بسم الله الرحمن الرحيم

“VIBRATION ANALYSIS AND EFFECT OF INTERNAL STIFFENER ON THE STRUCTURAL RESPONSE OF STEEL WIND TURBINE TOWER”

A THESIS SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND CHEMICAL ENGINEERING (MCE), ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

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DECLARATION

This is to certify that the work presented in this thesis is an outcome of the analysis, simulation and research carried out by the author themselves under the watchful supervision of Prof. Dr. Md. Zahid Hossain.

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We would also like to give thanks to all faculty members of the department for their advice and support throughout the project. All of us are indebted to our family members for their moral supports and prayers.

Although we tried our best to complete this thesis flawlessly, we seek apology if there is any mistake found in this report.

ABSTRACT

In this paper, the structural response of steel tubular wind turbine towers with various design configuration is analyzed using FEM modeling. 50m tower with 3 different design option as follows: i) tower without stiffener, ii) tower with horizontal stiffening ring, iii) tower with vertical stiffener. The model of the towers are designed in SolidWorks. Von-Mises stress and total deflection of the tower are analyzed to identify more efficient design approach adopting internal stiffeners. Here we analyzed the mode shapes, natural frequencies and harmonic response of von-mises stress and total deflection by using ANSYS Workbench 14.5. The studied model ignored the mass of nacelle-rotor system and the wind turbines, namely, only the isolated tower was included. Actually we validate an existing paper where tower without stiffening ring and with stiffening ring are analyzed and here another design option has been analyzed in which vertical stiffeners are used instead of stiffener ring. Finally best design option will be selected based on strength of the tower and vibration analysis.

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CHAPTER 1 : INTRODUCTION

Developing renewable energy is very indispensable as facing the issues of global warming and tightening energy supplies. Wind supplies a clean and inexhaustible energy to a social and economic development of any nation. In recent 20 years, wind energy was the fastest growing technology in range of renewable power generation sources and wind power industry was rapidly expanding. Moreover, wind power will be more extensively utilized in future. The global wind energy council (GWEC) and Greenpeace predict wind energy has become a mainstream power source in many countries and could meet 12% of world electricity demand by 2020. In Denmark, for example, 20% of electricity had produced from wind by 2007, and it is planned that 50% of Danish electricity needs will be met by wind generation by 2025. China's wind market has contributed its high growth rates in the past few years and additional capacity of 6.3GW of wind power has been installed in China, bringing the total capacity to 12.2 GW by 2008. Wind turbines are energy converters that convert kinetic energy from the moving air to electrical power; they are attached to supporting towers that also support the rotor and the power transmission and control systems. One of the most common design options for wind turbine towers is a tubular steel structure manufactured in sections of 20–30 m with flanges at both ends facilitating the bolting of these sections in situ.

1.1 LITERATURE REVIEW

A successful structural design of a tower should meet the design criteria of cost effectiveness, safety and functionality. Negm and Maalawi [1] considered the cross-sectional area, the radius of gyration and the height of each segment as the key design variables, and suggested five design options before reaching the final one. Bazeos et al. [2] analyzed a prototype wind turbine steel tower with respect to its static and dynamic behavior and other destabilizing effects. The refined and simplified models developed for static and seismic analyses are compared with each other and are in close agreement. Li et al. [3] proposed some advice, in terms of economic efficiency, for designing a typhoon-resistant wind turbine for use in countries where tropical cyclones often occur. Dimopoulos and Gantes [4] also compared different stiffening methods around the cutouts in tubular wind tower. It was found that simple stiffening types consisting of either a peripheral frame or two vertical stringers and a ring are particularly efficient and can be used instead of more complex ones. Lemak and Studnicka [5] investigated the effect of the spacing and stiffness of ring stiffeners on the behavior of a cylindrical steel shell subjected to wind loading. Murtagh et al. [6] demonstrated simple approximate methods of obtaining natural frequencies, and mode shapes of towers supporting utilities. The fundamental natural frequencies and mode shapes were extracted by analytical formulation and subsequently compared to the FEA model, and the values were observed to be in close agreement. Jiang et al. [7] numerically simulated the welded joints between the tower and bottom flanges in a wind turbine by taking the residual stress into consideration. Results show that complex residual stresses are generated in the fillet weld. Recently Chou and Tu [8] investigated the collapse mechanism of a large wind turbine tower, and reviewed similar accidents in other countries to identify potential risk factors affecting the lifecycle of wind turbines. Lee and Bang [9] described an accident involving a 600 kW wind turbine in Korea, and provided a buckling analysis method used for the slender shell structures. The analysis for a nonlinear FEM shell model was found to exhibit similar behavior to the actual accident situation during buckling. Fernando Pena et al. [10] assessed the seismic behavior of an old masonry tower using the finite element method. The static and dynamic analyses showed different behavior, indicating that the push-over analysis should be used carefully in the seismic assessment of masonry structures.

In this paper, wind towers of 50m has been numerically analyzed by means of the finite element program ANSYS. Tower has three design options, namely, the shell structure without rings, or with rings or with vertical stiffeners. Specifically, here the effect of internal stiffener such as stiffening ring and vertical stiffener on the structural strength are examined. In order to determine the strength of the each design, finite element analysis program ANSYS Workbech 14.5 is used and static structural, modal and harmonic analysis have been performed in this software. In addition to the von-mises stress and the total deflection, the dynamic characteristics of these isolated tower structures are also examined. Finally from the analysis, the best design is selected in terms of strength which has given the lower value of von mises stress and total deflection when same wind load is applied in every design.

CHAPTER 2 : MODELING OF 50M TOWER

2.1 CONSTRUCTION OF TOWER

In this study 50m tower [11] has been chosen to be numerically examined. The 50m tower is consists of two parts such as lower part and upper part. The height of the lower part and upper part is 22m and 28m respectively. The two parts are connected by flange with bolt connection. The diameter of the tower gradually decreases along with the increase of height. The thickness of the shell of the tower varies in sectional part. The thickness of the lower part is higher than the upper part. As the diameter gradually decreases along the height, the thickness of the tower shell also varies section by section. In other design option, internal stiffener ring and vertical stiffener are used in tower. Stiffening rings are used at a distance apart from each other and the distances [11] between two rings are shown in Fig. 2.3. The dimension of the stiffening ring [11] is given in the Table 2.3. The dimensions of the vertical stiffener are described in the tower with vertical stiffener section. In this paper this design [tower with vertical stiffener] is the modified design and the previous two designs [tower without stiffener and tower with stiffening ring] are taken from this paper. The dimensions except the dimension of the vertical stiffener are taken from this paper.

2.1.1 TOWER WITHOUT RINGS [TOWER 1]

The geometric characteristics and the relevant model [11] of the wind turbine tower 1 is shown in the Fig. 3.1.

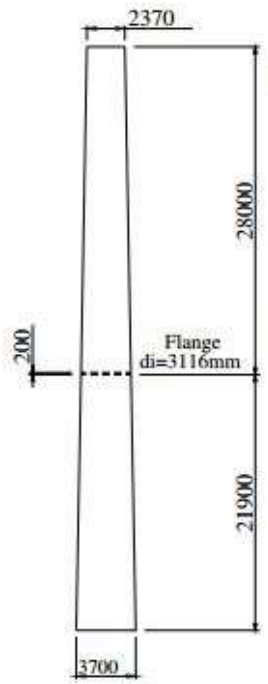

Figure 2.1 : Tower prototype of 50m height

The tower is drawn in SolidWorks and uploaded to ANSYS for simulation. A typical cross section and flange arrangement [11] of the tower is presented in the Fig. 3.2. The material properties of the steel tower are displayed in Table 3.1, whereas the thickness and the midsection width of the flanges, and shell thickness [11] are shown in Tables 3.2 and 3.3. The diameters of the towers' cross section from bottom to top vary linearly.

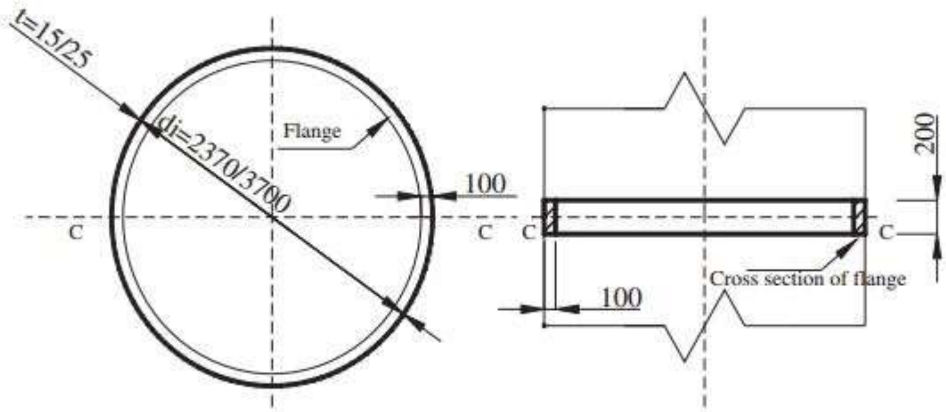

Figure 2.2 : Typical cross section of 50m tower

Table 2.1: Material properties of structural steel of the wind turbine tower

Material property	Elastic modulus(Gpa)	Density(g/cm^3)	Poisson's ratio
Steel	205	7.85	0.3

