Structural Evaluation of Steel Adapter and Door Type Ring Stiffener in Wind Turbine Tower for Certification

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***Abstract*— The steel consumption in steel towers for wind turbines in the period 2007-2009 has reach about 3.5 million tonnes of steel. The steel tower is about 20% of the total costs for the wind turbine. Optimization of the steel tower using improved assembling techniques and higher steel grades has targeted savings of about 10% of the tower costs. The first being an investigation for an improvement of the existing flange detail using an available technique from bridge construction to remedy unavoidable imperfections in the joint. The second is proposing a use of the friction type joint to allow higher strains in the shell. Creating a more slender shell is causing needs to review the stability issues and detailing such as door openings and optimizing door stiffening rings by varying plate thickness for structural standpoint. With the light of the above, the present paper demonstrate the static structural evaluation of steel adapter and door type ring stiffener of a wind turbine tower by making use of blend of analytical equations and European standards design codes. Finite element analysis has been effectively utilized for the verification of design calculation for extreme loads as well as for fatigue loads, considering the life of tower to be around 20 years.**

Keywords— Steel tower, door type ring stiffener, wind turbine, fatigue loading, optimization, finite element analysis

I. INTRODUCTION

When countries around the world were developing into industrialized and developed nations, renewable energy resources were not developed on a large scale. Fossil fuels, such as coal, oil, and natural gas, were abundant and cheap so the world's wealthy nations grew fast. Today, as the world watches developing nations turn into industrial power-houses; many people are advising that these newly developed nations start with renewable energy resources in order to save money as well as prevent more greenhouse gasses from entering our world's atmosphere. Therefore, a renewable source, such as wind is becoming a valuable resource around the world[1]. Wind power is the conversion of wind energy into a useful form of energy. A blade acts much like an airplane wing. When the wind blows; a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range.

Wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modeling is used to determine the optimum tower height, control systems, number of blades and blade shape. Wind turbines convert wind energy to electricity for distribution. Conventional horizontal axis turbines can be divided into three components. The rotor component, which is approximately 20% of the wind turbine cost, includes the blades for converting wind energy to low speed rotational energy. The generator component, which is approximately 34% of the wind turbine cost, includes the electrical generator, the control electronics, and most likely a gearbox. The structural support component, which is approximately 15% of the wind turbine cost, includes the tower and rotor yaw mechanism[2].

The work done by different researchers on wind turbine development lead the windmill initially developed to mill the food grain into one of the words emerging green energy production method. There are several scientists and researched who worked on the development of wind turbine/wind turbine components. Ring flanges are used in standard connections in tubular structures, especially in towers for wind energy converters. The design of ring flange connections is generally performed by using an approach of Petersen. The load bearing capacity can simply be calculated with the plastic hinge theory considering three failure mechanisms of the critical segment. The flange is considered as a beam and failure modes are defined with plastic hinges developing at different locations. Initially three failure modes were defined by Petersen [3]. Finite element method simulations are used to conduct stress analyses and to optimize the tower geometry [4]. The approaches for fatigue analyses used in the wind industry highlights the particular conditions for the design of these dynamically loaded components and the crack initiation life is predicted using methods of damage accumulation which include hysteresis properties of the material involved and stress or strain histories at highly stressed locations [5]. Fatigue analyses of weldments require detailed knowledge of the stress fields in critical regions[6]. The stress information is subsequently used for finding high local stresses where fatigue cracks may initiate and for calculating stress intensity factors and fatigue crack growth [7].

II. PROBLEM DESCRIPTION

The present work is carried out with two problem definitions of a wind turbine. In the first case of the study, we need do carry out static structural analysis of a steel adapter of a wind turbine. The analysis includes the pre tensioning of bolts, linear static analysis near the weldment and flange connection regions and to estimate the fatigue life of a steel adapter of a wind turbine tower. In second case of the present work, we have to carry out the structural analysis of a wind turbine tower door by varying the thickness of the ring type door stiffener.

