB-C1                            | 4621                                      | 51300                                  | 0.057                            | 6.700                   | 10.700                            | 2.000                          | 9.750                            | 31.290                        | 41.030                                         | 37.000                                            |
| DB-C2                            | 4621                                      | 51300                                  | 0.057                            | 6.600                   | 10.800                            | 1.500                          | 9.690                            | 42.110                        | 51.800                                         | 50.000                                            |
| DB-C3                            | 4621                                      | 51300                                  | 0.057                            | 6.500                   | 10.700                            | 5.000                          | 9.460                            | 12.520                        | 21.970                                         | 43.000                                            |
| DB-C4                            | 4621                                      | 51300                                  | 0.057                            | 6.400                   | 10.800                            | 3.000                          | 9.400                            | 21.050                        | 30.450                                         | 32.000                                            |
| DB-C5                            | 4621                                      | 51300                                  | 0.057                            | 6.500                   | 10.800                            | 4.000                          | 9.540                            | 15.790                        | 25.330                                         | 38.000                                            |
| <b>Average:</b>                  |                                           |                                        |                                  |                         |                                   |                                |                                  |                               | <b>34.120</b>                                  | <b>40.000</b>                                     |
| <b>Series DB -D : L/D = 4.00</b> |                                           |                                        |                                  |                         |                                   |                                |                                  |                               |                                                |                                                   |
| DB-D1                            | 4080                                      | 51300                                  | 0.057                            | 8.100                   | 10.500                            | 2.000                          | 10.870                           | 30.700                        | 41.570                                         | 38.000                                            |
| DB-D2                            | 4080                                      | 51300                                  | 0.057                            | 8.000                   | 10.500                            | 1.500                          | 10.730                           | 40.940                        | 51.670                                         | 30.000                                            |
| DB-D3                            | 4080                                      | 51300                                  | 0.057                            | 8.000                   | 10.500                            | 5.000                          | 10.730                           | 12.280                        | 23.010                                         | 40.000                                            |
| DB-D4                            | 4080                                      | 51300                                  | 0.057                            | 8.200                   | 10.900                            | 3.000                          | 11.420                           | 21.250                        | 32.670                                         | 40.000                                            |
| DB-D5                            | 4080                                      | 51300                                  | 0.057                            | 8.000                   | 10.500                            | 4.000                          | 10.730                           | 15.350                        | 26.080                                         | 40.000                                            |
| <b>Average:</b>                  |                                           |                                        |                                  |                         |                                   |                                |                                  |                               | <b>35.000</b>                                  | <b>37.600</b>                                     |
| <b>Series DB -E : L/D = 5.00</b> |                                           |                                        |                                  |                         |                                   |                                |                                  |                               |                                                |                                                   |
| DB-E1                            | 3856                                      | 51300                                  | 0.057                            | 12.500                  | 10.900                            | 2.000                          | 16.920                           | 31.870                        | 48.790                                         | 40.000                                            |
| DB-E2                            | 3856                                      | 51300                                  | 0.057                            | 12.300                  | 10.600                            | 1.500                          | 16.190                           | 41.330                        | 57.520                                         | 50.000                                            |
| DB-E3                            | 3856                                      | 51300                                  | 0.057                            | 12.200                  | 10.900                            | 5.000                          | 16.520                           | 12.750                        | 29.260                                         | 40.000                                            |
| DB-E4                            | 3856                                      | 51300                                  | 0.057                            | 12.000                  | 11.000                            | 3.000                          | 16.390                           | 21.440                        | 37.840                                         | 38.000                                            |
| DB-E5                            | 3856                                      | 51300                                  | 0.057                            | 12.200                  | 10.500                            | 4.000                          | 15.910                           | 15.350                        | 31.260                                         | 40.000                                            |
| <b>Average:</b>                  |                                           |                                        |                                  |                         |                                   |                                |                                  |                               | <b>40.930</b>                                  | <b>41.600</b>                                     |

Table 6.11 Observed Deflection at Mid Span of the Test Beams.

| Load Level | 0 <sup>k</sup> | 20 <sup>k</sup> | 40 <sup>k</sup> | 60 <sup>k</sup> | 80 <sup>k</sup> | 100 <sup>k</sup> | 120 <sup>k</sup> | 140 <sup>k</sup> | 160 <sup>k</sup> | 180 <sup>k</sup> | 190 <sup>k</sup> | 200 <sup>k</sup> |
|------------|----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Beam Mark  |                |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |



**Series DB -A : L/D = 1.00**

(Deflection in mm.)

|       |   |       |       |       |       |       |       |       |       |       |       |       |
|-------|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| DB-A1 | 0 | 0.240 | 0.487 | 0.680 | 0.866 | 1.099 | 1.299 | 1.467 | 1.614 | 1.794 | -     | -     |
| DB-A2 | 0 | 0.566 | 0.866 | 1.093 | 1.353 | 1.666 | 1.907 | 2.100 | 2.287 | 2.494 | -     | 2.760 |
| DB-A3 | 0 | 0.340 | 0.087 | 1.353 | 0.067 | 0.306 | 0.467 | 0.640 | 0.840 | 1.261 | -     | -     |
| DB-A4 | 0 | 0.047 | 0.126 | 1.666 | 0.127 | 0.333 | 0.487 | 0.641 | 0.854 | 1.181 | 1.414 | -     |
| DB-A5 | 0 | 0.359 | 0.640 | 1.907 | 1.126 | 1.366 | 1.573 | 1.800 | 1.980 | 2.24  | -     | -     |

**Series DB -B : L/D = 1.75**

|       |   |       |       |       |       |       |       |       |  |  |  |  |
|-------|---|-------|-------|-------|-------|-------|-------|-------|--|--|--|--|
| DB-B1 | 0 | 0.017 | 0.320 | 0.613 | 2.100 | 1.221 | 1.648 | 2.187 |  |  |  |  |
| DB-B2 | 0 | 0.006 | 0.440 | 0.774 | 2.287 | 1.600 | 1.933 | 2.607 |  |  |  |  |
| DB-B3 | 0 | 0.013 | 0.693 | 1.240 | 2.494 | 2.053 | 2.454 | 3.114 |  |  |  |  |
| DB-B4 | 0 | 0.012 | 0.667 | 1.034 | 2.760 | 1.881 | 3.008 | -     |  |  |  |  |
| DB-B5 | 0 | 0.006 | 0.187 | 0.413 | 2.821 | 0.987 | 1.307 | 1.954 |  |  |  |  |

**Series DB -C : L/D = 3.00**

|       |   |       |       |       |       |       |       |       |  |  |  |  |
|-------|---|-------|-------|-------|-------|-------|-------|-------|--|--|--|--|
| DB-C1 | 0 | 0.026 | 0.927 | 1.681 | -     | 3.102 | 3.955 | -     |  |  |  |  |
| DB-C2 | 0 | 0.066 | 0.118 | 0.700 | 0.006 | 1.601 | 2.381 | 3.569 |  |  |  |  |
| DB-C3 | 0 | 0.019 | 0.594 | 1.121 | 0.340 | 2.734 | -     | -     |  |  |  |  |
| DB-C4 | 0 | 0.042 | 0.061 | 0.087 | 0.087 | 0.567 | -     | -     |  |  |  |  |
| DB-C5 | 0 | 0.006 | 0.200 | 0.780 | 0.167 | 2.808 | -     | -     |  |  |  |  |

**Series DB -D : L/D = 4.00**

|       |   |       |       |       |       |       |       |  |  |  |  |  |
|-------|---|-------|-------|-------|-------|-------|-------|--|--|--|--|--|
| DB-D1 | 0 | 0.036 | 0.827 | 1.480 | 0.067 | 2.314 | 4.649 |  |  |  |  |  |
| DB-D2 | 0 | 0.007 | 1.388 | 1.874 | 0.306 | 3.509 | 4.882 |  |  |  |  |  |
| DB-D3 | 0 | 0.003 | 1.461 | 2.214 | 3.682 | 6.083 | -     |  |  |  |  |  |
| DB-D4 | 0 | 0.011 | 0.780 | 0.854 | 1.507 | 2.321 | 3.756 |  |  |  |  |  |
| DB-D5 | 0 | 0.013 | 0.100 | 1.319 | 0.593 | 1.860 | 2.128 |  |  |  |  |  |

**Series DB -E : L/D = 5.00**

|       |   |       |       |       |       |       |       |       |  |  |  |  |
|-------|---|-------|-------|-------|-------|-------|-------|-------|--|--|--|--|
| DB-E1 | 0 | 0.060 | 1.821 | 2.721 | 3.649 | 5.062 | 6.704 | 9.092 |  |  |  |  |
| DB-E2 | 0 | 0.011 | 1.374 | 1.821 | 2.834 | 4.309 | 6.290 | 9.298 |  |  |  |  |
| DB-E3 | 0 | 0.020 | 1.574 | 6.549 | 2.968 | 4.169 | 5.636 | -     |  |  |  |  |
| DB-E4 | 0 | 0.020 | 1.568 | 2.668 | 3.702 | 5.396 | 7.197 | 9.705 |  |  |  |  |
| DB-E5 | 0 | 0.006 | 1.120 | 1.921 | 3.149 | 5.089 | 7.737 | -     |  |  |  |  |

Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-A1     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.1060             | -0.3460       | -0.2400          | -0.007                   |
|           | 40         | -0.0530             | -0.5400       | -0.4870          | -0.015                   |
|           | 60         | -0.0130             | -0.6930       | -0.6800          | -0.022                   |
|           | 80         | 0.0330              | -0.8330       | -0.8660          | -0.030                   |
|           | 100        | 0.0660              | -1.0330       | -1.0990          | -0.037                   |
|           | 120        | 0.0860              | -1.2130       | -1.2990          | -0.045                   |
|           | 140        | 0.0930              | -1.3740       | -1.4670          | -0.052                   |
|           | 160        | 0.1000              | -1.5140       | -1.6140          | -0.059                   |
|           | 180        | 0.1200              | -1.6740       | -1.7940          | -0.067                   |
|           | 180.5      | 0.1400              | -1.6940       | -1.8340          | -0.067                   |
|           |            |                     |               |                  |                          |
| DB-A2     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | 0.1530              | -0.4130       | -0.5660          | -0.009                   |
|           | 40         | 0.2460              | -0.6200       | -0.8660          | -0.018                   |
|           | 60         | 0.2800              | -0.8130       | -1.0930          | -0.026                   |
|           | 80         | 0.3130              | -1.0400       | -1.3530          | -0.035                   |
|           | 100        | 0.3060              | -1.3600       | -1.6660          | -0.044                   |
|           | 120        | 0.3130              | -1.5940       | -1.9070          | -0.053                   |
|           | 140        | 0.2930              | -1.8070       | -2.1000          | -0.062                   |
|           | 160        | 0.2730              | -2.0140       | -2.2870          | -0.071                   |
|           | 180        | 0.2530              | -2.2410       | -2.4940          | -0.079                   |
|           | 200        | 0.2260              | -2.5340       | -2.7600          | -0.088                   |
|           | 201        | 0.2000              | -2.6210       | -2.8210          | -0.089                   |
|           |            |                     |               |                  |                          |
| DB-A3     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.5200             | -0.8600       | -0.3400          | -0.008                   |
|           | 40         | -0.6530             | -0.7400       | -0.0870          | -0.017                   |
|           | 60         | -0.7200             | -0.8870       | -0.1670          | -0.025                   |
|           | 80         | -0.7330             | -0.8000       | -0.0670          | -0.033                   |
|           | 100        | -0.7470             | -1.0530       | -0.3060          | -0.041                   |
|           | 120        | -0.7530             | -1.2200       | -0.4670          | -0.050                   |
|           | 140        | -0.7600             | -1.4000       | -0.6400          | -0.058                   |
|           | 160        | -0.7600             | -1.6000       | -0.8400          | -0.066                   |
|           | 180        | -0.7400             | -2.0010       | -1.2610          | -0.074                   |
|           | 183        | -0.7200             | -2.4010       | -1.6810          | -0.076                   |

Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-A4     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.5130             | -0.5600       | -0.0470          | -0.008                   |
|           | 40         | -0.7200             | -0.8460       | -0.1260          | -0.015                   |
|           | 60         | -0.7800             | -0.8730       | -0.0930          | -0.023                   |
|           | 80         | -0.8200             | -0.9470       | -0.1270          | -0.030                   |
|           | 100        | -0.8400             | -1.1730       | -0.3330          | -0.038                   |
|           | 120        | -0.8600             | -1.3470       | -0.4870          | -0.046                   |
|           | 140        | -0.8730             | -1.5140       | -0.6410          | -0.053                   |
|           | 160        | -0.8730             | -1.7270       | -0.8540          | -0.061                   |
|           | 180        | -0.8730             | -2.0540       | -1.1810          | -0.069                   |
|           | 190        | -0.8870             | -2.3010       | -1.4140          | -0.072                   |
| DB-A5     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | 0.0530              | -0.3060       | -0.3590          | -0.009                   |
|           | 40         | 0.1000              | -0.5400       | -0.6400          | -0.018                   |
|           | 60         | 0.2000              | -0.7270       | -0.9270          | -0.027                   |
|           | 80         | 0.2260              | -0.9000       | -1.1260          | -0.036                   |
|           | 100        | 0.2460              | -1.1200       | -1.3660          | -0.045                   |
|           | 120        | 0.2730              | -1.3000       | -1.5730          | -0.054                   |
|           | 140        | 0.2730              | -1.5270       | -1.8000          | -0.063                   |
|           | 160        | 0.2800              | -1.7000       | -1.9800          | -0.072                   |
|           | 180        | 0.3000              | -1.9400       | -2.2400          | -0.081                   |
|           | 185        | 0.3200              | -2.1410       | -2.4610          | -0.083                   |
| DB-B1     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.1800             | -0.5000       | -0.3200          | -0.038                   |
|           | 40         | -0.1800             | -0.7930       | -0.6130          | -0.075                   |
|           | 60         | -0.1930             | -1.1070       | -0.9140          | -0.113                   |
|           | 80         | -0.2330             | -1.4540       | -1.2210          | -0.150                   |
|           | 100        | -0.1660             | -1.8140       | -1.6480          | -0.188                   |
|           | 120        | -0.1400             | -2.3270       | -2.1870          | -0.225                   |
| DB-B2     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.0330             | -0.4730       | -0.4400          | -0.038                   |
|           | 40         | -0.0060             | -0.7800       | -0.7740          | -0.076                   |
|           | 60         | 0.0200              | -1.1870       | -1.2070          | -0.114                   |
|           | 80         | 0.0460              | -1.5540       | -1.6000          | -0.152                   |
|           | 100        | 0.0530              | -1.8800       | -1.9330          | -0.190                   |
|           | 120        | 0.1060              | -2.5010       | -2.6070          | -0.228                   |



Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-B3     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | 0.1600              | -0.5330       | -0.6930          | -0.038                   |
|           | 40         | 0.2130              | -1.0270       | -1.2400          | -0.075                   |
|           | 60         | 0.2400              | -1.4270       | -1.6670          | -0.113                   |
|           | 80         | 0.2460              | -1.8070       | -2.0530          | -0.151                   |
|           | 100        | 0.2330              | -2.2210       | -2.4540          | -0.188                   |
|           | 120        | 0.2130              | -2.9010       | -3.1140          | -0.226                   |
|           | 123        | 0.2130              | -3.3150       | -3.5280          | -0.232                   |
| DB-B4     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.0460             | -0.7130       | -0.6670          | -0.040                   |
|           | 40         | -0.0930             | -1.1270       | -1.0340          | -0.081                   |
|           | 60         | -0.1400             | -1.5540       | -1.4140          | -0.121                   |
|           | 80         | -0.1460             | -2.0270       | -1.8810          | -0.162                   |
|           | 100        | -0.1260             | -3.1340       | -3.0080          | -0.202                   |
|           | 102.5      | 0.1860              | -1.3470       | -1.5330          | -0.207                   |
| DB-B5     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.1460             | -0.3330       | -0.1870          | -0.035                   |
|           | 40         | -0.1930             | -0.6060       | -0.4130          | -0.070                   |
|           | 60         | -0.2530             | -0.9600       | -0.7070          | -0.105                   |
|           | 80         | -0.3200             | -1.3070       | -0.9870          | -0.140                   |
|           | 100        | -0.4000             | -1.7070       | -1.3070          | -0.175                   |
|           | 120        | -0.4800             | -2.4340       | -1.9540          | -0.210                   |
| DB-C1     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.3200             | -1.2470       | -0.9270          | -0.168                   |
|           | 40         | -0.2800             | -1.9610       | -1.6810          | -0.336                   |
|           | 60         | -0.3930             | -2.7280       | -2.3350          | -0.504                   |
|           | 80         | -0.5660             | -3.6680       | -3.1020          | -0.672                   |
|           | 100        | -0.7600             | -4.7150       | -3.9550          | -0.840                   |
|           | 105        | -0.6600             | -4.6950       | -4.0350          | -0.882                   |
| DB-C2     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.6530             | -1.2470       | -0.5940          | -0.168                   |
|           | 40         | -1.2200             | -1.9200       | -0.7000          | -0.336                   |
|           | 60         | -1.5600             | -2.6940       | -1.1340          | -0.503                   |
|           | 80         | -1.8670             | -3.4680       | -1.6010          | -0.671                   |
|           | 100        | -1.9940             | -4.3750       | -2.3810          | -0.839                   |
|           | 120        | -1.9200             | -5.4890       | -3.5690          | -1.007                   |
|           | 133        | -1.9940             | -6.4890       | -4.4950          | -1.116                   |

Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-C3     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.7530             | -1.3470       | -0.5940          | -0.176                   |
|           | 40         | -0.9600             | -2.0810       | -1.1210          | -0.352                   |
|           | 60         | -1.0670             | -2.8940       | -1.8270          | -0.528                   |
|           | 80         | -1.1670             | -3.9010       | -2.7340          | -0.704                   |
|           | 95         | -0.8200             | -4.2750       | -3.4550          | -0.836                   |
|           |            |                     |               |                  |                          |
| DB-C4     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.2720             | -0.3330       | -0.0610          | -0.177                   |
|           | 40         | -1.0060             | -1.0930       | -0.0870          | -0.355                   |
|           | 60         | -1.7670             | -1.9200       | -0.1530          | -0.532                   |
|           | 80         | -2.6810             | -3.2480       | -0.5670          | -0.709                   |
|           | 87.5       | -2.9810             | -4.1750       | -1.1940          | -0.776                   |
|           |            |                     |               |                  |                          |
| DB-C5     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.9130             | -1.1130       | -0.2000          | -0.173                   |
|           | 40         | -1.3140             | -2.0940       | -0.7800          | -0.346                   |
|           | 60         | -1.4270             | -3.0680       | -1.6410          | -0.520                   |
|           | 80         | -1.4800             | -4.2880       | -2.8080          | -0.693                   |
|           | 88         | -1.4670             | -5.1020       | -3.6350          | -0.762                   |
|           |            |                     |               |                  |                          |
| DB-D1     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.9800             | -1.8070       | -0.8270          | -0.368                   |
|           | 40         | -1.5940             | -3.0740       | -1.4800          | -0.736                   |
|           | 60         | -2.0540             | -4.3680       | -2.3140          | -1.104                   |
|           | 80         | -2.5270             | -5.7820       | -3.2550          | -1.472                   |
|           | 100        | -3.0010             | -7.6500       | -4.6490          | -1.840                   |
|           | 112        | -3.3880             | -9.5510       | -6.1630          | -2.061                   |
|           |            |                     |               |                  |                          |
| DB-D2     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.3460             | -1.7340       | -1.3880          | -0.373                   |
|           | 40         | -1.0000             | -2.8740       | -1.8740          | -0.745                   |
|           | 60         | -1.6870             | -4.2620       | -2.5750          | -1.118                   |
|           | 80         | -2.3470             | -5.8560       | -3.5090          | -1.491                   |
|           | 100        | -2.8810             | -7.7630       | -4.8820          | -1.864                   |
|           | 110        | -3.1740             | -8.9770       | -5.8030          | -2.050                   |
|           |            |                     |               |                  |                          |
| DB-D3     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.2860             | -1.7470       | -1.4610          | -0.366                   |
|           | 40         | -1.0000             | -3.2140       | -2.2140          | -0.732                   |
|           | 60         | -1.1730             | -4.8550       | -3.6820          | -1.098                   |
|           | 80         | -1.3940             | -7.4770       | -6.0830          | -1.464                   |



Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-D4     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.5400             | -1.3200       | -0.7800          | -0.324                   |
|           | 40         | -1.5400             | -2.3940       | -0.8540          | -0.647                   |
|           | 60         | -2.1940             | -3.7010       | -1.5070          | -0.971                   |
|           | 80         | -2.7140             | -5.0350       | -2.3210          | -1.294                   |
|           | 100        | -3.0340             | -6.7900       | -3.7560          | -1.618                   |
|           | 110        | -0.8330             | -7.6830       | -6.8500          | -1.779                   |
| DB-D5     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -1.2870             | -1.3870       | -0.1000          | -0.377                   |
|           | 40         | -1.2820             | -2.6010       | -1.3190          | -0.755                   |
|           | 60         | -3.6490             | -4.2420       | -0.5930          | -1.132                   |
|           | 80         | -4.1160             | -5.9760       | -1.8600          | -1.509                   |
|           | 100        | -6.6830             | -8.8110       | -2.1280          | -1.886                   |
|           | 103.5      | -6.6100             | -9.6580       | -3.0480          | -1.952                   |
| DB-E1     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -0.6400             | -2.4610       | -1.8210          | -0.413                   |
|           | 40         | -1.3140             | -4.0350       | -2.7210          | -0.826                   |
|           | 60         | -1.9200             | -5.5690       | -3.6490          | -1.239                   |
|           | 80         | -2.4810             | -7.5430       | -5.0620          | -1.652                   |
|           | 100        | -3.1010             | -9.8050       | -6.7040          | -2.065                   |
|           | 120        | -3.7810             | -12.8730      | -9.0920          | -2.478                   |
| DB-E2     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -1.2200             | -2.5940       | -1.3740          | -0.441                   |
|           | 40         | -2.5670             | -4.3880       | -1.8210          | -0.881                   |
|           | 60         | -3.9220             | -6.7560       | -2.8340          | -1.322                   |
|           | 80         | -4.4020             | -8.7110       | -4.3090          | -1.763                   |
|           | 100        | -4.6420             | -10.9320      | -6.2900          | -2.203                   |
|           | 120        | -4.7150             | -14.0130      | -9.2980          | -2.644                   |
| DB-E3     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -1.1070             | -2.6810       | -1.5740          | -0.417                   |
|           | 40         | 2.1470              | -4.4020       | -6.5490          | -0.834                   |
|           | 60         | -3.0810             | -6.0490       | -2.9680          | -1.251                   |
|           | 80         | -4.0150             | -8.1840       | -4.1690          | -1.668                   |
|           | 100        | -4.7420             | -10.3780      | -5.6360          | -2.085                   |
|           | 110        | -4.9750             | -11.6720      | -6.6970          | -2.293                   |