Table 2.2: Flange dimension of tower 1

Height of tower (m)	Thickness of flanges (mm)	Mid-section width of flanges (mm)
50	200	100

Table 2.3: Shell thickness of tower 1

50 m	Height zone	0-21.9 m	21.9-50 m
	Shell thickness (mm)	25	15

2.1.2 TOWER WITH STIFFENING RING [TOWER 2]

Steel shells are regularly stiffened by means of stiffening rings to prevent local buckling. The stiffening rings are added to the inner surface of the shell. The dimension and model of the tower is represented in Fig. 3.3. The dimension of the stiffening rings [11] of the tower

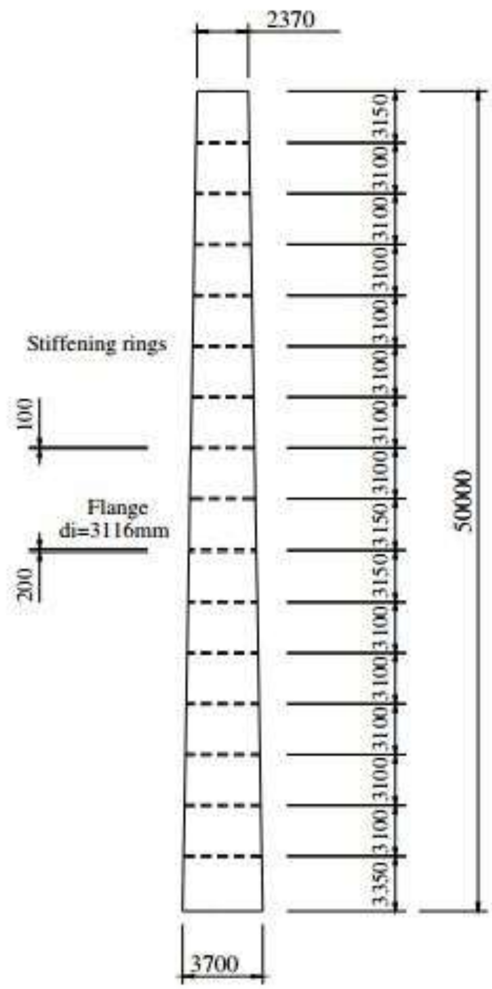

Figure 2.3 : Tower with stiffening rings

is shown in the table 3.4. The location and the dimension of flange are the same as the tower 1. The other dimensions are also identical to the tower 1.

Table 2.4: Stiffening ring dimension of tower 2

Height of tower (m)	Thickness (mm)	Mid-section width (mm)
50	100	50

2.1.3 TOWER WITH VERTICAL STIFFENER [TOWER 3]

Steel shells are regularly stiffened by means of vertical stiffener to prevent local buckling. The stiffener are added to the inner surface of the shell. The model of the tower is represented in the Fig.3.4. The dimensions of the vertical stiffener of the tower are 50mm

Figure 2.4 : Tower with vertical stiffener

mid-section width, total number of stiffener is 6 which are 60° apart from each other and the circumference of the each stiffener is extended to 5°. The location and the dimension of flange are the same as the tower 1. The other dimensions are also identical to the tower 1.

CHAPTER 3 : FINITE ELEMENT ANALYSIS

Finite Element Method (FEM) is a numerical approach to obtain approximate solutions to partial differential equations and their system. A complicated problem can be divided into finite number of small and simple elements; these are then solved in relations to each other, hence the overall solution for the whole problem can be evaluated. Thus this method provides a very good means to approximate the modal shape and frequency of the system.

The same technique can be applied for harmonic analysis and amplitude variation due to external actuation can be approximated and it can be obtained whether or not the maximum amplitude is concurrent with the modal frequency.

In this paper, wind towers of 50m has been numerically analyzed by means of the finite element program ANSYS. Tower has three design options, namely, the shell structure without rings, or with rings or with vertical stiffeners. In addition to the von-misses stress and the total deflection, the dynamic characteristics of these isolated tower structures are also examined. Finally from the analysis, the best design is selected in terms of strength which has given the lower value of von-misses stress and total deflection when same wind load is applied in every design.

3.1 ANSYS

ANSYS is engineering simulation software uses FEM to predict system response. Structural mechanics solution from ANSYS provide the ability to simulate every structural aspect of a product, including linear static analysis that simply provides stresses or deformations, modal analysis that determines vibration characteristics; through the advanced transient nonlinear phenomena involving dynamic effects and complex behavior. The ANSYS Workbench 14.5 software suite is used for both modal, static structural analysis and harmonic analysis.

3.2 MESHING

Finite element analysis is the process of dividing our geometry into finite nodes and elements and solving it for stress and strains and the particular process of discretization is known as meshing. Meshing is the way of communicating our geometry to the FEA solver. In meshing we will divide our geometry into any one of the following shapes of elements like triangles, quadrilaterals, tetrahedron, quadrilateral pyramid, triangular prism, and hexahedron and the selection of particular shape of the element depends on the type of analysis and the shape of the geometry. Elements on the mesh of the geometry will only capture the structural response of the system so it is mandatory to understand the impact of element type and mesh quality before solving a problem. Even the density of the mesh can affect the output so it is best to have a more elements.

First the geometry or model drawn in SolidWorks is uploaded to the ANSYS Workbench to analyze natural frequency, stresses and deformation. In order to analyze the tower more accurately the geometry must be divided into smaller finite elements by using the mesh option. Default meshing or manual meshing can be used to analyze the tower. In case of manual meshing, relevance center, sizing of the mesh element, smoothness, transition and span angle center etc. can be defined. Here element size 100mm, relevance center fine, smoothing medium and span angle center medium have been selected. Then generate mesh command has been given and after finishing the meshing of the tower, the tower is ready to analyze natural frequency, stresses and deformation etc. In Fig.3.1, smaller finite elements of the tower has been shown after completing the meshing.

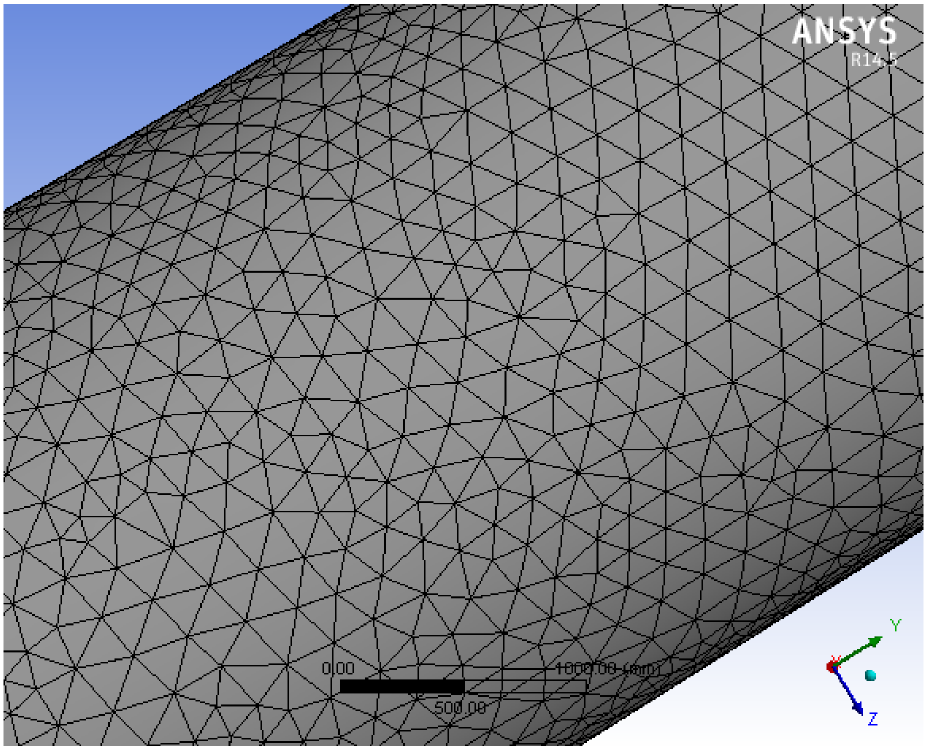

Figure 3.1: Meshing of the tower

3.3 WIND LOAD DISTRIBUTION

Here the contribution of the platforms and the ancillary equipment (ladders, cable racks, etc.) to the total weight of the tower are neglected. On the top of the tower, the weight of the nacelle, together with the blades and the rotor, will induce the vertical force and moment that act on the top of the tower, which are 750 kN and 400 kN-m, [11] respectively.

According to BS EN 1991-1-4 [12] , the wind loads over the tower stem are calculated based on the specific dynamic characteristics and the geometry of the tower structure. The distribution function of basic wind pressure along the height z of the 50 m tower stem is related to the diameter, D. Simplified distribution patterns of the wind loads are represented in Fig. 3.5 [11]. The maximum wind pressure for the tower [11] is represented in Table where the negative value represents wind suction. The wind pressure on the circumferential surface of the tower is symmetrical with respect to the horizontal axis of the cross section.