III. STATIC STUCTURAL ANLYSIS OF STEEL ADAPTERS

A. Design conditions

Maximum Moment = 9720 kNm
(Due to wind load)
Axial compression =1900kN
(Weight of the tower + Nacelle + rotor)

Steel Adapters are mechanical machine elements used for structural integrity of machine elements commonly found in offshore jackets, decks, oil and gas equipments, pipe line design, wind tunnels, vacuum tunnels and so on. Similar application is found in renewable wind turbine towers where the tower height is approximately 70-80 m.Here, a single structure of 80M height is impossible without adapter piece. Hence, they play a vital role as integrators.

TABLE I. MATERIL PROPERTIES

Material	Specification	Value
Steel Adapter S355 High grade steel (hot rolled)	Modulus of Elasticity	210 GPa
	Poisson Ratio	0.3
	Density	7850 kg/mm^3
Bolt	High grade steel 10.9 grade	
Concrete	Modulus of Elasticity	55 GPa
	Poisson Ratio	0.19
	Density	250 kg/mm^3
	No. of bolts top flange	24
	No. of bolts bottom flange	96
	Design Code	DIN Standards

B. Design considerations[8]

The tower should sustain a max moment of 1850 kNm
The tower should sustain a max compressive load = 750kN
Modeling: ANSYS Software is considered for geometric modeling as shown in Figure 1 and 3.

Meshing: Plane 42 Quad 4noded elements with solid 95 elements is used for meshing as shown in Figure 5.Rated Power of 2000 kW and Hub height of 67 m.

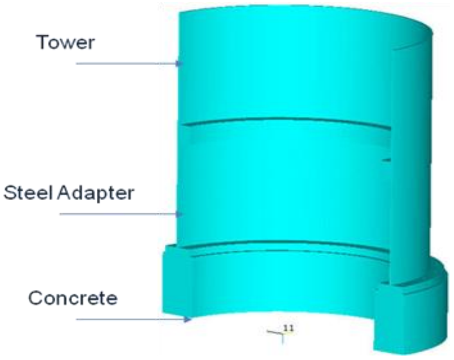


Fig. 1. Model of Steel Adapter Assembly

The loads considered for Tower Top verification are given below and these loads are given by Hamburg head office Dept of Civil Engineering and Rotor Blades are M_Z = 9720 KNm and F_Y = -1845 KN. Pre-Tensions applied for upper flange and lower flange are 1680 kN and 1380 kN respectively as shown in Figure 2 and 4.