Table 6.12 Observed and Computed Deflection at Mid Span

| Beam Mark | Load (Kip) | Observed Deflection |               |                  | Computed Deflection (mm) |
|-----------|------------|---------------------|---------------|------------------|--------------------------|
|           |            | Support (mm)        | Mid span (mm) | Differencen (mm) |                          |
| DB-E4     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -1.0930             | -2.6610       | -1.5680          | -0.414                   |
|           | 40         | -1.7000             | -4.3680       | -2.6680          | -0.828                   |
|           | 60         | -2.2070             | -5.9090       | -3.7020          | -1.241                   |
|           | 80         | -2.6340             | -8.0300       | -5.3960          | -1.655                   |
|           | 100        | -2.8610             | -10.0580      | -7.1970          | -2.069                   |
|           | 120        | -3.0680             | -12.7730      | -9.7050          | -2.483                   |
|           | 130        | -3.1540             | -14.5940      | -11.4400         | -2.690                   |
|           |            |                     |               |                  |                          |
| DB-E5     | 0          | 0.0000              | 0.0000        | 0.0000           | 0.000                    |
|           | 20         | -1.2070             | -2.3270       | -1.1200          | -0.462                   |
|           | 40         | -2.3070             | -4.2280       | -1.9210          | -0.925                   |
|           | 60         | -2.9340             | -6.0830       | -3.1490          | -1.387                   |
|           | 80         | -3.4950             | -8.5840       | -5.0890          | -1.849                   |
|           | 100        | -4.0220             | -11.7590      | -7.7370          | -2.311                   |
|           | 108.5      | -3.6550             | -13.8600      | -10.2050         | -2.508                   |

Note: The negative sign indicates downward deflection.

The crack pattern and the mode of failure of all the test beams were almost similar despite the variations in web reinforcement arrangement and L/D ratios. The first crack observed in the shear span during the tests were diagonal tension cracks with only few exceptions. Details of crack pattern characteristics have been described in the previous chapter.

The principal mode of failure observed in this investigation was diagonal tension in which the propagation of inclined cracks split the beam approximately along a line joining the inner edge of the support and the edge of loading block. The splitting of central zone under arch compression were mainly observed in the relatively shallower beams although the final failure seemed to have taken place due to diagonal cracking.

The concrete strut formed between two approximately parallel diagonal crack (characteristic of diagonal compression mode of failure) were observed in some of the beams viz. DB-A1, DB-A2, DB-A4, DB-A5, DB-B5, DB-D2, DB-D3. But the destruction of strut by crushing of concrete described as 'shear proper' by de Paiva and Siess <sup>(15)</sup> was never found to occur during these tests. It is possible that presence of the adequate web reinforcement inhibited such failure.

Leonhardt <sup>(16)</sup> has reported that crushing of concrete at bearing blocks was the principal cause of failure he has encountered in the very deep beams of his test. Such crushing was not observed during this investigation. Obviously the widths of the bearing blocks provided were sufficient to prevent such occurrences.

## 6.6 LOAD-STRAIN CHARACTERISTICS

The electrical resistance strain gauge readings on certain selected locations in the reinforcement assembly surface were recorded using a Data Logger. The load strain data and the description of the gauge locations are presented in the Appendix-C. The major problem with strain gauge readings was the lack of stable indication due to improper insulation of 22 gauges out of 150 gauges attached to the reinforcements. Moreover the gauge no.1 of DB-A4, the gauge no.4 of DB-A4, the gauge no.1 of DB-B2, the gauge no.3 of DB-B5, the gauge no.3 of DB-C2, the gauge no.5 of DB-D2, the gauge no.2 of DB-D3 and the gauge no.3 of DB-D4 are showing abnormal strain values which may be due to improper setting of gauges on the surface of the reinforcement. However, these data indicate some overall performance of the test beams at critical load conditions.

Tensile strains were recorded in the main flexural steels. Near cracking load, the tension steel of beam DB- A5 showed the maximum strain in the DBA series. This value was  $653 \times 10^{-6}$  in./in. which corresponds to 550 psi of stress ; And for same condition, in the DBB series, the maximum tensile steel strain was found in the beam DB-B4 with a value of  $769 \times 10^{-6}$  in./in. which corresponds to 520 psi of stress ; In the DBC series, the maximum tensile steel strain was found in the beam DB-C3 with a value of  $600 \times 10^{-6}$  in./in. which corresponds to 567 psi of stress; In the DBD series, the maximum tensile steel strain was found in the beam DB-D3 with a value of  $570 \times 10^{-6}$  in./in. which corresponds to 416 psi of stress and in the DBE series, the maximum tensile steel strain was found in the beam DB-E4 with a value of  $406 \times 10^{-6}$  in./in. which corresponds to 253psi of stress. It is seen that the maximum strain in flexural reinforcement at initial cracking load is found on a particular beam of a series where the quantity of shear reinforcement is minimum among other beams of that series.

At about ultimate load, the maximum tensile strain recorded in the vertical web steel (at mid depth) was found  $1014 \times 10^{-6}$  in the beam DB-A5 for series DBA ;  $1660 \times 10^{-6}$  in the beam DB-B3 for series DBB;  $3017 \times 10^{-6}$  in the beam DB-C4 for series DBC;  $4637 \times 10^{-6}$  in the beam DB-D1 for series DBD and  $2303 \times 10^{-6}$  in the beam DB-E4 for series DBE. The corresponding stresses were 1297 psi ,1561psi, 1111psi,1152psi and 886psi respectively. The maximum strain (near cracking load) in the horizontal web steel at mid span location for the five series were observed in the beams DB- A2, DB- B2, DB- C1, DB- D5 and DB- E3 respectively. These values were  $6421 \times 10^{-6}$  in./in,  $2202 \times 10^{-6}$  in./in,  $883 \times 10^{-6}$  in./in,  $18628 \times 10^{-6}$  in./in and  $3883 \times 10^{-6}$  in./in corresponding to 1460psi,1561psi, 1284psi, 1078psi and 740 psi stress.

## CHAPTER 7

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### CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

#### 7.1 CONCLUSIONS

The conclusions are based on the study of structural behavior and shear strength of twenty five reinforced brick aggregate concrete beams having span to overall depth ratio ( $L/D$ ) of 1 to 5, and subjected to mid span concentrated loading, load at the top (compression face) only. The findings pertain to the simply supported single span beams.

From the test results the following tentative conclusions may be drawn. It may be emphasized here that further investigations are necessary to confirm these findings.

- (01) Different web reinforcement arrangements have no appreciable effect on the formation of initial diagonal crack in a deep beam.
- (02) The de Cossio equation (Eq<sup>n</sup>. 6.1) may be used fairly reliable to predict the nominal shear stress at initial diagonal cracking but it is not reliable to predict the same for  $L/D$  ratio more than two, which has shown in table 6.2.
- (03) The shear strength capacity is decreasing from  $L/D$  ratio 1 to 2, but interestingly it is increasing from  $L/D$  ratio 2 to 5.
- (04) Under concentrated loading system, diagonal cracks are usually the first cracks to be observed in the clear shear span of a deep beam. On some occasions they are simultaneously accompanied by flexural cracks.
- (05) ACI 318-89 Recommendations underestimates the shear stress causing diagonal cracking in deep beams.
- (06) The increase in vertical or horizontal web reinforcement alone has no significant influence upon the diagonal cracking shear stress of deep beam subjected to mid span concentrated loading.
- (07) For the test beams, difference in web steel spacings are found to have no significant influence over the ultimate shear strength of the beams but it has significant effect on the initial diagonal cracking strength. On the other hand, the percentage of tension reinforcement has some positive bearing upon the nominal shear stress at failure.
- (08) The maximum moment at mid span is about 37% of the ultimate flexural capacity of the beam when diagonal cracks first appear.



- (09) Deep beam with L/D ratios of 1 and 2 attains its full flexural capacity prior to failure. But deep beams with L/D ratio 3 to 5 attains only 60% flexural capacity prior to failure. So this can not be used as a basis to obtain the ultimate shear which was concluded by kabir<sup>(7)</sup>
- (10) The principal mode of failure in deep beams having adequate (to prevent temperature and shrinkage cracks) web steel is diagonal tension cracking. The concrete 'strut' between two parallel diagonal cracks may sometimes be formed but, in general, the failure of a deep beam is not due to the compression failure by crushing of such a 'strut'.
- (11) ACI 318-89 code provisions for determination of ultimate shear strength of deep beams seem to be conservative. It appears that the limit of  $8\sqrt{f'_c}$  for maximum shear stress as suggested in the code may be raised to  $10\sqrt{f'_c}$
- (12) Ultimate loads in shear of deep reinforced concrete beams can be readily estimated with a fair degree of accuracy by Ramkrishnan and Ananthanarayana's formula if the splitting co-efficient 'K' be assigned a value slightly lower than that assigned in the formula.
- (13) Singh, Ray, and Reddy<sup>(12)</sup> method of computing ultimate load capacity of deep beams under mid span concentrated loading can be used effectively.
- (14) After analysing all the available information, comparing the measured and computed shear stress of deep beam by various method and finally comparing the shear stress of rectangular beam with deep beam of same size having L/D ratio 5, it is clear that the beam having L/D ratio 5 may not be a deep beam, but it will be more transparent if both the flexural and shear strength capacity of deep beams having L/D ratio 4 to 6 will be studied and analyzed.