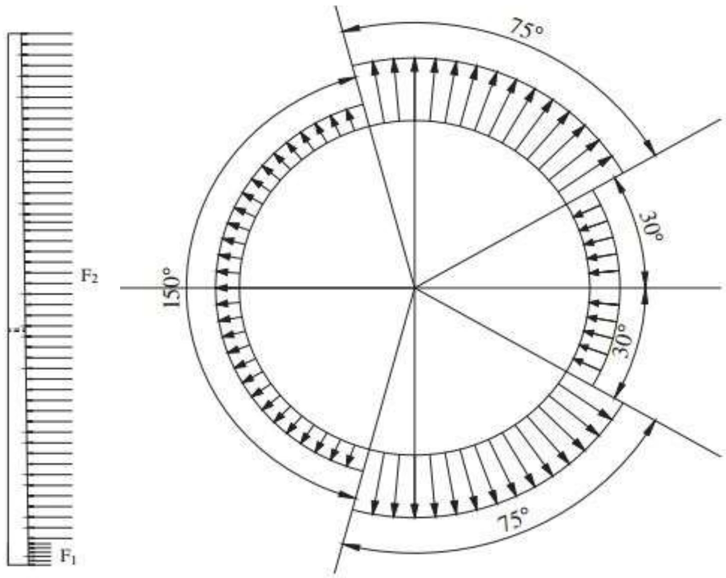

Figure 3.2 : Distribution pattern of wind load along the tower height and around the circumference

Table 3.1 : Maximum wind pressure along the tower (Pa)

Angle / Vertical zone	(0°, 30°)	(30°, 105°)	(105°, 180°)
0-2 m	975	-1455	-768
2-50 m	2390	-3585	-1893

3.4 STATIC STRUCTURAL ANALYSIS

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. The types of loading that can be applied in a static analysis include:

- Externally applied forces and pressures
- Steady-state inertial forces (such as gravity or rotational velocity)
- Imposed (nonzero) displacements
- Temperatures (for thermal strain)

Here we are going to find the von mises stress and total deflection of tower during static external wind pressure and vertical load. The bottom of the tower is assumed to be fixed supported.

3.5 VON MISES STRESS

Von Mises stress (also called Equivalent stress) is often used in design work because it allows any arbitrary three-dimensional stress state to be represented as a single positive stress value. Equivalent stress is part of the maximum equivalent stress failure theory used to predict yielding in a ductile material. Von Mises stress is widely used by designers to check whether their design will withstand a given load condition. Using this information an engineer can say his design will fail, if the maximum value of Von Mises stress included in the material is more than strength of the material.

3.6 VON-MISES STRESS & TOTAL DEFLECTION OF TOWER WITHOUT RINGS [TOWER 1]

Fig. 3.3 shows the minimum and maximum value of von-mises stress of tower 1 and the value of the maximum von-mises stress is 54.28 MPa which is less than the modulus of elasticity of the structural steel.

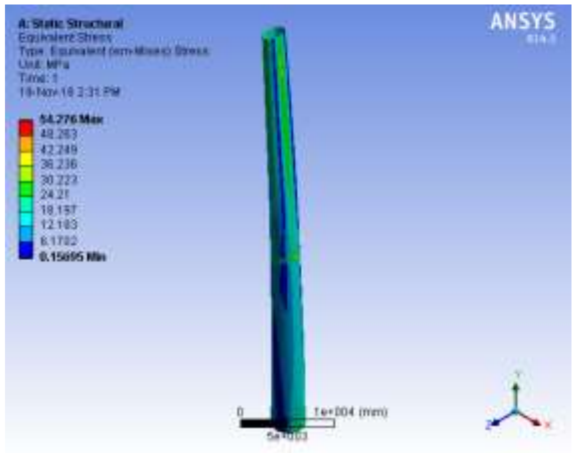

Figure 3.3 : Von-Mises Stress of Tower 1

Fig.3.4 shows the total deflection of the tower 1 under the wind load. Maximum deflection occurs at the top of the tower which is 59.34mm and the deflection is in the x-direction.

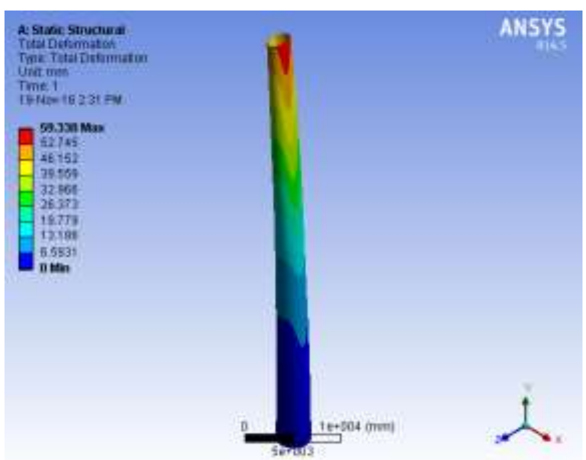

Figure 3.4 : Total Deflection of Tower 1

3.7 VON-MISES SRESS & TOTAL DEFLECTION OF TOWER WITH STIFFENING RING [TOWER 2]

Fig. 3.5 shows the minimum and maximum value of von-mises stress of tower 2 and the value of the maximum von-mises stress is 49.97 MPa which is less than the modulus of elasticity of the structural steel and the maximum von-mises stress of tower 1. As internal stiffener rings are used in the tower, the strength of the tower 2 increases and more than tower 1.Stress concentration occurs at bottom, joining of sections and around the ring.

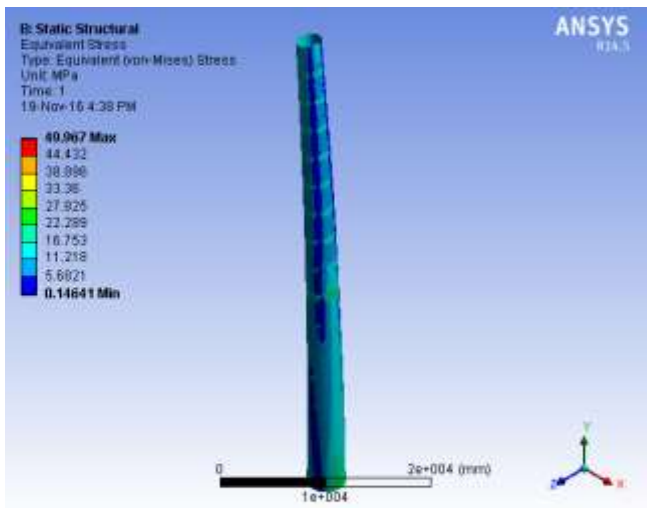

Figure 3.5 : Von-Mises Stress of Tower 2

Fig.3.6 shows the total deflection of the tower 2 under the wind load. Maximum deflection occurs at the top of the tower which is 54.99mm which is less than the maximum deflection of tower 1 and the deflection is in the x-direction.

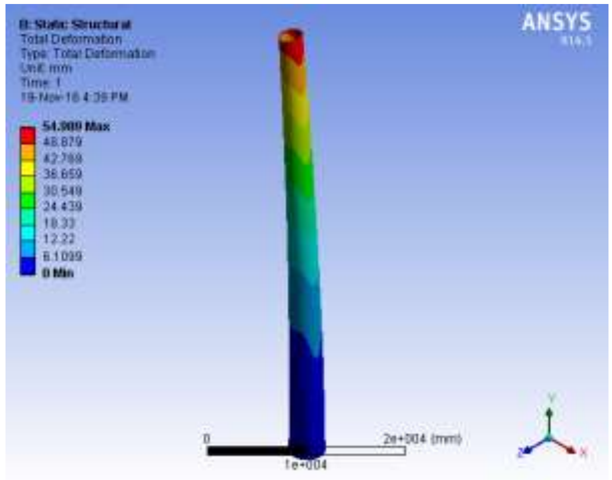

Figure 3.6 : Total Deflection of Tower 2

3.8 VON-MISES STRESS & TOTAL DEFLECTION OF TOWER WITH VERTICAL STIFFENER [TOWER 3]

Fig. 3.7 shows the minimum and maximum value of von-mises stress of tower 3 and the value of the maximum von-mises stress is 47.39 MPa which is less than the modulus of elasticity of the structural steel and the maximum von-mises stress of tower 1 and tower 2. In case of using vertical stiffener instead of stiffening ring, the strength of tower increases more. Stress concentration occurs at bottom, joining of sections.

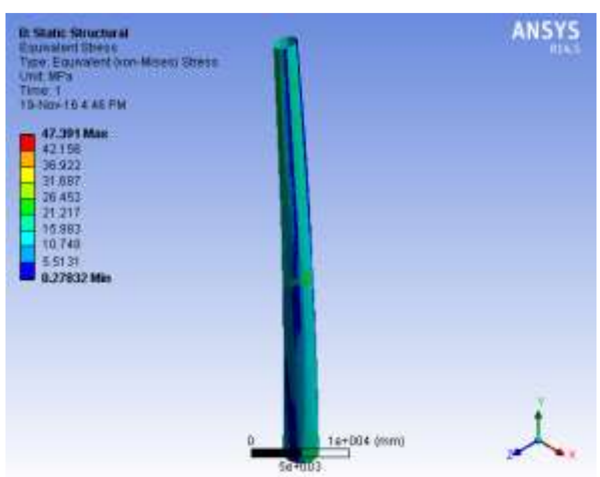

Figure 3.7 : Von-Mises Stress of Tower 3

Fig.3.8 shows the total deflection of the tower 3 under the wind load. Maximum deflection occurs at the top of the tower which is 52.74 mm which is less than the maximum deflection of tower 1 and tower 2 and the deflection is in the x-direction.