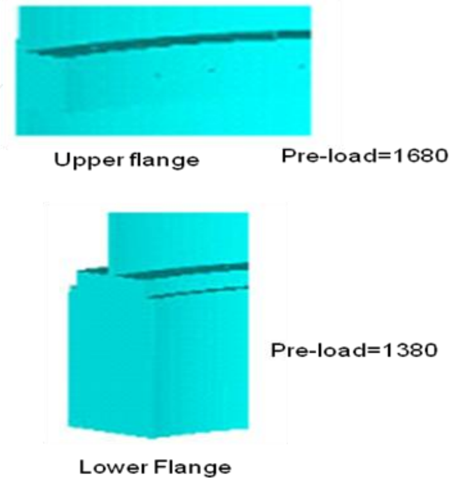


Fig. 2. Pre-tension loading for upper and lower flange

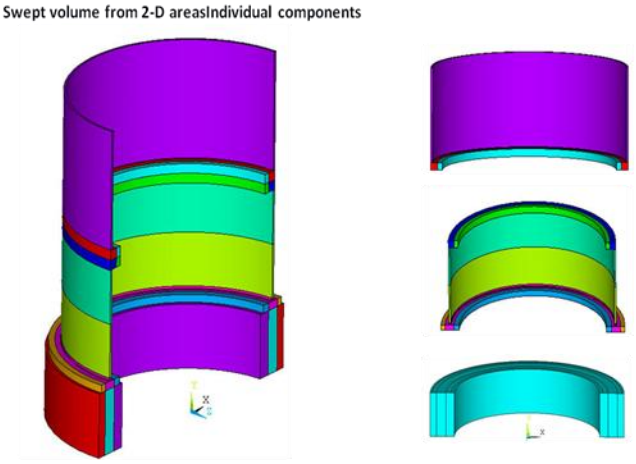


Fig. 3. Geometry of steel adapter assembly

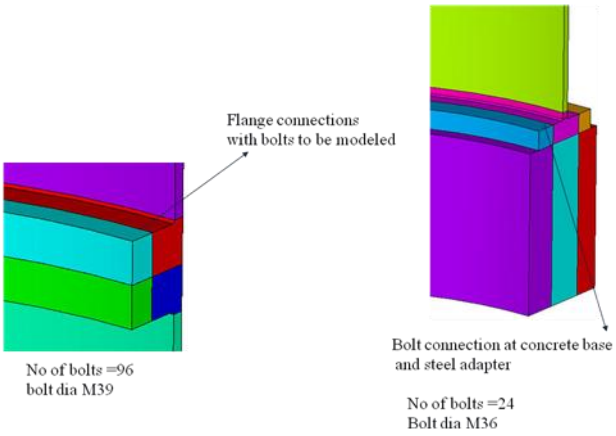


Fig. 4. Bolts area of interest

C. *Design of bolt for flane connection in steel adopters*

From DDHB (Lingaiah) for M42 Bolt size following parameter is taken

Major Diameter, d=42 mm
Minor Diameter, d_1 =37.092523 mm
Pitch Diameter, d_2= 39.401924 mm
Pitch of thread, p = 4 mm

Initial stress due to screwing up forces:

Tensile stress due to stretching of bolts initial tightening load for making a fluid tight joint.

$F_i = 2804.69 \times d$
$F_i = 117796.98$ N

If the bolt is not initially stressed, then the maximum safe axial load

$F=A_s \times \sigma$ (1)

Where:
Permissible stress in Bolt Material, σ=1040 MPa (From DDHB)
Stress Area of Bolt,
$A_s = \pi/4 \times (d_1+d_2/2)^2$ (2)
A_s=1149.06 mm²

Substitute A_s& σ values in above equation

F = 1040 ×1149.06
F= 1195.02 kN

Torsional Shear stress :

τ_t = (3)

Where:
Frictional Torque, $M_t = 0.2 \times F_a$
Applied Load, F_a = 750 KN
M_t = 150000 N mm

Torsional Shear Stress τ_t = 555.25 N/ mm²

Shear stress across threads :

τ= (4)

Where:
Number of Threads in Engaged, i= 21 mm
Width of Thread at root, b= 0.471 mm
Shear Stress, τ= 1036.81 N/mm²

Crushing stress on thread:

σ_c = (5)

σ_c = 186.66 MPa

Bending stress:

σ_b = (6)

Where:
Length of shank of the Bolt, L= 84 mm
Difference in height between extreme corners of the nut or head, a= 0.25 mm
Young's modulus, E=2e5 N/mm²
σ_b = 297.61 N/mm²

Stress due to external forces

Tensile stress :

σ_t = (7)

Where:
Applied Load, F_a =750 kN
Core Area, A_c = (8)
A_c = 1080.594 mm²
σ_t = 694.062 N/mm²

Shear stress :

τ= (9)

Where:
Area of Bolt, A =
A = 1385.44 mm² .
Therefore, τ = 541.51 N/mm²

Combined stress :

Maximum Principal Shear stress,

τ_{max} = ½ (10)
τ_{max} = 643.166 MPa

Maximum principal normal stress,

σmax = ½ (11)
σ_{max} = 990.197 MPa
$\sigma_{max} < \sigma_t$

The design is safe.

Final Load on the Bolt:

$F_f = F_a + F_i$ (12)
F_f = 867.796 KN
$F_f < F$

The design is safe.

The finite element model consists of 51,504 elements and 66,042 Nodes.Tower-13758 elements, Concrete base - 5760 elements and Adapter- 20736 elements