## **7.2 RECOMMENDATIONS FOR FUTURE STUDY**

The conclusions stated above were limited by the scope of the tests. It is believed that a wide area in this field remains unexplored in order to develop the guidelines for laying out a proper code of practice for designers. It should, therefore, be mentioned that the investigation on the influence of span to depth ratio upon the shear strength of deep reinforced brick aggregate concrete beams should be continued and all the possible variables should be studied. The following recommendations are made for further research in brick aggregate reinforced concrete deep beams:

- (01) Influence of span to depth ratio on the flexural strength of brick aggregate R. C deep beams.
- (02) Influence of span to depth ratio on the shear strength of deep R. C. beams using stone chips.
- (03) Influence of span to depth ratio on the shear strength of deep R. C. beams using deformed bars (both flexural and web).
- (04) Influence of span to depth ratio ( $L/D$ ) and shear span to depth ratio ( $a/D$ ) on the ultimate strength of brick aggregate R. C. beams.
- (05) Influence of different types of loading on the strength of deep beams.
- (06) Effect of cyclic and sustained loading on the shear strength of deep beams.
- (07) Influence of the dimensions of reaction blocks and loading block/blocks on the load carrying capacity of deep reinforced brick aggregate concrete beams.
- (08) Behavior of brick aggregate reinforced concrete deep T-beams.
- (09) Influence of and anchorage plates and standard hooks on the performance of deep beams.
- (10) Effect of different bar size used as web reinforcement on the strength of deep beams.
- (11) Influence of openings in the web of reinforced brick aggregate deep beams on the strength of such beams.
- (12) Effect of beam width upon the strength of deep beams.

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## APPENDIX-A

### 1. DESIGN OF TEST BEAM DB-A1

There is no method for designing brick aggregate R.C. deep beams. Here the test beams were designed according to ACI Building Code (ACI 318-89) recommendations. Beams DB-A1, DB-B1, DB-C1, DB-D1 and DB-E1 were designed according to ACI Code. For all other beams, the amount of either the flexural or the horizontal web reinforcement or both were increased in relation to those of first beam of the corresponding series. Sample calculations for the design of test beams, DB-A1, DB-B1, DB-C1, DB-D1 and DB-E1 to fail in shear as per ACI 318-89 code provision is presented here.

#### (a) Given Data for Beam DB-A1:

|                                                           |                                           |
|-----------------------------------------------------------|-------------------------------------------|
| Effective span of beam                                    | : $L = 21''$                              |
| Nominal width                                             | : $b = 6''$                               |
| Overall depth                                             | : $D = 21''$                              |
| Effective depth                                           | : $d = 19.50''$                           |
| Nominal shear span                                        | : $X_n = 10.5''$                          |
| Clear shear span                                          | : $a = 9.0''$                             |
| Distance of critical section from the support center line | : $X_c = (1.5 + 0.5 \times 9.0) = 6.00''$ |
| Area of tension steel                                     | : $A_s = 0.96 \text{ in.}^2$              |
| Nominal concrete strength                                 | : $f'_c = 3000 \text{ psi}$               |
| Yield strength of flexural steel                          | : $f_y = 54.7 \text{ ksi}$                |
| Yield strength of web steel                               | : $f_{wy} = 51.3 \text{ ksi}$             |
| Area of web steel bar                                     | : $A_y = A_{yh} = 0.057 \text{ in.}^2$    |

#### CALCULATIONS :

$$\begin{aligned} \text{Spacing of vertical stirrups, } s_{\max} &= \frac{A_v}{0.0015b} = \frac{2 \times 0.057}{0.0015 \times 6} \\ &= 12.67'' > (d/5 = 10.5/5 = 2.1'') \end{aligned}$$



∴ Selected Spacing = 2"

$$\begin{aligned}\text{Spacing of horizontal stirrups, } (s_h)_{\max} &= \frac{A_{vh}}{0.0025b} \\ &= \frac{0.057 \times 2}{0.0025 \times 6} = 7.6'' > (d/3 = 6.5'') \\ \therefore \text{ Selected } s_h &= 6.5''\end{aligned}$$

$$\text{Flexural steel ratio, } p = \frac{0.96}{6 \times 19.5} = 0.0082$$

Now,

$$\begin{aligned}v_c &= (3.5 - 2.5 \frac{M_u}{V_u d}) (1.9 \sqrt{f'_c} + 2500 p \frac{V_u d}{M_u}) \leq 6 \sqrt{f'_c} \quad \text{Where, } \frac{M_u}{V_u} = 6.0 \\ &= (3.5 - 2.5 \frac{6.0}{19.5}) (1.9 \sqrt{3000} + 2500 \times 0.0082 \times \frac{19.5}{6.0}) \\ &= (2.73) \times (170.69)\end{aligned}$$

But the 1st term cannot be greater than 2.5

$$v_c = 2.5 \times 170.69 = 426.73 > (6 \sqrt{f'_c} = 328.63)$$

$$\text{So, } V_c = 328.63 \times 19.5 \times 6 = 38450 \text{ lb} = 38.45^k$$

$$V_s = \left[ \frac{A_v}{12s} \left( 1 + \frac{l_n}{d} \right) + \frac{A_{vh}}{12s_h} \left( 11 - \frac{l_n}{d} \right) \right] f_{wy} d$$

$$\text{Here } \frac{l_n}{d} = \frac{18}{19.5} = 0.923$$

$$\begin{aligned}\therefore V_s &= \left[ \frac{2 \times 0.057}{12 \times 2.0} (1 + 0.923) + \frac{2 \times 0.057}{12 \times 6.5} (11 - 0.923) \right] \times 51.3 \times 19.5 \\ &= 14.74^k\end{aligned}$$

$$V_u = V_c + V_s = 38.45^k + 14.74^k = 53.19^k > [8\sqrt{f'_c}bd = 51.26^k]$$

$$V_u = 51.26^k, \text{ and } M_{us} = V_u \times X_n = 51.26 \times 10.5 = 538.23 \text{ Kip-in.}$$

$$M_{uf} = A_s f_y (d - a'/2)$$

$$a = \frac{A_s f_y}{0.85 f'_c b} = \frac{0.96 \times 54.7}{0.85 \times 3 \times 6} = 3.43 \text{ in.}$$

$$M_{uf} = 0.96 \times 54.7 [19.5 - 3.43/2] = 933.93 \text{ Kip-in.}$$

$$\therefore M_{us} < M_{uf}$$

(b) Given Data for Beam DB-B1:

|                                                           |                                           |
|-----------------------------------------------------------|-------------------------------------------|
| Effective span of beam                                    | : $L = 21''$                              |
| Nominal width                                             | : $b = 6''$                               |
| Overall depth                                             | : $D = 12''$                              |
| Effective depth                                           | : $d = 10.5''$                            |
| Nominal shear span                                        | : $X_n = 10.5$                            |
| Clear shear span                                          | : $a = 9''$                               |
| Distance of critical section from the support center line | : $X_c = (1.5 + 0.5 \times 9.0) = 6.00''$ |
| Area of tension steel                                     | : $A_s = 0.96 \text{ in.}^2$              |
| Nominal concrete strength                                 | : $f'_c = 3000 \text{ psi}$               |
| Yield strength of flexural steel                          | : $f_y = 54.7 \text{ ksi}$                |
| Yield strength of web steel                               | : $f_{wy} = 51.3 \text{ ksi}$             |
| Area of web steel bar                                     | : $A_v = A_{vh} = 0.057 \text{ in.}^2$    |

**Calculation :**

$$\text{Spacing of vertical stirrups, } s_{\max} = \frac{A_v}{0.0015b} = 12.67'' > (d/5 = 10.5/5 = 2.1'')$$

∴ Selected spacing = 2''

$$\begin{aligned} \text{Spacing of horizontal stirrups, } (s_h)_{\max} &= \frac{A_{vh}}{0.0025b} \\ &= \frac{0.057 \times 2}{0.0025 \times 6} = 7.6'' > (d/3 = 10.5/3 = 3.5'') \end{aligned}$$

∴ Selected spacing =  $(s_h)_{\max} = 3.5''$

$$\text{Flexural steel ratio, } \rho = \frac{0.96}{6 \times 10.5} = 0.01524$$

$$\begin{aligned} \text{Now, } v_c &= (3.5 - 2.5 \frac{M_u}{V_u d}) (1.9 \sqrt{f'_c} + 2500 P \frac{V_u d}{M_u}) \leq 6 \sqrt{f'_c} \\ &= (3.5 - 2.5 \frac{6.0}{19.5}) (1.9 \sqrt{3000} + 2500 \times 0.0082 \times \frac{19.5}{6.0}) \\ &= (2.73) \times (170.69) \end{aligned}$$

But the 1st term cannot be greater than 2.5

$$v_c = 2.5 \times 170.69 = 426.73 > (6 \sqrt{f'_c} = 328.63)$$

$$V_c = 328.63 \times 10.5 \times 6 = 20703.69 \text{ lb}$$

$$= 20.7^k$$

$$\frac{l_n}{d} = \frac{18}{10.5} = 1.71$$

$$V_s = \left[ \frac{2 \times 0.057}{12 \times 2} (1 + 1.71) + \frac{2 \times 0.057}{12 \times 3.5} (9.29) \right] \times 51.3 \times 10.5$$

$$= 20.52^k$$

$$V_u = V_c + V_s = 20.7 + 20.52 = 41.22^k > (8 \sqrt{f'_c} bd = 27.6^k)$$

$$\therefore V_u = 27.6^k$$

$$\text{and } M_{us} = 27.6 \times 12 = 331.2 \text{ kip-in}$$

$$M_{uf} = A_s f_y (d - a'/2)$$

$$a' = \frac{A_s f_y}{0.85 f'_c b} = \frac{0.96 \times 54.7}{6.85 \times 3 \times 6} = 3.43 \text{ in}$$

$$M_{uf} = 0.96 \times 54.7 (10.5 - 3.43/2)$$

$$= 461.32 \text{ kip-in}$$

$$\therefore M_{us} < M_{uf}$$

(c) Given Data for Beam DB-C1:

|                                                           |                                            |
|-----------------------------------------------------------|--------------------------------------------|
| Effective span of beam                                    | : $L = 36''$                               |
| Nominal width                                             | : $b = 6''$                                |
| Overall depth                                             | : $D = 12''$                               |
| Effective depth                                           | : $d = 10.5''$                             |
| Nominal shear span                                        | : $X_n = 18''$                             |
| Clear shear span                                          | : $a = 16.5''$                             |
| Distance of critical section from the support center line | : $X_c = (1.5 + 0.5 \times 16.5) = 9.75''$ |
| Area of tension steel                                     | : $A_s = 2.46 \text{ in.}^2$               |
| Nominal concrete strength                                 | : $f'_c = 3000 \text{ psi}$                |

Yield strength of flexural steel :  $f_y = 56.0$  ksi

Yield strength of web steel :  $f_{wy} = 51.3$  ksi

Area of web steel bar :  $A_v = A_{vh} = 0.057$  in.<sup>2</sup>

### Calculation

$$\text{Spacing of vertical stirrups, } s_{\max} = \frac{A_v}{0.0015b} = 12.67'' > (d/5 = 10.5/5 = 2.1'')$$