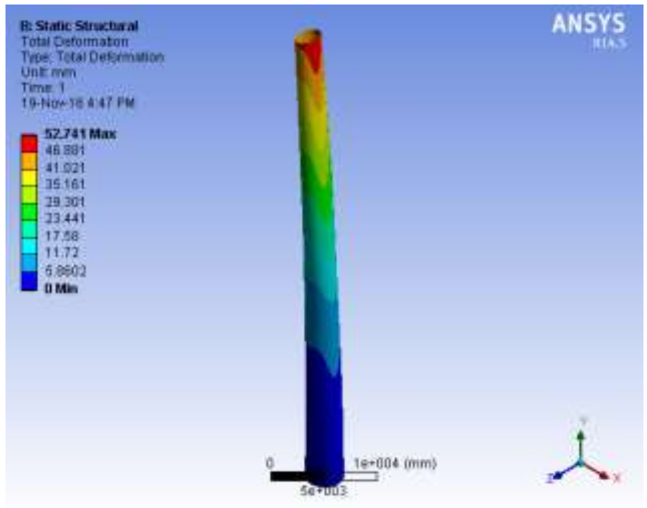

Figure 3.8 : Total Deflection of Tower 3

3.9 MODAL ANALSIS

Modal analysis is a process of obtaining innate dynamic characteristics of a system in the forms of natural frequencies, damping factors and mode shapes and using them to formulate mathematical model for its dynamics behavior. The natural modes of vibration are inherent to a dynamic system and are determined completely by it physical properties like mass, stiffness, damping and their spatial distribution. Each mode is described by the modal parameters: natural frequency, damping factor and characteristics displacement pattern, which is mode shape. The mode shape corresponds to a natural frequency.

The modal analysis is performed in ANSYS Workbench 14.5. The model which is drawn in SolidWorks, is inputted into ANSYS Workbench 14.5 to analyze the natural frequencies of the tower and the mode shape of the tower at each natural frequency. Meshing of the tower is done by selecting the relevance center fine, smoothing medium, span angle center medium and the element size 100mm. Here the natural frequencies and the mode shapes of the three design options are given below.

3.10 TOWER WITHOUT RINGS [TOWER 1]

3.10.1 NATURAL FREQUENCY OF TOWER 1

Table 3.2: Natural Frequency of Tower 1

Mode	Frequency [Hz]
1	1.89
2	1.89
3	6.72
4	6.76

Table 3.3: Meshing Statistics of Tower 1

Nodes	472364
Elements	230300

3.10.2 MODE SHAPES OF TOWER 1

In Fig.3.9 and Fig.3.10, mode shapes or deformation of the tower 1 are shown at different natural frequency.

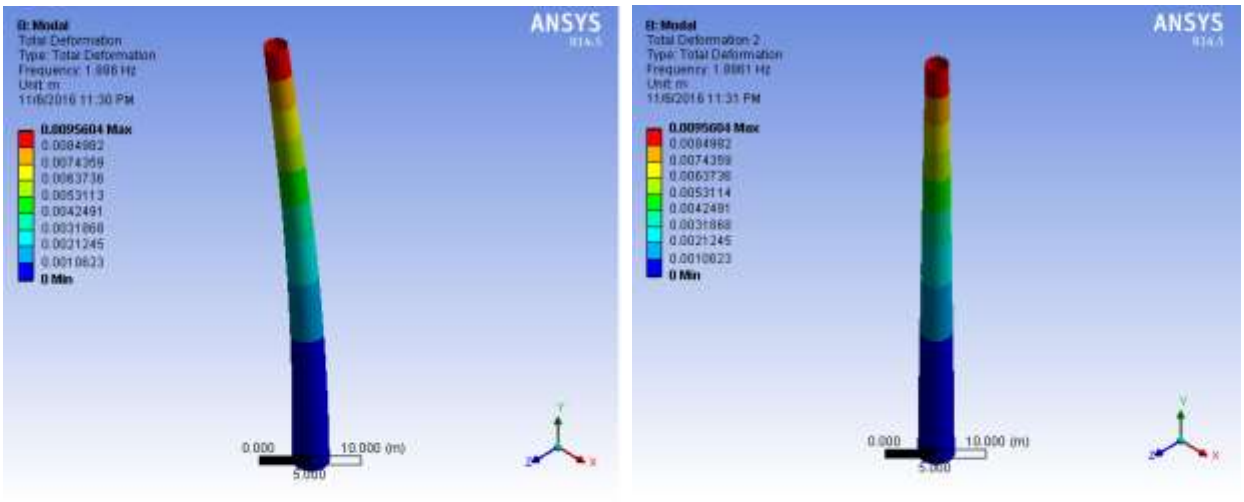

Figure 3.9 : 1st & 2nd Mode Shape of Tower 1 at NF 1.89Hz & 1.89Hz respectively

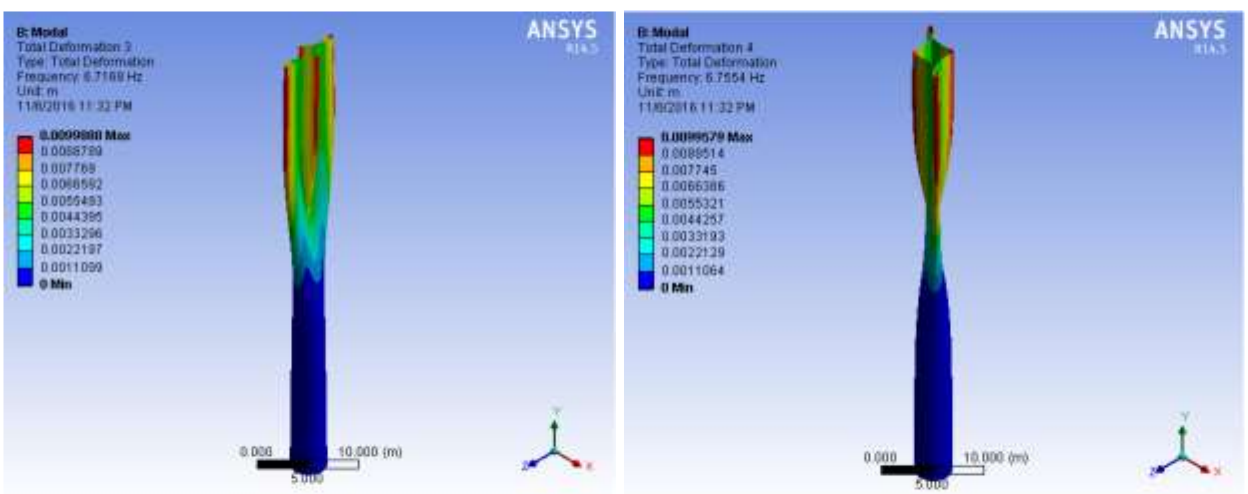

Figure 3.10 : 3rd & 4th Mode Shape of Tower 1 at NF 6.72Hz & 6.76Hz respectively

3.11 TOWER WITH STIFFENING RING [TOWER 2]

3.11.1 NATURAL FREQUENCY OF TOWER 2

Table 3.4: Natural Frequency of Tower 2

Mode	Frequency [Hz]
1	1.84
2	1.84
3	7.73
4	7.73

Table 3.5: Meshing Statistics of Tower 2

Nodes	450062
Elements	223105

3.11.2 MODE SHAPES OF TOWER 2

In Fig.3.11 and Fig.3.12, mode shapes or deformation of the tower 2 are shown at different natural frequency.

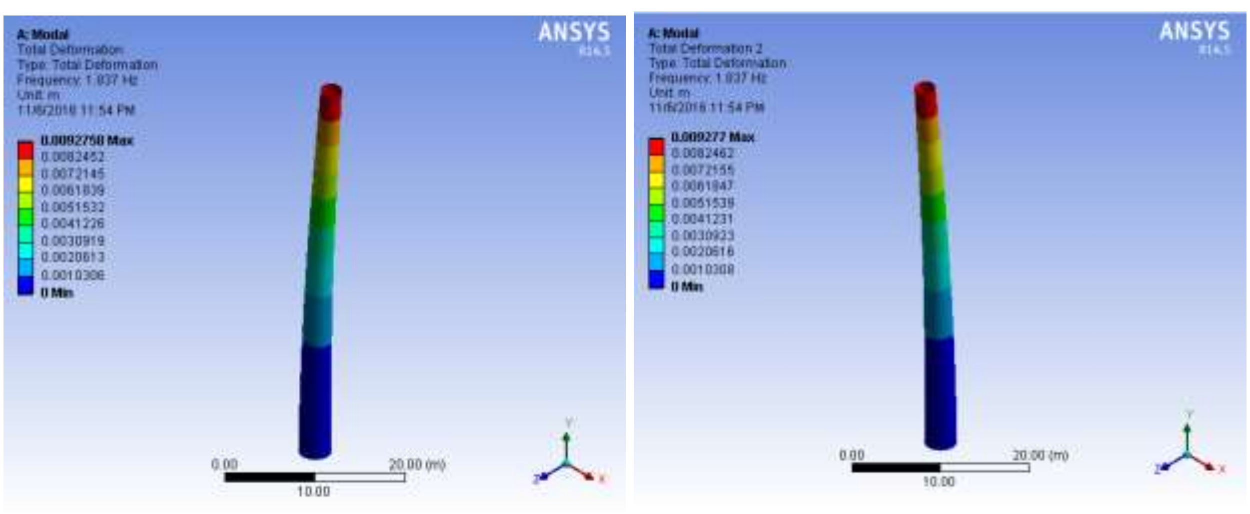

Figure 3.11 : 1st & 2nd Mode Shape of Tower 2 at NF 1.84Hz & 1.84 Hz respectively