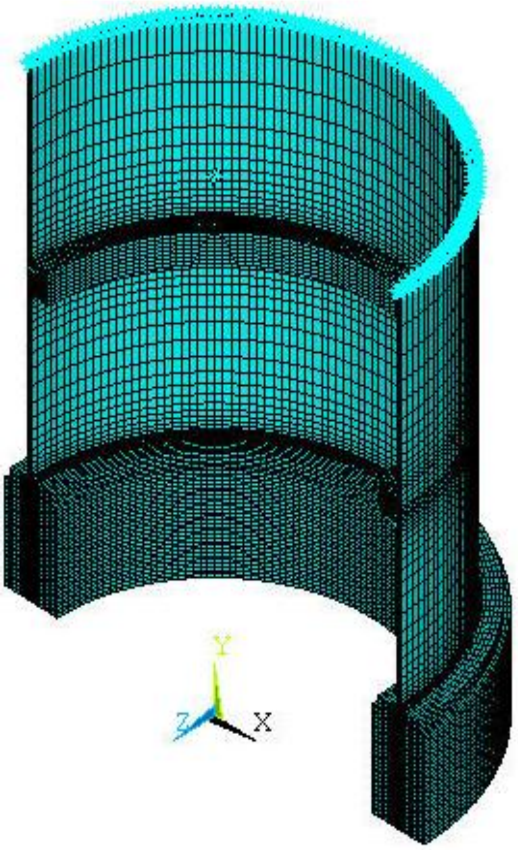


Fig. 5. Finite Element Model of steel tower

D. Boundary conditions

- Base of the Adapter is fixed in all DOF.
- Moment and Axial force is applied at pilot node at the centre.
- Through contact wizard (pilot node option)

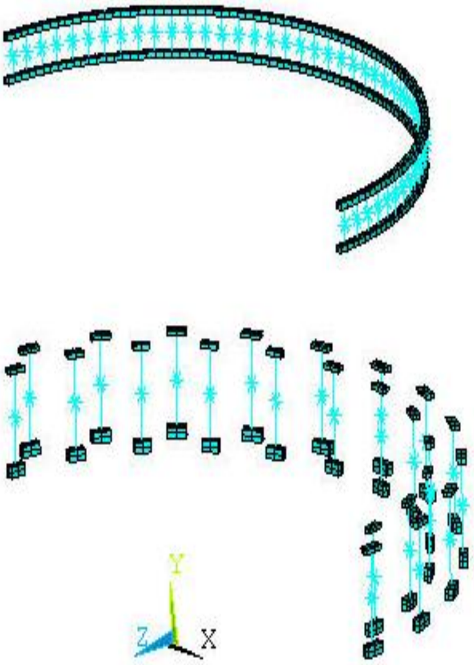


Fig. 6. Bolted connections to ensure the nodal connectivity

E. Results of steel adopter of wind turbine tower

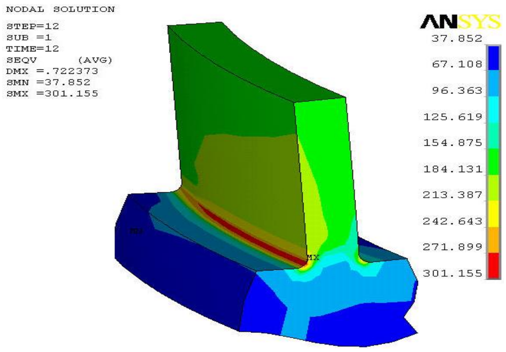


Fig. 7. Von mises plot for Tower Adapter bottom flange (radius) Nodal Solution

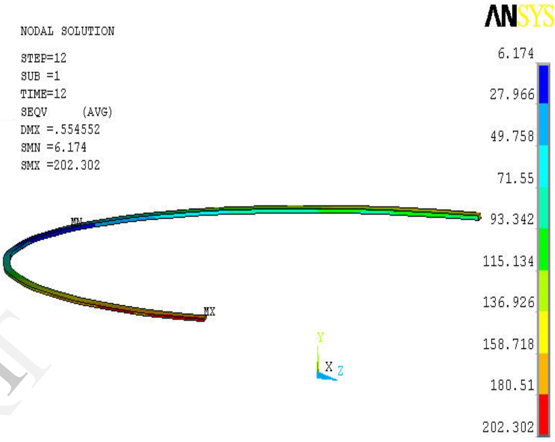


Fig. 8. Von mises plot for Tower Adapter bottom weld seem (Nodal Solution)

Maximum Von Mises stress of 301 MPa has occurred near the steel adapter bottom flange region which indicates the crack initiation of the bottom flange as shown in Figure 7. But Figure 8 shows the maximum Von Mises stress of 202 MPa near the weld seem of the bottom flange region which is well within the limits.