$\therefore$  Selected spacing = 2''

$$\text{Spacing of horizontal stirrups, } (s_h)_{\max} = \frac{A_{vh}}{0.0025 \times 6}$$

$$= \frac{0.057 \times 2}{0.0025 \times 6} = 7.6'' > (d/3 = 10.5/3 = 3.5'')$$

$\therefore$  Selected spacing =  $(s_h)_{\max} = 3.5''$

$$\text{Flexural steel ratio } p = \frac{1.23 \times 2}{6 \times 10.5} = 0.03905$$

$$V_c = (3.5 - 2.5 \frac{9.75}{10.5}) (1.9 \sqrt{3000} + 2500 \times 0.03905 \times \frac{10.5}{9.75})$$

$$= 1.179 \times 209.2 = 246.65 > (6 \sqrt{f'_c} = 328.63)$$

$$V_c \therefore = 209.2 \times 10.5 \times 6 = 13179.6 \text{ lb} = 13.18^k$$

$$\frac{l_n}{d} = \frac{33}{10.5} = 3.14$$

$$V_s = [ \frac{2 \times 0.057}{12 \times 2} (1 + 3.14) + \frac{2 \times 0.057}{12 \times 3.5} (11 - 3.14) ] \times 51.3 \times 10.5$$

$$= 22.1^k$$

$$V_u = V_c + V_s = 13.18 + 22.1 = 35.28 > (2/3)(10 + \frac{ln}{d})(\sqrt{f'_c} bd = 30.23^k)$$

$$\therefore V_u = 30.23^k$$

$$\text{and } M_{us} = 30.23 \times 18 = 544.14 \text{ k-in}$$

$$M_{uf} = A_s f_y (d - a'/2)$$

$$a' = \frac{A_s f_y}{0.85 f'_c b} = \frac{2.46 \times 56}{0.85 \times 3 \times 6} = 9 \text{ in}$$

$$M_{uf} = 2.46 \times 56 (10.5 - 4.5) \text{ kip-in}$$

$$= 826.56 \text{ kip-in}$$

$$\therefore M_{us} < M_{uf}$$

(d) Given Data for Beam DB-D1:

Effective span of beam :  $L = 48''$

Nominal width :  $b = 8''$

Overall depth :  $D = 12''$

Effective depth :  $d = 10.5''$

Nominal shear span :  $X_n = 24''$

Clear shear span :  $a = 22.5''$

Distance of critical section from the support center line :  $X_c = (1.5 + 0.5 \times 22.5) = 12.75''$

Area of tension steel :  $A_s = 3.69 \text{ in.}^2$

Nominal concrete strength :  $f'_c = 3000 \text{ psi}$



Yield strength of flexural steel :  $f_y = 56.0$  ksi

Yield strength of web steel :  $f_{wy} = 51.3$  ksi

Area of web steel bar :  $A_v = A_{vh} = 0.057$  in.<sup>2</sup>

### Calculation

$$\text{Spacing of vertical stirrups, } s_{\max} = \frac{A_v}{0.0015b} = \frac{2 \times 0.057}{0.0015 \times 8} = 9.5'' > (d/s = 10.5/5 = 2.1'')$$

$\therefore$  Selected spacing = 2''

$$\text{Spacing of horizontal stirrups, } (s_h)_{\max} = \frac{A_{sh}}{0.0025b}$$

$$= \frac{2 \times 0.057}{0.0025 \times 8} = 5.7'' > (d/3 = 10.5/3 = 3.5'')$$

$\therefore$  Selected spacing =  $(s_h)_{\max} = 3.5''$

$$\text{Flexural steel ratio } p = \frac{3.96}{8 \times 10.5} = 0.04714$$

$$v_c = (3.5 - 2.5 \frac{12.75}{10.5}) (1.9 \sqrt{3000} + 2500 \times 0.04714 \times \frac{10.5}{12.75})$$

$$= 1.00 \times 221.92 = 221.92 < (6 \sqrt{f'_c} = 328.63)$$

$$\therefore V_c = 221.92 \times 10.5 \times 8 = 18641.28 \text{ lb} = 18.64^k$$

$$\frac{l_n}{d} = \frac{45}{10.5} = 4.29$$

$$V_s = \left[ \frac{2 \times 0.057}{12 \times 2} (1 + 4.29) + \frac{2 \times 0.057}{12 \times 3.5} (11 - 4.29) \right] \times 51.3 \times 10.5$$

$$= 23.3^k$$

$$V_u = V_c + V_s = 18.64 + 23.3 = 41.94^k > 2/3(10 + \frac{l_n}{d}) \sqrt{f'_c} bd = 43.83^k$$

$$\therefore v_u = 41.94^k$$

$$\text{and } M_{us} = 41.94 \times 24 = 1006.56 \text{ kip-in}$$

$$M_{uf} = A_s f_y (d - a'/2)$$

$$a' = \frac{A_s f_y}{0.85 f'_c b} = \frac{3.69 \times 56}{0.85 \times 3 \times 8} = 10.13 \text{ in}$$

$$\begin{aligned} M_{uf} &= 3.69 \times 56 (10.5 - 10.13/2) \text{ kip-in} \\ &= 1123.15 \text{ kip-in} \end{aligned}$$

$$\therefore M_{us} < M_{uf}$$

(e) Given Data for Beam DB-E1:

|                                                           |                                             |
|-----------------------------------------------------------|---------------------------------------------|
| Effective span of beam                                    | : $L = 60''$                                |
| Nominal width                                             | : $b = 12''$                                |
| Overall depth                                             | : $D = 12''$                                |
| Effective depth                                           | : $d = 10.5''$                              |
| Nominal shear span                                        | : $X_n = 30''$                              |
| Clear shear span                                          | : $a = 28.5''$                              |
| Distance of critical section from the support center line | : $X_c = (1.5 + 0.5 \times 28.5) = 15.75''$ |
| Area of tension steel                                     | : $A_s = 4.92 \text{ in.}^2$                |
| Nominal concrete strength                                 | : $f'_c = 3000 \text{ psi}$                 |
| Yield strength of flexural steel                          | : $f_y = 56.0 \text{ ksi}$                  |
| Yield strength of web steel                               | : $f_{wy} = 51.3 \text{ ksi}$               |
| Area of web steel bar                                     | : $A_v = A_{vh} = 0.057 \text{ in.}^2$      |

### Calculation

$$\text{Spacing of vertical stirrups, } s_{\max} = \frac{A_v}{0.0015b} = \frac{2 \times 0.057}{0.0015 \times 12} = 6.33'' > (d/s = 10.5/5 = 2.1'')$$

∴ Selected spacing = 2''

$$\text{Spacing of horizontal stirrups, } (s_h)_{\max} = \frac{A_{vh}}{0.0025 \times 12}$$

$$= \frac{2 \times 0.057}{0.0025 \times 12} = 3.8'' > (d/3 = 10.5/3 = 3.5'')$$

∴ Selected spacing =  $(s_h)_{\max} = 3.5''$

$$\text{Flexural steel ratio } p = \frac{4.92}{12 \times 10.5} = 0.039$$

$$v_c = (3.5 - 2.5 \frac{15.785}{10.5}) (1.9 \sqrt{3000} + 2500 \times 0.039 \times \frac{10.5}{15.785})$$

$$= 1.00 \times 201.57 = 201.57 > (6 \sqrt{f'_c} = 328.63)$$

$$\therefore V_c = 201.57 \times 10.5 \times 12 = 25397.82 \text{ lb} = 25.4^k$$

$$\frac{l_n}{d} = \frac{57}{10.5} = 5.428$$

$$v_s = \left[ \frac{2 \times 0.057}{12 \times 2} (1 + 5.428) + \frac{2 \times 0.057}{12 \times 3.5} (11 - 5.428) \right] \times 51.3 \times 10.5$$

$$= 24.59^k$$

$$V_u = V_c + V_s = 25.4 + 24.56 = 49.96^k < (10 \sqrt{f'_c} \text{ bd} = 78.87^k)$$

$$\therefore V_u = 49.96^k$$

and  $M_{us} = 49.96 \times 30 = 1498.8 \text{ kip-in}$

$$M_{uf} = A_s f_y (d - a'/2)$$

$$a' = \frac{A_s f_y}{0.85 f'_c b} = \frac{4.92 \times 56}{0.85 \times 3 \times 12} = 9 \text{ in}$$

$$M_{uf} = 4.92 \times 56 (10.5 - 4.5)$$

$$= 4.92 \times 56 (10.5 - 4.5)$$

$$= 1653.12 \text{ k-inch}$$

$$\therefore M_{us} < M_{uf}$$

## APPENDIX-B

### SAMPLE CALCULATIONS FOR ULTIMATE LOAD CAPACITY OF TEST BEAM BY VARIOUS METHODS

#### 1. DESIGN OF TEST BEAM DB-A1

There is no method for designing brick aggregate R.C. deep beams. Here the test beams were designed according to ACI Building Code (ACI 318-89) recommendations. Beams DB-A1, DB-B1, DB-C1, DB-D1 and DB-E1 were designed according to ACI Code. For all other beams, the amount of either the flexural or the horizontal web reinforcement or both were increased in relation to those of first beam of the corresponding series. Sample calculations for the design of test beams, DB-A1, DB-B1, DB-C1, DB-D1 and DB-E1 to fail in shear as per ACI 318-89 code provision is presented here.

(a) Given Data for Beam DB-A1:

|                                                           |                                           |
|-----------------------------------------------------------|-------------------------------------------|
| Effective span of beam                                    | : $L = 22.1''$                            |
| Nominal width                                             | : $b = 6.5''$                             |
| Overall depth                                             | : $D = 21.4''$                            |
| Effective depth                                           | : $d = 19.9''$                            |
| Nominal shear span                                        | : $X_n = 11.05''$                         |
| Clear shear span                                          | : $a = 9.0''$                             |
| Distance of critical section from the support center line | : $X_c = (1.5 + 0.5 \times 9.0) = 6.00''$ |
| Area of tension steel                                     | : $A_s = 0.884 \text{ in.}^2$             |
| Nominal concrete strength                                 | : $f'_c = 4886 \text{ psi}$               |
| Yield strength of flexural steel                          | : $f_y = 54.7 \text{ ksi}$                |
| Yield strength of web steel                               | : $f_{wy} = 51.3 \text{ ksi}$             |
| Area of web steel bar                                     | : $A_y = A_{vh} = 0.057 \text{ in.}^2$    |

#### CALCULATIONS :

$$\text{Spacing of vertical stirrups, } s_{\max} = \frac{A_v}{0.0015b} = \frac{2 \times 0.057}{0.0015 \times 6.5}$$

$$\therefore \text{Selected Spacing} = 3'' = 11.69'' > (d/s = 19.9/5 = 3.98'')$$

$$\begin{aligned} \text{Spacing of horizontal stirrups, } (s_h)_{\max} &= \frac{A_{vh}}{0.0025b} \\ &= \frac{2 \times 0.057}{0.0025 \times 6.5} = 7.01'' > (d/3 = 6.6'') \end{aligned}$$

$$\therefore \text{Selected } s_h = 6.5''$$

$$\text{Flexural steel ratio, } p = \frac{0.884}{6.5 \times 19.9} = 0.0068$$

Now, Ultimate load carried by the concrete is

$$\begin{aligned} v_c &= (3.5 - 2.5 \frac{M_u}{V_u d}) (1.9 \sqrt{f'_c} + 2500 p \frac{V_u d}{M_u}) \leq 6 \sqrt{f'_c} \\ &= (3.5 - 2.5 \frac{6}{19.9}) (1.9 \sqrt{4886} + 2500 \times 0.0068 \times \frac{19.9}{6}) \\ &= (2.74) \times (189.19) \end{aligned}$$