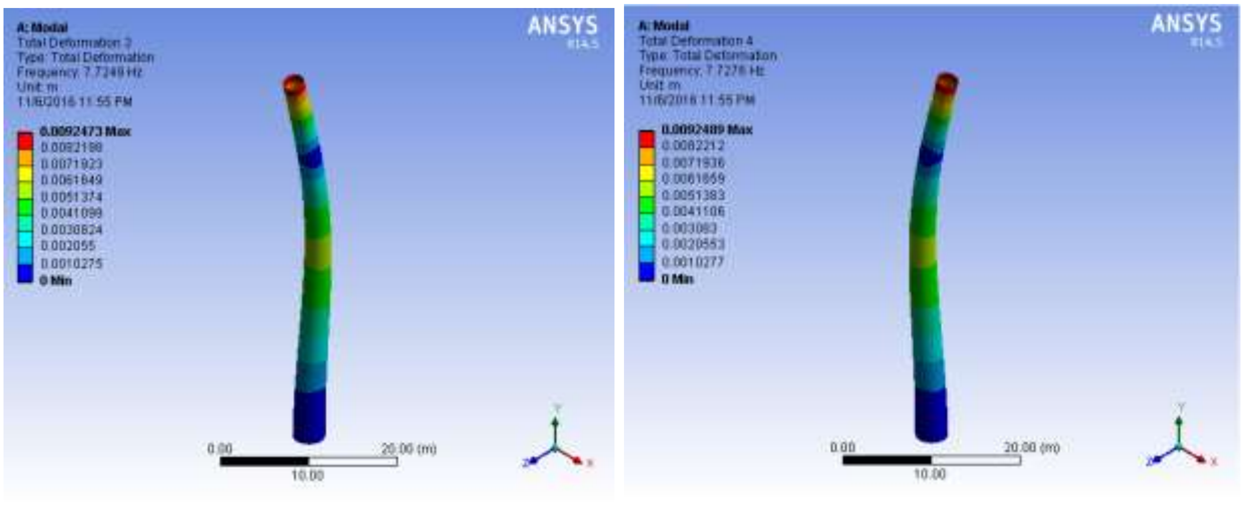

Figure 3.12 : 3rd & 4th Mode Shape of Tower 2 at NF 7.73Hz & 7.73Hz respectively

3.12 TOWER WITH VERTICAL STIFFENER [TOWER 3]

3.12.1 NATURAL FREQUENCY OF TOWER 3

Table 3.6: Natural Frequency of Tower 3

Mode	Frequency [Hz]
1	1.85
2	1.85
3	7.13
4	7.19

Table 3.7: Meshing Statistics of Tower 3

Nodes	565923
Elements	277475

3.12.2 MODE SHAPES OF TOWER 3

In Fig.3.13 and Fig.3.14, mode shapes or deformation of the tower 2 are shown at different natural frequency.

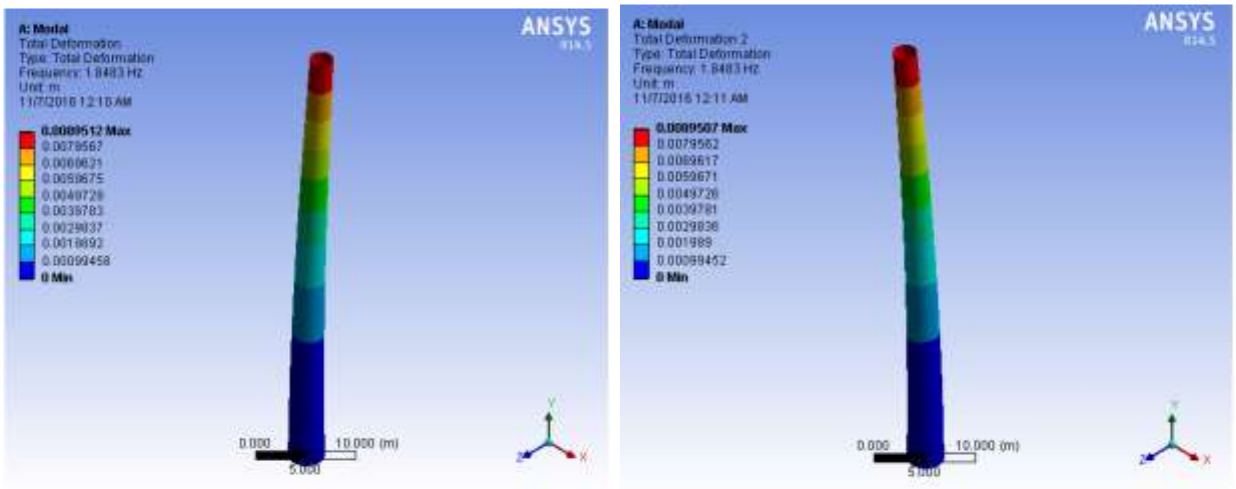

Figure 3.13 : 1st & 2nd Mode Shape of Tower 3 at NF 1.85Hz & 1.85Hz respectively

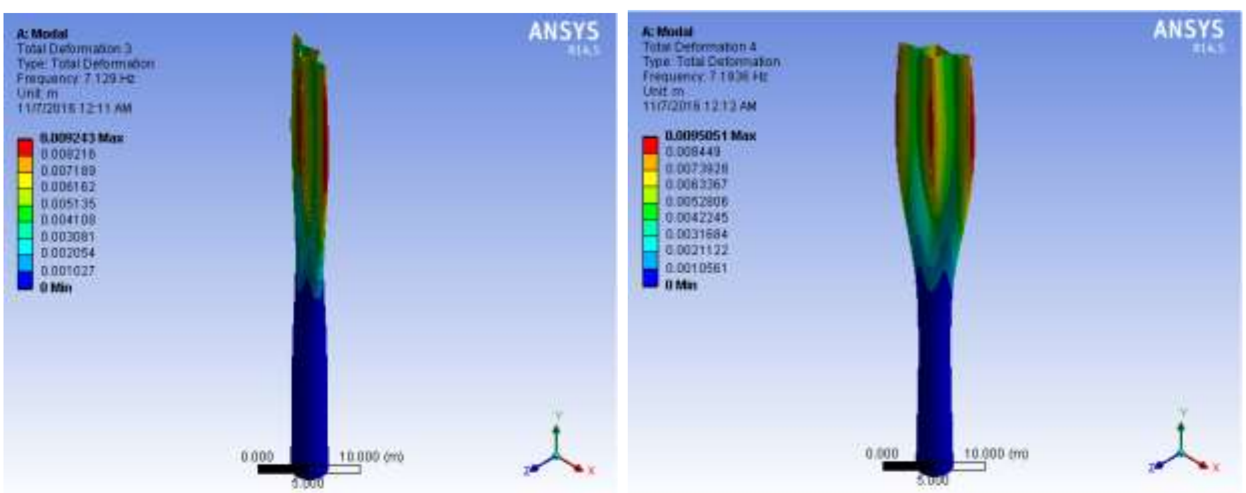

Figure 3.14 : 3rd & 4th Mode Shape of Tower 3 at NF 7.13Hz & 7.13Hz

3.13 HARMONIC RESPONSE ANALYSIS

In a structural system, any sustained cyclic load will produce a sustained cyclic or harmonic response. Harmonic analysis results are used to determine the steady-state response of a linear structure to loads that vary sinusoidally (harmonically) with time, thus enabling you to verify whether or not your designs will successfully overcome resonance, fatigue, and other harmful effects of forced vibrations.

In this analysis all loads as well as the structure's response vary sinusoidally at the same frequency. A typical harmonic analysis will calculate the response of the structure to cyclic loads over a frequency range (a sine sweep) and obtain a graph of some response quantity (usually displacements) versus frequency. "Peak" responses are then identified from graphs of response vs. frequency and stresses are then reviewed at those peak frequencies.

Here we are going to find the harmonic response of von-mises stress and harmonic response of total deflection of the towers. The bottom of the tower is considered as fixed supported.

3.14 RESONANCE

A certain system has more than one natural frequency. If the frequency of the external force coincides with one of the natural frequencies of the system, a condition known as

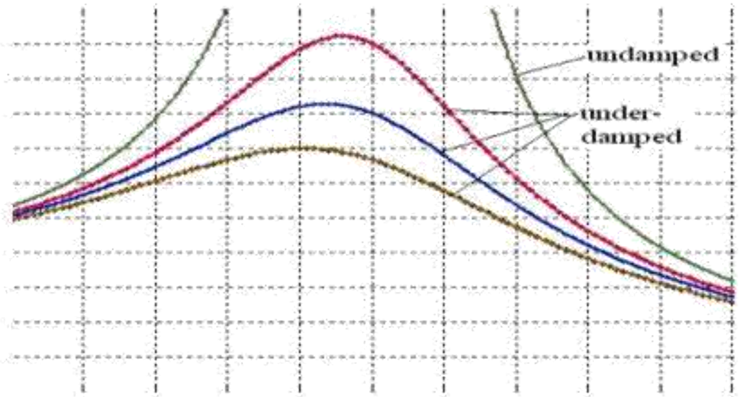

Figure 3.15 : Resonance Curve

resonance occurs. When resonance happens, the amplitude of vibration will increase without bound and is governed only by the amount of damping present in the system and the system undergoes dangerously large oscillations. Therefore, in order to avoid disastrous effects resulting from very large amplitude of vibration at resonance the natural frequency of a system must be known and properly taken care of. Otherwise failures of such structures as buildings, bridges, turbines and airplane wings maybe occurred.