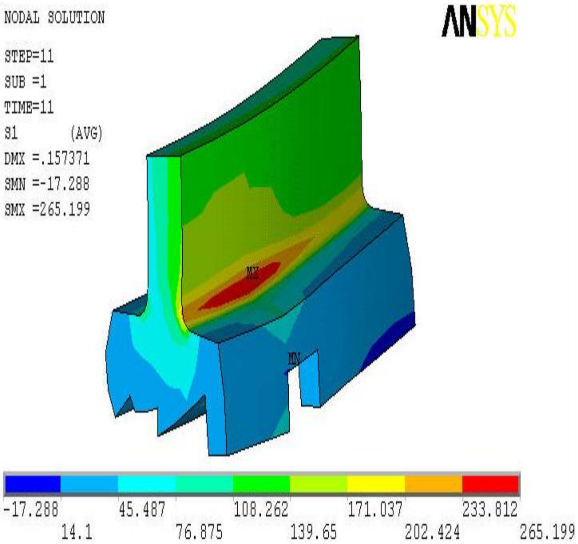


Fig. 9. Principal Stress Plot-I for Tower Adapter bottom flange (Radius) Nodal Solution

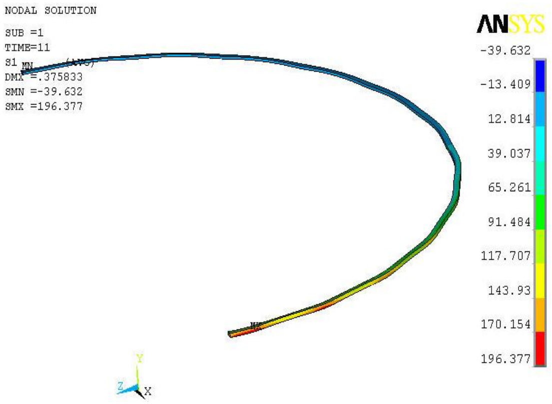


Fig. 10. Principal Stress Plot-I for Tower Adapter bottom weld seem (Nodal Solution)

Maximum principal stress of 265 MPa has occurred near the steel adapter bottom flange region which helps in life estimation of the flange due to fatigue as shown in Figure 9. But Figure 10 shows the maximum principal stress of 196 MPa near the weldseem of the bottom flange region which is well within the limits.

IV. STRUCTURAL EVALUATION OF RING TYPE DOOR STIFFENER IN WIND TURBINE TOWER

A. Preliminary design considerations

- The foundation of the tower is made fixed rigidly to the ground and bolts are arranged in zigzag fashion.
- Elliptical door placed in vertical direction helps in utilization of space over circumferential area compared elliptical door placed in horizontal direction and circular door.
- The mass is assumed to be rigidly attached to the bottom tower door frame.
- Material of tower door frame is linearly elastic, isotropic and homogeneous.
- Under any load combination (including any load safety factors), the material of the load bearing structural elements of the tower should remain in the linear elastic region of its stress-strain diagram i.e. no plastic deformation has occurred.
- Height of Tower is assumed to be 80 meters.
- Tower and door opening stiffener is assumed to be made out of S355 Steel [10].
- For thickness above 16 mm and up to 40 mm which is used in our door and tower bottom has allowable yield of 345 MPa.
- For wind turbine design a material safety factor of 1.1 is assumed hence Allowable stress is 345/1.1=313 MPa.
- Modeling: CATIA software is considered for geometric modeling as shown in Figure 11.