But the 1st term cannot be greater than 2.5

$$\therefore v_c = 2.5 \times 189.19 = 472.98 > (6 \sqrt{f'_c} = 419.39)$$

$$\text{So, } V_c = 419.39 \times 19.9 \times 6.5 \times 2 / 1000 = 108.50^k$$

Ultimate load carried by the web steel is

$$V_s = [ \frac{A_v}{12s} (1 + \frac{l_n}{d}) + \frac{A_{vh}}{12s_h} (11 - \frac{l_n}{d}) ] f_{wy} d$$

$$\text{Here } \frac{l_n}{d} = \frac{19.1}{19.9} = 0.959$$

$$\begin{aligned} \therefore V_s &= [ \frac{2 \times 0.057}{12 \times 3} (1 + 0.959) + \frac{2 \times 0.057}{12 \times 6.5} (11 - 0.959) ] \times 51.3 \times 19.9 \\ &= 22.56^k \end{aligned}$$



$$V_u = V_c + V_s = 108.50^k + 22.56^k = 130.06^k > [8\sqrt{f'_c b d} = 72.33^k]$$

$$\therefore V_u = 130.06^k$$

## 2. Ray and Reddy Approach :

$$c = \frac{\sqrt{f'_c \cdot f'_{sp}}}{2} = \frac{\sqrt{4886 \times 622}}{2} = 871.6496$$

$$\tan \Phi = \frac{f'_c - f'_{sp}}{2\sqrt{f'_c \cdot f'_{sp}}} = (4886 - 622)/(4 \times 871.65) = 1.223$$

$$\tan \beta = 4D/(L-3) = 4.4816$$

$$\therefore \beta = 77.42^\circ \text{ and}$$

$$\sin \beta = 0.976$$

$$\cos \beta = 0.2178$$

$$P_c = \frac{cbD}{\sin \beta \cos \beta (\tan \beta + \tan \phi)}$$

$$= \frac{871.6496 \times 6.5 \times 21.4}{0.976 \times 0.2178 (4.4816 + 1.223)}$$

$$= 99985.3 \text{ lbs} = 99.985^k$$

$$\lambda_1 = \left(1 - \frac{1}{3} \cdot \frac{X_n}{D}\right) = \left(1 - \frac{1}{3} \times \frac{11.05}{21.4}\right) = 0.827882$$

$$\lambda_1 P_c = 0.827882 \times 99.985 = 82.78^k$$

$$P_s = A_s f_{sy} \left( \frac{\tan \beta \tan \phi - 1}{\tan \beta + \tan \phi} \right)$$

$$= 0.884 \times 54.7 \left( \frac{4.4816 \times 1.223 - 1}{4.4816 + 1.223} \right)$$

$$= 37.98^k$$

$$\begin{aligned}
 P_{wv} &= \sum_{n1} A_v f_v \frac{\tan \phi}{\tan \beta + \tan \phi} \\
 &= (7 \times 2 \times 0.057) \times 51.3 \times \frac{1.223}{4.4816 + 1.223} \\
 &= 8.78^k
 \end{aligned}$$

$$\begin{aligned}
 P_{wh} &= \sum_{n2} A_v f_v \left( \frac{\tan \beta \cdot \tan \phi - 1}{\tan \beta + \tan \phi} \right) \\
 &= (2 \times 2 \times 0.057) \times 51.3 \times \left( \frac{4.4816 \times 1.223 - 1}{4.4816 + 1.223} \right) \\
 &= 9.19^k
 \end{aligned}$$

$$\therefore P_w = P_{wv} + P_{wh} = 8.78 + 9.19 = 17.97^k$$

Hence,

$$\begin{aligned}
 Q_u &= \lambda_1 P_c + \Psi_s P_s + \Psi_w P_w \\
 &= (82.78 + 1 \times 37.98 + 0.5 \times 17.97)^k \\
 &= 129.75^k
 \end{aligned}$$

$$\therefore P_u = 2 \times Q_u = 2 \times 129.75 = 259.50^k$$

### 3. Ramkrishnan and Ananthanarayan Approach

$$P_u = 2Kf_{sp}bD$$

where,  $K = 1.12$

$$\begin{aligned}
 \therefore P_u &= 2 \times 1.12 f_{sp} b D \\
 &= 2.24 \times 622 \times 6.5 \times 21.4 \\
 &= 193805 \text{ lbs} \\
 &\cong 193.81^k
 \end{aligned}$$

## APPENDIX-C

Table C.1 Observed strain values (in micro strain) in reinforcements of beam DB-A1 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |                  |                  |                    |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|--------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 140 <sup>k</sup> | 150 <sup>k</sup> | 160 <sup>k</sup> | 170 <sup>k</sup> | 180 <sup>k</sup> | 180.5 <sup>k</sup> |
| 1        | +17                                     | +96             | +263            | +350            | +324            | +201            | -122            | -403            | -491            | -465            | -245             | -69              | -26              | +8               | -69              | -87              | +44              | +17              | 0                | +61                |
| 2        | +66                                     | +65             | +123            | +133            | +158            | +144            | +257            | +303            | +389            | +483            | +584             | +666             | +734             | +805             | +886             | +945             | +988             | +1072            | +1156            | +1159              |
| 3        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                  |
| 4        | 0                                       | +1              | +5              | +8              | +16             | +18             | +26             | +40             | +93             | +174            | +239             | +253             | +304             | +397             | +628             | +716             | +790             | +869             | +986             | +1050              |
| 5        | +17                                     | -33             | -61             | -93             | -131            | -174            | -172            | -224            | -250            | -249            | -201             | -17              | -8               | +50              | +83              | +97              | +100             | +32              | +115             | +150               |
| 6        | +4                                      | -8              | -32             | -62             | -85             | -99             | -121            | -147            | -150            | -151            | -128             | -158             | -144             | -162             | -118             | -120             | -123             | -158             | -194             | -79                |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 49 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -233 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 337 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 1050 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 150 MS (micro strain)

Table C.2 Observed strain values (in micro strain) in reinforcements of beam DB-A2 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 140 <sup>k</sup> | 150 <sup>k</sup> | 160 <sup>k</sup> | 170 <sup>k</sup> | 180 <sup>k</sup> | 190 <sup>k</sup> |
| 1        | +3990                                   | +38             | +57             | +91             | +149            | +187            | +268            | +427            | +561            | +763            | +889             | +981             | +1088            | +1174            | +1285            | +1370            | +1459            | +1536            | +1615            | +1760            |
| 2        | -13223                                  | +23             | +50             | -50             | +33             | +94             | +72             | +53             | +222            | -513            | -1203            | -1638            | -1692            | -1597            | -1522            | -1449            | -1290            | -1152            | -1040            | -990             |
| 3        | +2555                                   | +8              | +16             | +25             | +29             | +54             | +67             | +160            | +523            | +780            | +1020            | +1148            | +1271            | +1498            | +1771            | +2148            | +2591            | +3051            | +3762            | +5108            |
| 4        | -15838                                  | +1              | +4              | +13             | +65             | +29             | +44             | +86             | +54             | -2176           | -2545            | -2815            | -3190            | -3610            | -4008            | -1380            | -1001            | -1745            | -1933            | -2425            |
| 5        | +3123                                   | -40             | -79             | -119            | -158            | -200            | -237            | -275            | -261            | -245            | -283             | -318             | -331             | -331             | -343             | -356             | -364             | -393             | -433             | -430             |
| 6        | +2335                                   | -10             | -26             | -41             | -56             | -67             | -83             | -107            | -114            | -8              | +63              | +103             | +160             | +184             | +205             | +243             | +269             | +285             | +310             | +330             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 160 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -275 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 427 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 6421 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = -691 MS (micro strain)

Table C.3 Observed strain values (in micro strain) in reinforcements of beam DB-A3 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 140 <sup>k</sup> | 150 <sup>k</sup> | 160 <sup>k</sup> | 170 <sup>k</sup> | 180 <sup>k</sup> | 183 <sup>k</sup> |
| 1        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                |
| 2        | -16                                     | +71             | +44             | +68             | +95             | +117            | +140            | +236            | +241            | +342            | +406             | +482             | +521             | +582             | +597             | +646             | +681             | +719             | +816             | +790             |
| 3        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                |
| 4        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                |
| 5        | +30                                     | +6              | -29             | -68             | -109            | -170            | -200            | -221            | -253            | -316            | +34              | +100             | +137             | +167             | +212             | +252             | +262             | +223             | +46              | -68              |
| 6        | +49                                     | -107            | +25             | -52             | -36             | -79             | -118            | -147            | -156            | -171            | -15              | +75              | +156             | +216             | +288             | +351             | +324             | +429             | +639             | +1100            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 0 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -316 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 482 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 0 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 1100 MS (micro strain)

Table C.4 Observed strain values (in micro strain) in reinforcements of beam DB-A4 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 140 <sup>k</sup> | 150 <sup>k</sup> | 160 <sup>k</sup> | 170 <sup>k</sup> | 180 <sup>k</sup> | 190 <sup>k</sup> |
| 1        | -333                                    | -555            | -650            | -674            | -634            | -467            | +1072           | +8157           | +8910           | +9542           | +9574            | +9445            | 14421            | 14282            | 14627            | 14200            | 12677            | 13111            | 16840            | 18146            |
| 2        | +18                                     | +29             | +47             | +68             | +86             | +121            | +180            | +326            | +432            | +533            | +612             | +702             | +766             | +839             | +894             | +956             | +1007            | +1083            | +1170            | +1107            |
| 3        | +5                                      | 0               | 0               | 0               | -4              | +1              | +8              | +132            | +684            | +1005           | +1151            | +1357            | +1533            | +1560            | +1873            | +2073            | +2282            | +2586            | +2901            | +3034            |
| 4        | +112                                    | +362            | +434            | +475            | +539            | +766            | +1379           | +7613           | +7801           | +9692           | +7728            | +7392            | 39497            | +8196            | 11854            | 19703            | 19030            | 40070            | 49286            | 24966            |
| 5        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                | 0                |
| 6        | -17                                     | -40             | -79             | -88             | -125            | -140            | -164            | -201            | -220            | -153            | -143             | -137             | -148             | -153             | -142             | -158             | -188             | -220             | -127             | +199             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 7613MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -201 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 8533.5MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 24966 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 199 MS (micro strain)