3.15 HARMONIC RESPONSE OF VON MISES STRESS & TOTAL DEFLECTION OF TOWERS

In harmonic analysis wind load is applied only in a particular section of the tower which is 0° to 30°, shown in the Fig.3.2 and the wind loads are given in Table 3.8. The frequency range over which the harmonic response analyzed is in between 0.5 to 8 Hz. Harmonic response of von-mises stress and total deflection of the tower are discussed in the following sections.

Table 3.8 : Maximum wind pressure along the tower (Pa)

Angle / Vertical zone	(0°, 30°)
0-2 m	975
2-50 m	2390

3.15.1 TOWER WITHOUT RINGS [TOWER 1]

Harmonic response of von-mises stress of tower 1 is shown in Fig.3.16. The maximum von-stress of tower 1 is 72.39 MPa, less than the value of modulus of elasticity of the material of the structure and the stress is allowable.

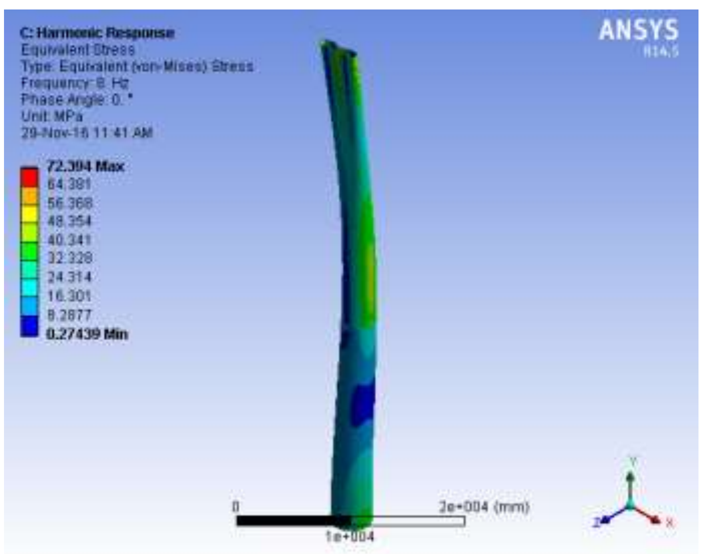

Figure 3.16 : Harmonic Response of Von-Mises Stress of Tower 1

Harmonic response of total deflection of the tower 1 is shown in the Fig.3.17. The maximum total deflection of the tower 1 is 38.58 mm and maximum deflection occurs at the top of the tower 1.

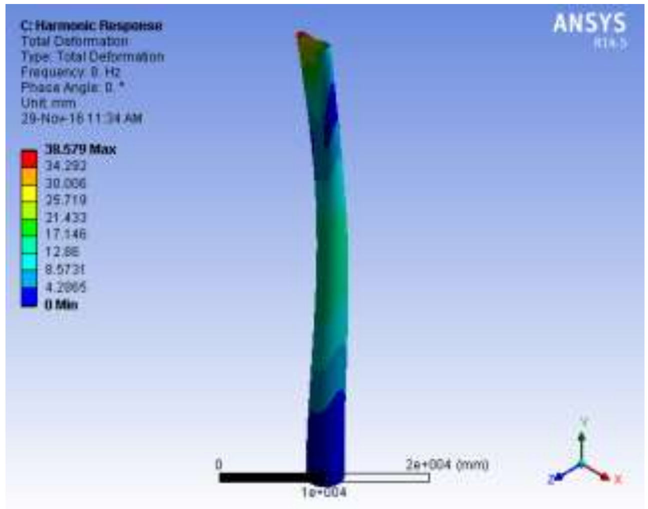

Figure 3.17 : Harmonic Response of Total Deflection of Tower 1

The amplitude of stress at different frequency is shown in Table 3.9. Maximum amplitude happens when resonance occurs at frequency around 6.5 Hz because it matches with natural frequency of the tower 1. The graph of amplitude vs. frequency is given in Fig.3.18.

Table 3.9 : Amplitude of Stress at Different Frequency of Tower 1

Tabular Data

	Frequency [Hz]	Amplitude [MPa]	Phase Angle [°]
1	1.	0.26023	180.
2	1.5	0.26686	180.
3	2.	0.27689	180.
4	2.5	0.29083	180.
5	3.	0.31017	180.
6	3.5	0.33696	180.
7	4.	0.37489	180.
8	4.5	0.43101	180.
9	5.	0.5205	180.
10	5.5	0.68334	180.
11	6.	1.0704	180.
12	6.5	3.2163	180.
13	7.	2.2053	0.
14	7.5	0.67398	0.
15	8.	0.30106	0.

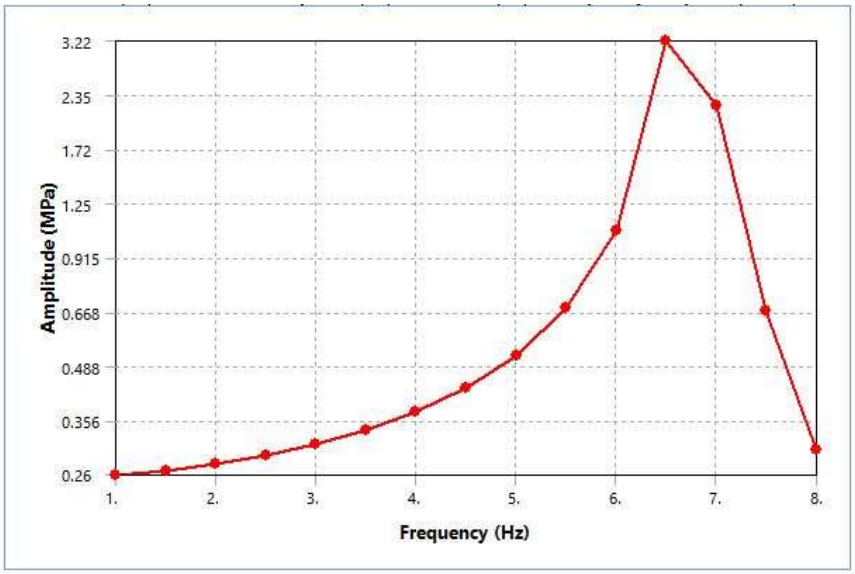

Figure 3.18 : Amplitude of Stress at Different Frequency of Tower 1

The amplitude of deflection of tower 1 at different frequency is shown in Table 3.10. The variation of amplitude of deflection at different frequency is also represented as a graph in Fig.3.19. Maximum deflection occurs at frequency around 2 Hz which is similar to the natural frequency of tower 1. At this time resonance occurs.

Table 3.10 : Amplitude of Deflection at Different Frequency of Tower 1

Tabular Data

	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
1	1.	17.374	180.
2	1.5	33.831	180.
3	2.	99.202	0.
4	2.5	16.156	0.
5	3.	7.8905	0.
6	3.5	4.8549	0.
7	4.	3.3119	0.
8	4.5	2.3877	0.
9	5.	1.7702	0.
10	5.5	1.3164	0.
11	6.	0.94079	0.
12	6.5	0.52262	0.
13	7.	0.2739	0.
14	7.5	1.0018	180.
15	8.	4.4252	0.

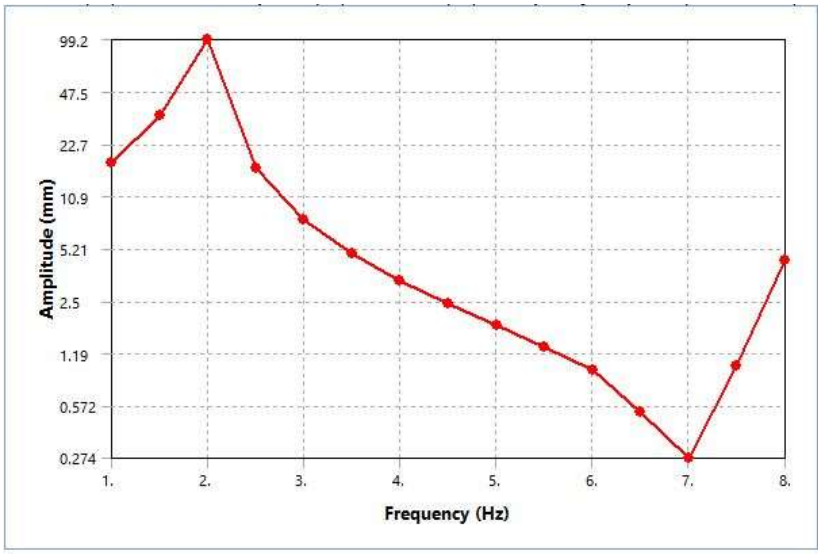

Figure 3.19 : Amplitude of Deflection at Different Frequency of Tower 1

3.15.2 TOWER WITH STIFFENING RING [TOWER 2]

Harmonic response of von-mises stress of tower 2 is shown in Fig.3.16. The maximum von-stress of tower 2 is 39.06 MPa, less than the value of modulus of elasticity of the material of the structure and also the von-mises stress of tower 1. It proves that strength increases.