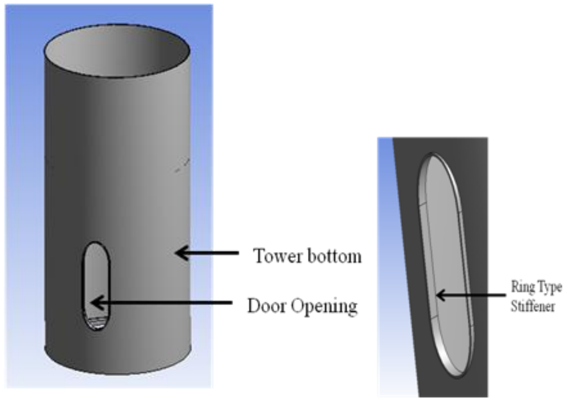
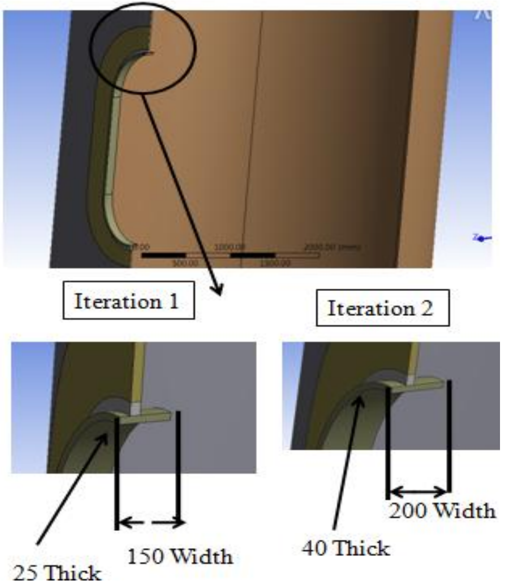


Fig. 11. Geometry of bottom tower with ring type stiffener door frame



All dimensions are in mm

Fig. 12. Dimensions of the tower cut out view shows the ring type door stiffener

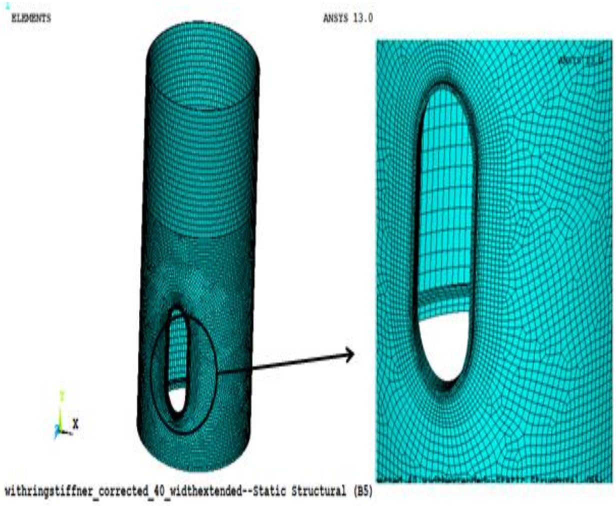
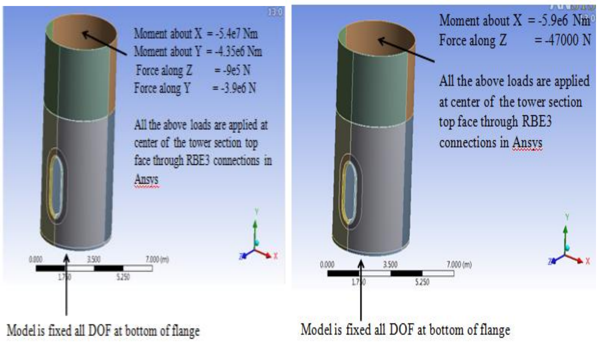


Fig. 13. FE Model of ring type door stiffener

Element type used for discritizing the geometry is higher order tet and hex element as shown in Figure 13, the total number of elements and nodes are 22676 and 133453 respectively.

B. Boundary conditions for static and fatigue loading


Moment about X = -5.4e7 Nm
Moment about Y = -4.35e6 Nm
Force along Z = -9e5 N
Force along Y = -3.9e6 N

All the above loads are applied at center of the tower section top face through RBE3 connections in Ansys

Model is fixed all DOF at bottom of flange

Moment about X = -5.9e6 Nm
Force along Z = -47000 N

All the above loads are applied at center of the tower section top face through RBE3 connections in Ansys

Model is fixed all DOF at bottom of flange

(A) (B)

Fig. 14. (A) Static loading (B) Fatigue loading

C. Results of wind turbine door ring type stiffener

The dimensioning of a structure or component depends primarily on the type of possible failure. If two or more types of loading occur simultaneously, the combined resulting stresses shall be assessed. As a rule, the ultimate limit state verifications shall be carried out with regard to the material and loading, using the following equivalent stress hypotheses. For ductile materials, the Von-Mises hypothesis, the maximum shear stress hypothesis or maximum shear strain energy hypothesis are used. Other hypotheses, such as the shear stress intensity may be used[9].