Table C.5 Observed strain values (in micro strain) in reinforcements of beam DB-A5 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 140 <sup>k</sup> | 150 <sup>k</sup> | 160 <sup>k</sup> | 170 <sup>k</sup> | 180 <sup>k</sup> | 185 <sup>k</sup> |
| 1           | +1337                                   | +14             | +33             | +64             | +95             | +135            | +184            | +252            | +366            | +522            | +672             | +774             | +883             | +1004            | +1111            | +1241            | +1353            | +1482            | +1640            | +1760            |
| 2           | -2405                                   | +30             | +51             | +79             | +105            | +128            | +201            | +265            | +442            | +586            | +720             | +841             | +950             | +1050            | +1143            | +1251            | +1315            | +1402            | +1515            | +1759            |
| 3           | +950                                    | +16             | +44             | +57             | +61             | +109            | +116            | +147            | +225            | +337            | +476             | +709             | +685             | +829             | +899             | +949             | +1012            | +1052            | +1221            | +1222            |
| 4           | +2355                                   | -17             | -21             | -13             | -12             | -6              | +4              | +24             | +66             | +160            | +372             | +474             | +590             | +685             | +685             | +741             | +757             | +786             | +785             | +627             |
| 5           | +1992                                   | -19             | -35             | -53             | -73             | -95             | -110            | -110            | -84             | -43             | +9               | +60              | +174             | +207             | +264             | +161             | +7               | -62              | -166             | -583             |
| 6           | -16511                                  | +290            | +181            | +766            | +589            | +537            | +872            | +733            | +543            | +714            | +780             | +770             | +752             | +828             | +648             | +647             | +761             | +698             | +840             | +1014            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 147 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 733 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 653 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 1222 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 1014 MS (micro strain)

Table C.6 Observed strain values (in micro strain) in reinforcements of beam DB-B1 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 122 <sup>k</sup> |
| 1           | +534                                    | +39             | +132            | +239            | +445            | +635            | +776            | +939            | +1081           | +1226           | +1442            | +1753            | +2386            | +793             |
| 2           | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                |
| 3           | +2252                                   | +5              | +13             | +23             | +17             | +39             | +289            | +427            | +71             | +304            | +618             | +781             | +1335            | -1630            |
| 4           | +2761                                   | +15             | +19             | +28             | +94             | +194            | +201            | +232            | +269+           | +305            | +364             | +434             | +585             | +141             |
| 5           | +781                                    | +25             | +26             | -9              | -1              | -22             | +77             | +232            | +433            | +503            | +555             | +481             | -2096            | -2442            |
| 6           | +1639                                   | -12             | -28             | -38             | -40             | -3              | +118            | +274            | +339            | +416            | +262             | +262             | +320             | +22              |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 194MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -24 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 635 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -1630 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = -2442 MS (micro strain)



Table C.7 Observed strain values (in micro strain) in reinforcements of beam DB-B2 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> |
| 1           | -6                                      | +60             | +432            | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | +130049          |
| 2           | -3                                      | +56             | +132            | +298            | +259            | +312            | +435            | +573            | +698            | +800            | +902             | +1003            | +1091            |
| 3           | 0                                       | +27             | +69             | +212            | +1033           | -1878           | -826            | -1082           | -616            | -581            | -1500            | -1782            | -2202            |
| 4           | 0                                       | +26             | +71             | +181            | +363            | +477            | +588            | +640            | +650            | +685            | +728             | +904             | +1062            |
| 5           | 0                                       | -26             | -33             | -29             | +100            | +626            | +704            | +653            | +510            | +470            | +427             | +391             | +500             |
| 6           | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 1033 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 100 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = +259 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -2202 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 500 MS (micro strain)

Table C.8 Observed strain values (in micro strain) in reinforcements of beam DB-B3 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 123 <sup>k</sup> |
| 1           | +7787                                   | +53             | +150            | +295            | +482            | +630            | +785            | +919            | +1057           | +1207           | +1319            | +1424            | +1541            | +1557            |
| 2           | +5897                                   | +58             | +164            | +351            | +612            | +702            | +855            | +1004           | +1151           | +1290           | +1433            | +1599            | +1812            | +1895            |
| 3           | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                |
| 4           | +3798                                   | +38             | +80             | +147            | +280            | +446            | +639            | +865            | +1052           | +1192           | +1333            | +1433            | +1518            | +1494            |
| 5           | +5958                                   | +1              | +35             | +125            | +278            | +479            | +636            | +766            | +896            | +955            | +966             | +1027            | +1031            | +1660            |
| 6           | +5404                                   | -17             | -40             | -71             | -150            | -115            | -83             | -15             | +10             | +107            | +232             | +325             | +449             | +374             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 147 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 125 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 630 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 1494 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 1660 MS (micro strain)



Table C.9 Observed strain values (in micro strain) in reinforcements of beam DB-B4 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                    |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|--------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 102.5 <sup>k</sup> |
| 1        | +59                                     | +197            | +412            | +602            | +769            | +931            | +1108           | +1317           | +1508           | +1670           | +1469            | +248               |
| 2        | +50                                     | +167            | +386            | +560            | +716            | +853            | +989            | +1106           | +1221           | +1299           | +1058            | -58                |
| 3        | -10                                     | -10             | +12             | +228            | +756            | +872            | +1015           | +1205           | +1287           | +734            | -1213            | -1286              |
| 4        | -577                                    | -86             | -388            | +113            | -363            | +444            | +178            | +16             | +346            | +317            | +86              | -121               |
| 5        | -13                                     | -6              | +3              | +162            | +359            | +381            | +357            | +377            | +475            | +495            | +538             | -388               |
| 6        | +14                                     | -33             | +16             | +72             | +505            | +698            | +810            | +931            | +1087           | +1049           | +931             | +202               |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 756 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 505 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 769 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -1286 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = -388 MS (micro strain)

Table C.10 Observed strain values (in micro strain) in reinforcements of beam DB-B5 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> |
| 1        | -2                                      | +40             | +108            | +283            | +477            | +598            | +733            | +866            | +995            | +1134           | +1251            | +1362            | +1463            |
| 2        | -11                                     | +44             | +104            | +279            | +469            | +833            | +970            | +1103           | +1200           | +1338           | +1479            | +1572            | +1690            |
| 3        | +226                                    | +1000           | +565            | -95             | 1139            | +652            | +278            | -51             | -616            | -424            | +1444            | +3374            | +16420           |
| 4        | 0                                       | +11             | +17             | +63             | +212            | +277            | +310            | +384            | +457            | +557            | +682             | +753             | +857             |
| 5        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                |
| 6        | +8                                      | +36             | +34             | -18             | -57             | -100            | -233            | -244            | -255            | -232            | -216             | +18              | -46              |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -95 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -18 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 283 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 16420 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = -46 MS (micro strain)

Table C.11 Observed strain values (in micro strain) in reinforcements of beam DB-C1 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 105 <sup>k</sup> |
| 1        | 0                                       | +61             | +155            | +268            | +374            | +467            | +557            | +644            | +782            | +899            | +983             | +933             |
| 2        | 0                                       | +43             | +124            | +220            | +323            | +449            | +559            | +686            | +783            | +885            | +982             | +900             |
| 3        | 0                                       | -3              | -1              | +17             | +360            | +600            | +717            | +767            | +819            | +909            | +994             | +883             |
| 4        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                |
| 5        | +152                                    | +12             | -84             | -148            | +228            | +39             | +141            | -1738           | -1945           | -3008           | -4020            | -5752            |
| 6        | 0                                       | -1              | -2              | -16             | -12             | +189            | +332            | +434            | +470            | +602            | +826             | +839             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 220 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -45 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 374 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 883 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 839 MS (micro strain)

Table C.12 Observed strain values (in micro strain) in reinforcements of beam DB-C2 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 133 <sup>k</sup> |
| 1        | -8                                      | +8              | +4              | +11             | +39             | +394            | +479            | +576            | +700            | +861            | +1038            | +1290            | +1748            | +2408            | +2572            |
| 2        | -1                                      | +54             | +119            | +213            | +328            | +409            | +493            | +572            | +648            | +701            | +753             | +826             | +926             | +1046            | +1043            |
| 3        | +127                                    | +236            | +265            | +319            | +313            | +1348           | +82             | -1146           | -1039           | -1426           | -1639            | -1582            | -1071            | -1195            | +11687           |
| 4        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                |
| 5        | -3                                      | -3              | -5              | +13             | +53             | +585            | +863            | +1029           | +1260           | +1524           | +1769            | +2029            | +2189            | +2343            | +2848            |
| 6        | 0                                       | +69             | +128            | +257            | +412            | +525            | +645            | +735            | +807            | +912            | +935             | +996             | +1033            | +992             | +851             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 1348 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 585 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 409 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 11687 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 2848 MS (micro strain)

Table C.13 Observed strain values (in micro strain) in reinforcements of beam DB-C3 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 95 <sup>k</sup> |
| 1           | -2                                      | +51             | +137            | +232            | +331            | +395            | +481            | +561            | +642            | +727            | +616            |
| 2           | +13                                     | +150            | +170            | +178            | +323            | +352            | +464            | +600            | +718            | +585            | +1268           |
| 3           | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               |
| 4           | 0                                       | -4              | -15             | -27             | +20             | +242            | +342            | +255            | +333            | +444            | +371            |
| 5           | +4                                      | +1              | +5              | +9              | +20             | +25             | +73             | +1276           | +1233           | +1292           | +779            |
| 6           | -3                                      | +7              | -2              | +1              | +187            | +460            | +607            | +780            | +765            | +631            | +592            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 159 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 398 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 600 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 371 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 779 MS (micro strain)

Table C.14 Observed strain values (in micro strain) in reinforcements of beam DB-C4 at different load levels.

| Gauge<br>No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                   |
|-------------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------------------|
|             | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 87.5 <sup>k</sup> |
| 1           | +2816                                   | +56             | +156            | +251            | +350            | +459            | +561            | +655            | +712            | +703              |
| 2           | +1927                                   | +69             | +190            | +290            | +417            | +508            | +572            | +608            | +707            | +691              |
| 3           | +2386                                   | -34             | -82             | -113            | +66             | +138            | +183            | +16             | +17             | +15               |
| 4           | +2050                                   | -9              | -70             | -111            | -124            | -175            | -233            | -247            | +77             | -93               |
| 5           | +1166                                   | +6              | +2              | -15             | +550            | +814            | +1032           | +1242           | +1316           | +1626             |
| 6           | +2772                                   | +38             | +76             | +153            | +712            | +980            | +1469           | +2095           | +3603           | +3017             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -123 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 232 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 350 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -93 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 3017 MS (micro strain)

Table C.15 Observed strain values (in micro strain) in reinforcements of beam DB-C5 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 88 <sup>k</sup> |
| 1        | -2                                      | +87             | +163            | +264            | +320            | +405            | +516            | +571            | +629            | +693            |
| 2        | +1                                      | +67             | +155            | +265            | +353            | +474            | +585            | +685            | +811            | +927            |
| 3        | 0                                       | -17             | -23             | +85             | +494            | +670            | +780            | +846            | +813            | +823            |
| 4        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               |
| 5        | +10                                     | +16             | +20             | +100            | +820            | +1103           | +1364           | +1794           | +2107           | +2315           |
| 6        | -285                                    | -401            | -433            | -448            | -317            | -170            | -10             | +66             | +322            | +392            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 508 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 827 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 585 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 823 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 2315 MS (micro strain)