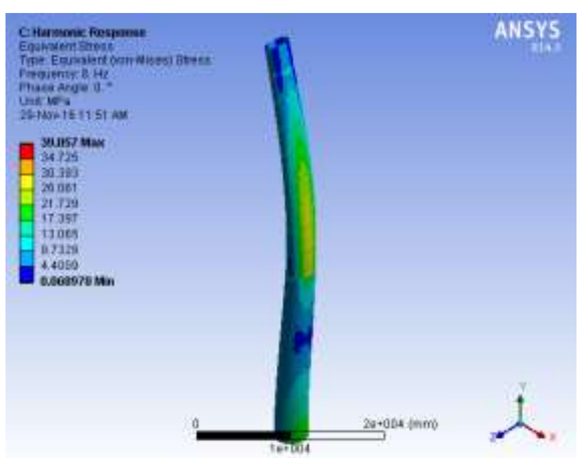

Figure 3.20 : Harmonic Response of Von-Mises Stress of Tower 2

Harmonic response of total deflection of the tower 2 is shown in the Fig.3.21. The maximum total deflection of the tower 2 is 15.35 mm and maximum deflection occurs at the top. The total deflection of tower 2 is less than the tower 1. It means that the strength of the tower increases.

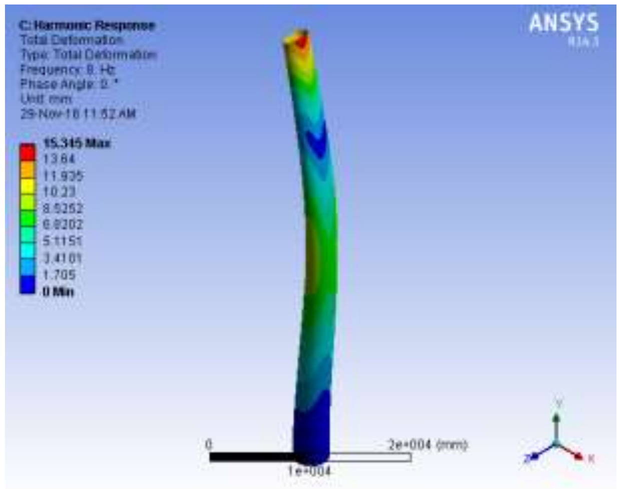

Figure 3.21: Harmonic Response of Total Deflection of Tower 2

The amplitude of stress at different frequency is shown in Table 3.11. Maximum amplitude of stress happens when resonance occurs at frequency around 8 Hz because it matches with natural frequency of the tower 2. The graph of amplitude vs. frequency is given in Fig.3.22.

Table 3.11: Amplitude of Stress at Different Frequency of Tower 2

Tabular Data

	Frequency [Hz]	Amplitude [MPa]	Phase Angle [°]
1	1.	0.13625	180.
2	1.5	0.13813	180.
3	2.	0.13876	180.
4	2.5	0.14261	180.
5	3.	0.14661	180.
6	3.5	0.15153	180.
7	4.	0.15759	180.
8	4.5	0.16507	180.
9	5.	0.17431	180.
10	5.5	0.1858	180.
11	6.	0.20027	180.
12	6.5	0.21883	180.
13	7.	0.24328	180.
14	7.5	0.27734	180.
15	8.	0.32087	180.

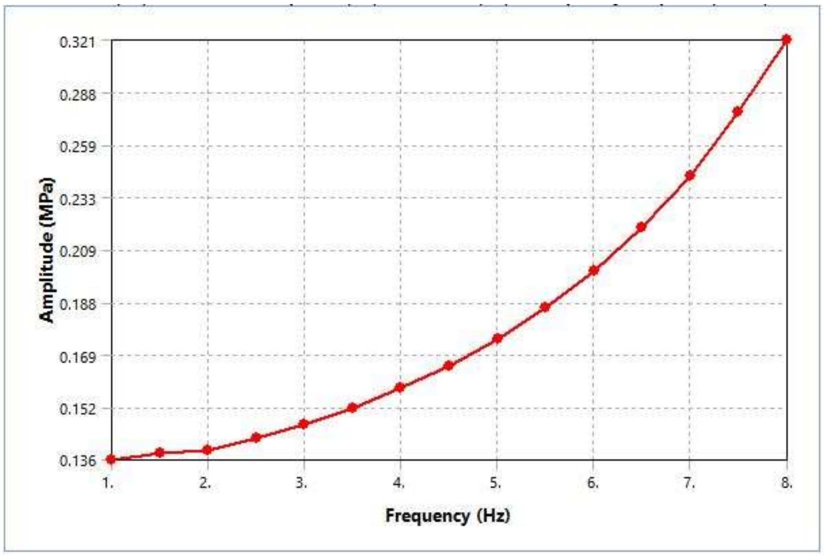

Figure 3.22: Amplitude of Stress at Different Frequency of Tower 2

The amplitude of deflection of tower 2 at different frequency is shown in Table 3.12. The variation of amplitude of deflection at different frequency is also represented as a graph in Fig.3.23. Maximum deflection occurs at frequency around 2 Hz which is similar to the natural frequency of tower 2. At this time resonance occurs.

Table 3.12: Amplitude of Deflection at Different Frequency of Tower 2

Tabular Data

	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
1	1.	14.52	180.
2	1.5	30.466	180.
3	2.	54.237	0.
4	2.5	11.644	0.
5	3.	5.8449	0.
6	3.5	3.6144	0.
7	4.	2.4561	0.
8	4.5	1.7511	0.
9	5.	1.2716	0.
10	5.5	0.91042	0.
11	6.	0.6012	0.
12	6.5	0.27598	0.
13	7.	0.2295	180.
14	7.5	2.3642	180.
15	8.	2.9858	0.

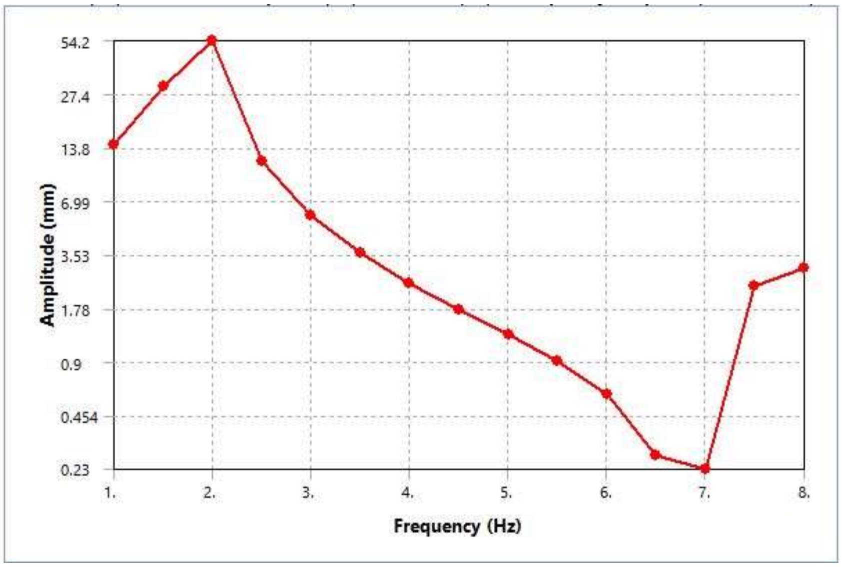

Figure 3.23: Amplitude of Deflection at Different Frequency of Tower 2

3.15.3 TOWER WITH VERTICAL STIFFENER [TOWER 3]

Harmonic response of von-mises stress of tower 3 is shown in Fig.3.24. The maximum von-stress of tower 3 is 67.57 MPa, less than the value of modulus of elasticity of the material of the structure and also the von-mises stress of tower 1 but greater than the von-mises stress of tower 2. It proves that strength of tower 3 is less than tower 2 but greater than tower 1 in case of harmonic response.

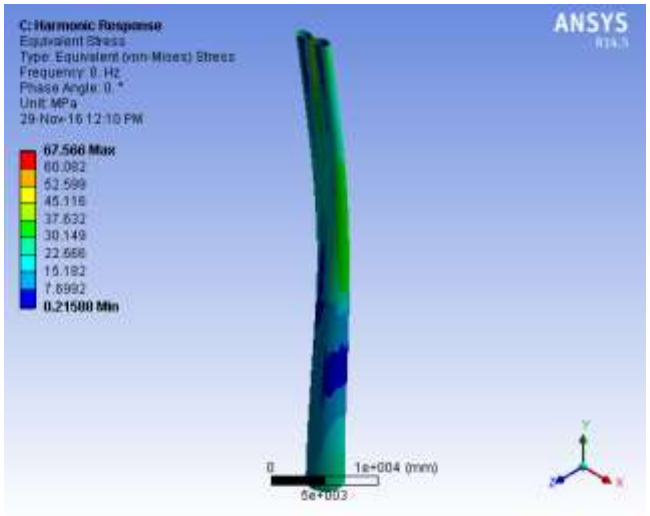

Figure 3.24: Harmonic Response of Von-Mises Stress of Tower 3

Harmonic response of total deflection of the tower 3 is shown in the Fig.3.25. The maximum total deflection of the tower 2 is 31.6 mm and it occurs at the top. The total deflection of tower 3 is less than the tower 1 but greater than tower 2. It means that the strength of the tower is more than tower 1 but less than tower 2.