Von mises stress of 380 MPa is observed at the location of stiffener region for first iteration i.e. width of 150 mm and is greater than allowable stress and the Von mises stress reduced to 302 MPa for second iteration i.e. of stiffener width 200 mm and it is well below the allowable stress of 313 MPa as shown in Figure 15 and 16. Principal stress near the weld connection is averaged for three weld length away from Max stress at weld. Hence the Principal stress for weld is 21.8 MPa.

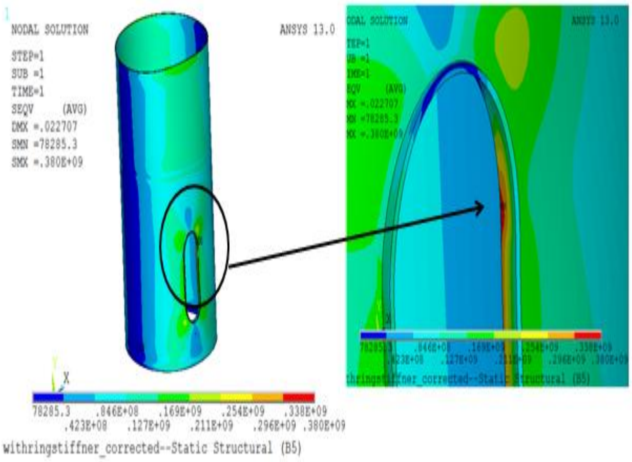


Fig. 15. Plot of Von mises result of first iteration

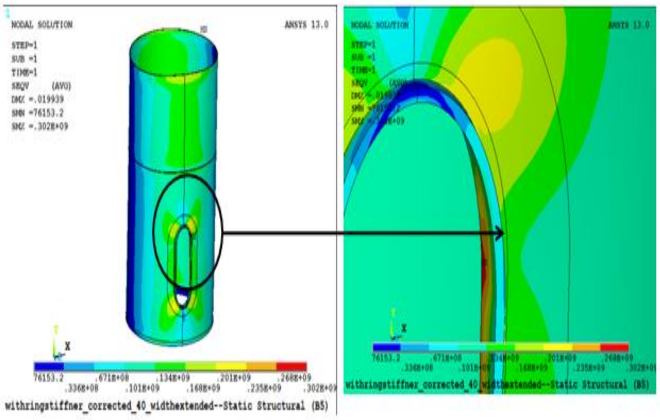


Fig. 16. Plot of Von mises result of second iteration

Max Principal stress in Ring stiffener is 30MPa and for wind turbine fatigue evaluation is done for weld as shown in Figure 17 and 18. Here the weld connection between the ring stiffener and the tower shell is evaluated.