Table C.16 Observed strain values (in micro strain) in reinforcements of beam DB-D1 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 112 <sup>k</sup> |
| 1        | 0                                       | +58             | +137            | +234            | +335            | +416            | +502            | +588            | +660            | +716            | +782             | +841             | +854             |
| 2        | -1                                      | +44             | +90             | +182            | +261            | +333            | +404            | +473            | +528            | +567            | +592             | +626             | +608             |
| 3        | -1                                      | -16             | -31             | -44             | -64             | -39             | +57             | +99             | +134            | +149            | +153             | +95              | -158             |
| 4        | -1                                      | +26             | +68             | +160            | +269            | +383            | +466            | +585            | +681            | +798            | +1023            | +1198            | +1239            |
| 5        | 0                                       | +1              | +1              | -2              | -2              | -5              | +106            | +323            | +542            | +664            | +752             | +1333            | +4637            |
| 6        | -1                                      | 0               | +2              | +1              | +8              | +288            | +435            | +534            | +662            | +757            | +1076            | +1277            | +1189            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 248 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 8 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 316 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 1239 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 4637 MS (micro strain)



Table C.17 Observed strain values (in micro strain) in reinforcements of beam DB-D2 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 118 <sup>k</sup> |
| 1        | +1                                      | +61             | +147            | +233            | +340            | +421            | +512            | +597            | +668            | +729            | +778             | +827             | +836             |
| 2        | 0                                       | +66             | +164            | +266            | +382            | +466            | +563            | +658            | +737            | +804            | +850             | +920             | +995             |
| 3        | -7                                      | +1              | +3              | +7              | 0               | -126            | -58             | +92             | +179            | +248            | +294             | +328             | +464             |
| 4        | +4                                      | +20             | +45             | +76             | +152            | +232            | +325            | +443            | +550            | +640            | +733             | +840             | +691             |
| 5        | +12                                     | +25             | +47             | +36             | +14             | -12             | 0               | +48             | +73             | +123            | +231             | +283             | +2394            |
| 6        | -1                                      | +11             | +20             | +25             | +21             | +29             | +48             | +77             | +105            | +150            | +855             | +999             | +1364            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 76 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 36 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 266 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 691 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 2394 MS (micro strain)

Table C.18 Observed strain values (in micro strain) in reinforcements of beam DB-D3 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> |
| 1        | 0                                       | +64             | +149            | +247            | +341            | +416            | +495            | +570            | +635            |
| 2        | -16210                                  | -20298          | -34853          | -24364          | -17833          | +6866           | -4049           | -8184           | -20126          |
| 3        | +6                                      | -32             | -39             | -58             | -48             | +161            | +159            | +133            | -11             |
| 4        | 0                                       | +15             | +40             | +101            | +162            | +184            | +228            | +279            | +480            |
| 5        | 0                                       | +4              | +10             | +25             | +154            | +1596           | +2529           | +2891           | +3099           |
| 6        | +5                                      | +3              | +6              | +14             | +98             | +628            | +837            | +1206           | 1650            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -17833 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 154 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 570 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -20126 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 3099 MS (micro strain)

Table C.19 Observed strain values (in micro strain) in reinforcements of beam DB-D4 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> |
| 1        | 0                                       | +49             | +114            | +206            | +311            | +388            | +475            | +561            | +642            | +702            | +716             | -406             |
| 2        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                |
| 3        | +4                                      | -29             | -23             | -67             | -76             | +85             | +263            | +352            | +387            | +416            | +317             | +2879            |
| 4        | 0                                       | -33             | -55             | -82             | -98             | -95             | -120            | -116            | +6              | +83             | +175             | +1438            |
| 5        | 0                                       | -10             | -10             | +7              | +8              | +63             | +383            | +694            | +896            | +897            | +947             | +691             |
| 6        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -98 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 8 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 475 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 2879 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 691 MS (micro strain)

Table C.20 Observed strain values (in micro strain) in reinforcements of beam DB-D5 at different load levels.

| Gauge | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                    |
|-------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|--------------------|
| No    | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 103.5 <sup>k</sup> |
| 1     | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                  |
| 2     | 0                                       | +62             | +139            | +257            | +352            | +435            | +528            | +619            | +682            | +753            | +879             | +872               |
| 3     | +3932                                   | +16357          | -49858          | -47916          | -47371          | -48857          | -45530          | -39856          | -33663          | -31711          | -17262           | -18628             |
| 4     | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                  |
| 5     | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                  |
| 6     | 0                                       | +5              | +10             | +21             | +98             | +188            | +352            | +630            | +899            | +1145           | +1329            | 3312               |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -47371 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 98 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 528 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = -18628 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 3312 MS (micro strain)



Table C.21 Observed strain values (in micro strain) in reinforcements of beam DB-E1 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> | 131 <sup>k</sup> |
| 1        | +33                                     | +92             | +161            | +230            | +301            | +376            | +443            | +495            | +570            | +661            | +708             | +782             | +824             | +848             | +836             |
| 2        | +3                                      | +33             | +44             | +62             | +96             | +124            | +142            | +141            | +156            | +131            | +154             | +163             | +154             | +161             | +157             |
| 3        | +1                                      | +2              | +6              | +15             | +21             | +17             | +10             | -31             | -68             | +16             | +125             | +204             | +276             | +340             | +348             |
| 4        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                | 0                |
| 5        | +3                                      | +7              | +6              | +12             | +11             | +27             | +56             | +68             | +68             | +86             | +100             | +141             | +186             | +261             | +285             |
| 6        | -2                                      | -4              | -1              | 0               | +1              | +10             | +14             | +35             | +58             | +82             | +134             | +186             | +233             | +492             | +822             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 21 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 11 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 301 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 348 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 822 MS (micro strain)

Table C.22 Observed strain values (in micro strain) in reinforcements of beam DB-E2 at different load levels.

| Gauge | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |  |
|-------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|--|
| No    | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 126 <sup>k</sup> |  |
| 1     | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                |  |
| 2     | +2957                                   | +63             | +113            | +227            | +300            | +391            | +571            | +649            | +740            | +835            | +959             | +1035            | +1101            | +1058            |  |
| 3     | +2822                                   | -1              | -3              | -4              | -5              | -2              | -28             | +142            | +251            | +307            | +268             | +391             | +346             | +278             |  |
| 4     | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                | 0                | 0                |  |
| 5     | +2950                                   | +11             | +14             | +16             | +8              | 0               | +51             | +173            | +255            | +364            | +441             | +720             | +969             | +969             |  |
| 6     | +1940                                   | -6              | 0               | -1              | -4              | -12             | -36             | +104            | +220            | +259            | +259             | +288             | +379             | +352             |  |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -2 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = -12 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 391 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 278 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 969 MS (micro strain)

Table C.23 Observed strain values (in micro strain) in reinforcements of beam DB-E3 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 112 <sup>k</sup> |
| 1        | -2                                      | +27             | +54             | +110            | +160            | +173            | +116            | +186            | +6950           | +13068          | +9820            | +12068           | -8980            |
| 2        | -3                                      | +44             | +119            | +202            | +292            | +372            | +439            | +499            | +569            | +639            | +717             | +761             | -805             |
| 3        | +10                                     | +6              | -8              | -16             | -57             | -74             | -110            | -33             | +108            | +198            | +306             | +394             | +897             |
| 4        | 0                                       | +23             | +50             | +120            | +218            | +332            | +501            | +566            | +664            | +765            | +876             | +1011            | +3883            |
| 5        | -2                                      | 0               | -13             | -30             | +31             | -36             | +11             | +44             | +90             | +173            | +278             | +392             | +276             |
| 6        | +3                                      | -5              | -4              | 0               | -1              | -14             | +58             | +660            | +862            | +1080           | +1271            | +1450            | +382             |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 218 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 31 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 292 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 3883 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 382 MS (micro strain)

Table C.24 Observed strain values (in micro strain) in reinforcements of beam DB-E4 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                  |                  |                  |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 110 <sup>k</sup> | 120 <sup>k</sup> | 130 <sup>k</sup> |
| 1        | -3                                      | +39             | +99             | +183            | +250            | +320            | +399            | +481            | +572            | +660            | +761             | +840             | +925             | +1022            |
| 2        | +65                                     | +98             | +211            | +316            | +428            | +555            | +625            | +734            | +839            | +921            | +1012            | +1075            | +1171            | +1170            |
| 3        | +3                                      | -25             | -52             | -78             | -96             | -117            | -98             | +205            | +414            | +587            | +704             | +795             | +644             | +715             |
| 4        | +3                                      | -35             | -69             | -96             | -118            | -144            | -123            | -8              | +33             | +57             | +108             | +212             | +310             | +273             |
| 5        | +13                                     | +14             | +14             | +57             | +65             | +89             | +175            | +921            | +1163           | +1376           | +1588            | +1794            | +1986            | +2303            |
| 6        | +5                                      | +18             | +34             | +43             | +59             | +61             | +87             | +349            | +587            | +756            | +888             | +963             | +1053            | +1141            |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = -118 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 61 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 406 MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 715 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 2303 MS (micro strain)

Table C.25 Observed strain values (in micro strain) in reinforcements of beam DB-E5 at different load levels.

| Gauge No | Load level at which strain was measured |                 |                 |                 |                 |                 |                 |                 |                 |                 |                  |                    |
|----------|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|--------------------|
|          | 0 <sup>k</sup>                          | 10 <sup>k</sup> | 20 <sup>k</sup> | 30 <sup>k</sup> | 40 <sup>k</sup> | 50 <sup>k</sup> | 60 <sup>k</sup> | 70 <sup>k</sup> | 80 <sup>k</sup> | 90 <sup>k</sup> | 100 <sup>k</sup> | 108.5 <sup>k</sup> |
| 1        | 0                                       | +48             | +119            | +231            | +345            | +445            | +522            | +631            | +735            | +835            | +952             | +993               |
| 2        | 0                                       | +45             | +99             | +177            | +252            | +351            | +442            | +529            | +617            | +700            | +783             | +783               |
| 3        | +9                                      | -1              | +2              | +6              | +128            | +16             | +716            | +984            | +1202           | +1381           | +1051            | +590               |
| 4        | +3                                      | +12             | +28             | +72             | +167            | +236            | +312            | +368            | +460            | +574            | +781             | +802               |
| 5        | 0                                       | +4              | +5              | +5              | +7              | +19             | +694            | +996            | +1288           | +1473           | +1660            | +1563              |
| 6        | 0                                       | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0                | 0                  |

- The exact location of the gauge no. 1 to gauge no. 6 on the reinforcement assembly is shown in Fig. 4.11.
- Maximum strain in horizontal web reinforcement corresponding to initial cracking = 167 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to initial cracking = 7 MS (micro strain)
- Maximum strain in flexural reinforcement corresponding to initial flexural cracking = 345MS (micro strain)
- Maximum strain in horizontal web reinforcement corresponding to ultimate stress = 802 MS (micro strain)
- Maximum strain in vertical web reinforcement corresponding to ultimate stress = 1563 MS (micro strain)