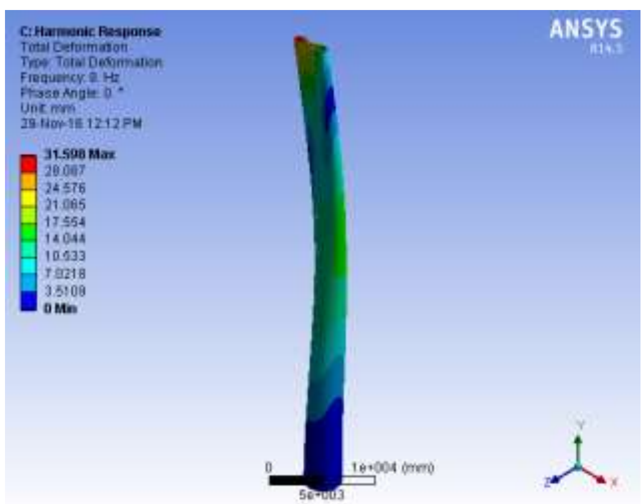

Figure 3.25: Harmonic Response of Total Deflection of Tower 3

The amplitude of stress at different frequency is shown in Table 3.13. Maximum amplitude of stress happens when resonance occurs at frequency around 7 Hz because it matches with natural frequency of the tower 3. The graph of amplitude vs. frequency is given in Fig.3.26.

Table 3.13: Amplitude of Stress at Different Frequency of Tower 3

Tabular Data

	Frequency [Hz]	Amplitude [MPa]	Phase Angle [°]
1	1.	0.28519	180.
2	1.5	0.29099	180.
3	2.	0.30125	180.
4	2.5	0.31294	180.
5	3.	0.32961	180.
6	3.5	0.35214	180.
7	4.	0.38284	180.
8	4.5	0.42583	180.
9	5.	0.48896	180.
10	5.5	0.58948	180.
11	6.	0.77401	180.
12	6.5	1.2308	180.
13	7.	4.7035	180.
14	7.5	1.7128	0.
15	8.	0.49853	0.

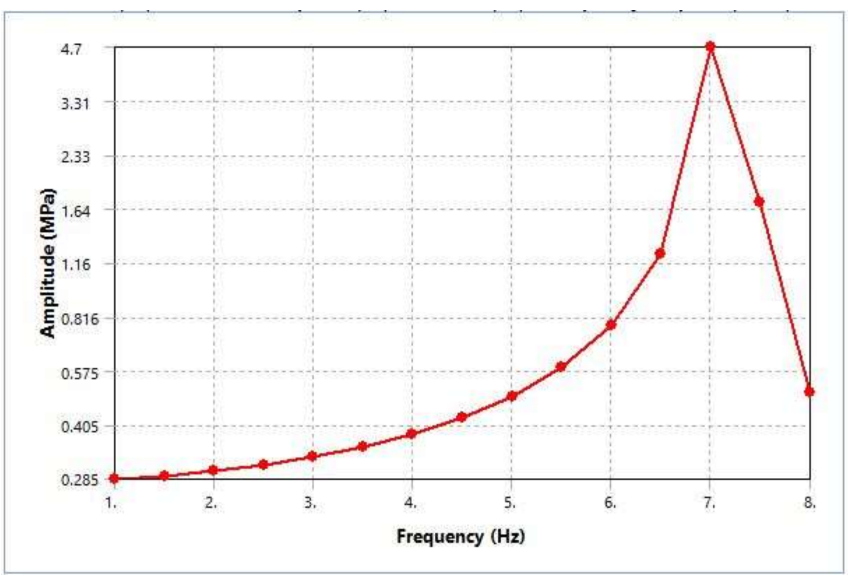

Figure 3.26: Amplitude of Stress at Different Frequency of Tower 3

The amplitude of deflection of tower 3 at different frequency is shown in Table 3.14. The variation of amplitude of deflection at different frequency is also represented as a graph in

Fig.3.27. Maximum deflection happens when resonance occurs at frequency around 2 Hz because it matches with the natural frequency of tower 3.

Table 3.14: Amplitude of Deflection at Different Frequency of Tower 3

Tabular Data

	Frequency [Hz]	Amplitude [mm]	Phase Angle [°]
1	1.	16.327	180.
2	1.5	33.655	180.
3	2.	66.705	0.
4	2.5	13.599	0.
5	3.	6.8031	0.
6	3.5	4.2177	0.
7	4.	2.8836	0.
8	4.5	2.0774	0.
9	5.	1.5351	0.
10	5.5	1.1347	0.
11	6.	0.80485	0.
12	6.5	0.4828	0.
13	7.	8.9653e-002	0.
14	7.5	1.1681	180.
15	8.	4.2244	0.

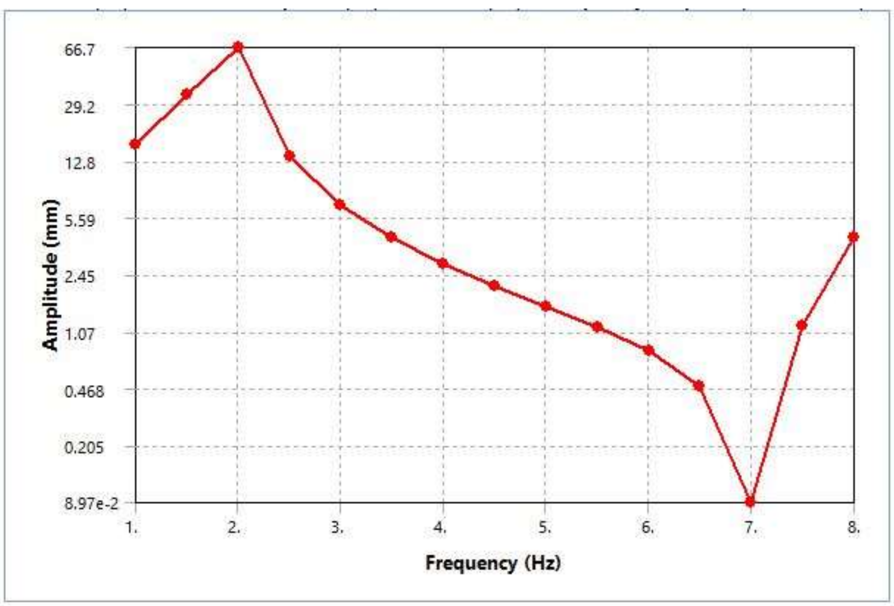

Figure 3.27: Amplitude of Deflection at Different Frequency of Tower 3

CHAPTER 4 : RESULT AND DISCUSSION

4.1 RESULT

The cases of three wind turbine towers with or without stiffening rings have been modeled by using SolidWorks and numerical simulation has been done in ANSYS Workbench 14.5. The results of numerical solution are displayed in Tables 4.1, 4.2 and 4.3 which show the maximum von-mises stress, maximum total deflection, natural frequencies and harmonic response of von-mises stress and total deflection.

Table 4.1: Maximum Von-Mises stress & Total Deflection of Towers

Tower	Maximum Von-Mises Stress (MPa)	Maximum Total Deflection (mm)
Tower 1	54.28	59.34
Tower 2	49.97	54.99
Tower 3	47.39	52.74

Table 4.2: Natural Frequencies of Towers

Mode	NF of Tower 1 (Hz)	NF of Tower 2 (Hz)	NF of Tower 3 (Hz)
1st	1.89	1.84	1.85
2nd	1.89	1.84	1.85
3rd	6.72	7.73	7.13
4th	6.76	7.73	7.19

In this analysis our main objective is to find how the strength of wind turbine towers vary with or without stiffener. Von-mises stress of tower without stiffener is 54.28 MPa and when stiffening rings are used in the structure internally it reduces to 49.97 MPa and further when vertical stiffener are used instead of stiffening ring it again reduces and becomes 47.39 MPa. Also total deflection of tower without stiffener is 59.34 mm and when stiffening rings are used in the structure internally it reduces to 54.99 mm and further when vertical stiffener are used instead of stiffening ring it again reduces and becomes 52.74 mm. From this analysis, it can be said that stiffeners increase the strength of the tower structure. Again in between stiffening ring and vertical stiffener when vertical stiffener is used instead of stiffening rings, the strength of the tower increases more.

4.2 CONCLUSION

The present research work concerns the investigation of the strength of the wind turbine towers under wind load. The von-mises stress and the deflection of the towers are analyzed when towers with (stiffening ring and vertical stiffener) or without stiffener has been considered. From analysis in can be said that using of vertical stiffener is more efficient. The natural frequencies and mode shapes have been obtained by ignoring the mass of the nacelle-rotor system at the top of tower in order to study the effect of the tower design on its own dynamic behavior. However, such concentrated mass should be considered if the entire wind turbine system is to be examined because the mass of the nacelle-rotor system can account for more than 30% of the total mass.

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