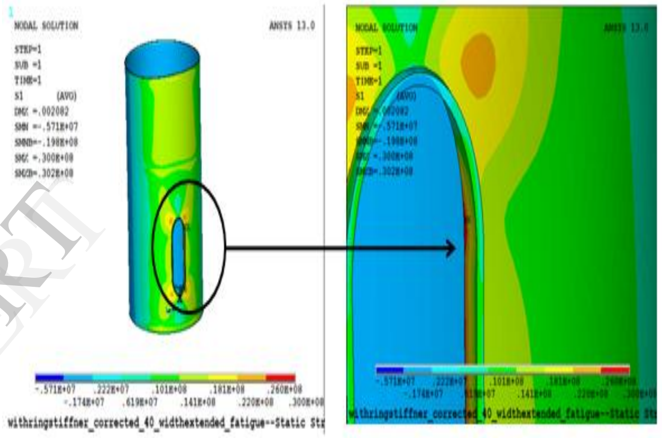


Fig. 17. Stress plots of fatigue analysis

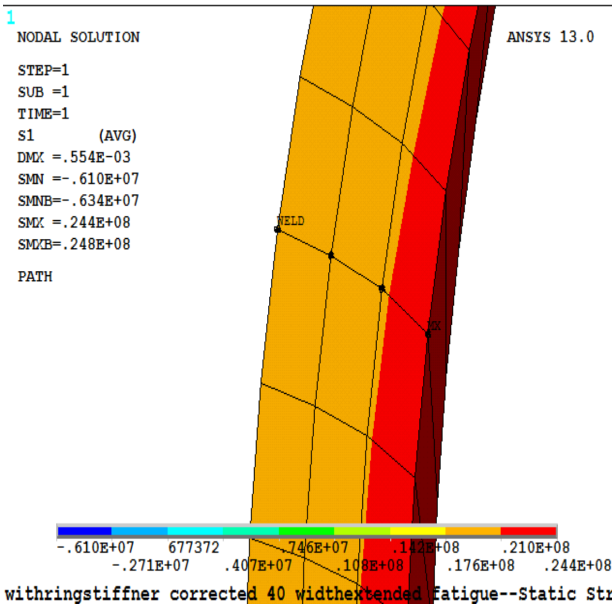


Fig. 18. Stress plots of fatigue analysis near weld connection region

Stress allowable for 1e8 cycles is (90/1.15).(2e6/1e8)^(1/4)= 29.4 N/mm^2.

Wind turbines are designed for specific fatigue cycles. For this wind turbine of 80m height we assume 1E8 Fatigue Cycles. Since weld Principal stress 21.8 N/mm^2 < 29.4 N/mm^2 Allowable fatigue stress the design is safe for fatigue.

V. CONCLUSIONS

The following are the conclusions made from the present work:

- Steel Adapter bottom flange radius has stress of 301 MPa which is within the design limits for extreme load case.
- Principal stress plots are obtained to estimate the life of the flange subjected to fatigue loading. Principal stress value near the steel tower bottom flange fillet radius of 270 MPa subjected to tension has been visualized which is within the fatigue design stress limits and principal stress of 196 MPa is visualized near weld seem region which is well within the limits.
- Static structural analysis of turbine door frame is carried out and stresses and displacement plots are obtained for two cases and it has been concluded that the stress and displacement value has reduced by increasing the width of the stiffener.
- Wind turbines are designed for specific fatigue cycles. For this wind turbine of 80m height we assume 1E8 fatigue cycles. Since the weld principal stress is within allowable limits, one can conclude our design is safe for fatigue for 20 years.

REFERENCES

[1] “Wind turbines”, Coherent Application Threads (CAT’s) Publication, Boston University.

[2] Cosgrove T. C. “Tension Control Bolts, Grade S10T, in Friction Grip Connections”, *The Steel Construction Institute*, Vol 4,2004

[3] Petersen, C.: Stahlbau (Steel Construction), 3. Edition: Vieweg-Verlag. Braunschweig, 1997 [in German]

[4] Eurocode 3: “Design of Steel structures; Part 1-1: General rules and rules and buildings”. DIN V ENV 1993-1-1,European Committee for Standardisation CEN. Brussels 1992.

[5] Milan Ristow and Ali Muhammad, “Fatigue Life of Wind Turbine Structural Components”, NAFEMS Seminar, Wiesbaden, Germany, November 10 - 11, 2010.

[6] Thomas Frese and Peter Dalhoff, “Fatigue Analysis of Bolted and Welded Joints”, NAFEMS Seminar: Fatigue Analysis, Wiesbaden, Germany.VDI 2230, February 2003

[7] MustafaAygul, “Fatigue Analysis of Welded Structures using the Finite Element Method”, Department of Civil and Environmental Engineering, Chalmers University Publication, Gothenburg, Sweden, 2010

[8] ChawinChantharasenawong, PattaramonJongpradist and SasarajLaoharatchapruek, “Preliminary Design of 1.5-MW Modular Wind Turbine”, 2nd TSME International Conference on Mechanical Engineering Vol. 19-21,Krabi, Thailand, October 2011.

[9] A. Chattopadhyay, G. Glinka, M. El-Zein, J. Qianand R. Formas, “Stress analysis and fatigue of welded structures”, Online ISSN1878-6669.

[10] Hani M. Negm and Karam Y. Maalawi,”Structural design optimization of wind turbine towers” , Journal of Computers and Structures, Volume 74, pp 649-666, 2000.