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Analysis of Wind Turbine Towers subjected to Blast Loading

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Abstract
The research work in this paper mainly focuses on the dynamic simulation of a High strength steel wind turbine tower subjected to blast loading in increasing order, conducted by using ABAQUS. The analysis of the wind turbine tower evaluates the response and performance of the structure when subjected to blast load levels in the form of TNT charges ranging from 500 kgs to 2000 kgs applied at the base and at the top of the tower respectively. The study focuses mainly on the key parameters such as Von Mises stress, displacement, and reaction forces in which the results indicate that the High strength steel wind turbine tower passes the Von Mises stress limit up to a blast load of 1500 kgs at the base but fails under higher loads of 1750 kgs and 2000 kgs respectively where stresses of the wind turbine tower exceeds the tensile strength of the material. Moreover, at the top of the tower, the structure fails at a low charge of 500 kgs demonstrating its vulnerability to the blast load. Displacement of the wind turbine tower surpasses its recommended limit for TNT charges beyond 1500 kgs at the base with a maximum displacement of 129.49 mm at 2000 kgs. The maximum reaction force recorded was 2890 KN at a TNT charge of 1750 kgs. The study concludes by revealing the findings of the limitations of High-strength steel wind turbine towers under extreme blast conditions and throws spotlight on the need for structural reinforcement or alternative designs and hybrid towers for the wind turbine for improved performance and use in high-risk environmental zones.
Keywords: *ABAQUS, Dynamic Simulation, Wind turbine tower, Blast Loading, High strength steel.*

1. Introduction
The adoption of renewable energy sources is becoming progressively more important in meeting the world energy needs and in reducing the harmful effects that the conventional energy sources has on the environment. The emphasis has turned towards utilizing the energy from naturally regenerating resources available as the globe looks for cleaner and more sustainable energy solutions. In addition to the mechanism for reducing greenhouse gas emissions, renewable energy resources also encourage the economic growth and energy security. Sustainable energy supplies are guaranteed by renewable energy sources, which draw their power from naturally occurring processes that replenish themselves over time. Renewable energy uses the power of abundant and largely untapped natural resources like sunlight, wind, water, and biomass instead of fossil fuels, which are of a finite quantity and will eventually get depleted. The structural framework of the wind turbine tower which supports the nacelle and rotor blades of wind turbines demonstrates that the wind turbine towers are an essential part of wind energy systems [1]. Design and engineering of the wind turbine towers are becoming very much crucial as the contribution to the wind energy sector rapidly developes in the field of renewable energy sources. In addition to having to withstand a variety of external stresses, these tower's strength and resistance are very much essential for maximizing the turbine's energy output. Wind turbines use the rotation of blades attached to a generator to transform the kinetic energy of the wind into electrical energy which experiences lot of stresses and also develop unwanted accidental loads in the worst case scenario. The wind turbine tower's height and stability are crucial to this process since they have a direct impact on the energy capture efficiency [2]. Higher the wind turbine towers higher will be the capabilities of the

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wind tubirne to capture more energy effectively, consistently and efficiently.

1.1 Different Types of Loads Acting on the Wind Turbine Tower

The different types of loads acting on the wind turbine tower can be differentiated into two types i.e Static loads and dynamic loads.nStatic loads includes loads such as dead loads, live loads, etc; and in the case of dynamic loads, loads such as wind load, seismic loads, aerodynamic load, cyclic load, operational loads, vibrational load, blast load, thermal load, impact load, ice load etc; takes place.

1.2 Influence of Blast Load on a Structure

The influence of blast loads on the various structures is significant which necessitates special consideration in the design to ensure the structure's safety and durability. An explosion exerts tremendous forces to the structure which it encounters by creating a short termed high-intensity pressure wave that rapidly radiates outward [3]. Depending on the blast's proximity and severity level, the intensity of these forces can result in quick and significant damage to the structure such as deformation, fracturing, or even collapse. It is vital that structures are engineered to efficiently absorb and release this energy (Figure 1). This can be achieved by utilizing reinforcing the materials, strategically placing the structural components, increasing the thickness of the materials and also by integrating dampening systems to mitigate the adverse effects of these dynamic loads at least up to certain extend or to completely dissipate it.

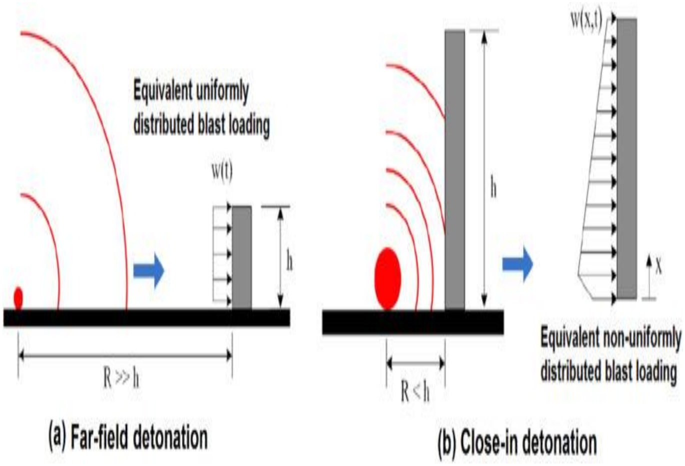

Figure 1 Representation of Blast Load Detonation Acting on the Structure

The influence of blast loads on a structure is one of the critical factor in the field of structural engineering particularly in the areas where the risk of explosions is very much high such as in industrial sites, military zones, and also in the urban environments where potential threat probability is very higher [4]. Proper analysis of the structure subjected to blast loads and its design considerations are very much essential in order to enhance the structure's ability to withstand the blast forces which will act on it in adverse events, thereby protecting both integrity of the structure and the safety of its occupants.

2. Methodology

The following methodology outlines the steps which are undertaken to model and simulate the response of a wind turbine tower of the specific material subjected to blast loading using ABAQUS which is a powerful finite element analysis (FEA) software. The Johnson-Cook material model which effectively represents the dynamic behaviour of the materials under high strain rates is employed. ABAQUS is one of the most powerful finite element analysis (FEA) software suite available and is widely used in the field of engineering and scientific research for simulating the behaviour of structures and materials subjected to various loading conditions [5]. It also includes a wide variety of material models which can help simulate the behaviour of materials such as metals, plastics, composites, rubber, and other different materials under different loading conditions. The inclusion of advanced material models like the Johnson-Cook model, Concrete Damage Plasticity, etc; is proven to be highly and particularly useful for high-strain-rate applications such as impact, blast, and crash simulations of the materials almost similar to real world. This capability of the application enables users to accurately predict the behaviour of the material under extreme conditions.

2.1 Johnson Cook Material Model

The Johnson-Cook (JC) material model is one of the widely used constitutive model that describes the behaviour of the specific materials under various conditions including the high strain rates, large strains and also varying temperature [6]. Johnson Cook Model is developed by the researchers named Gordon R. Johnson and William H. Cook in the early 1980s. This Johnson Cook model is particularly very

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well-suited for simulating the dynamic events such as impact, explosion and ballistic penetration where materials are subjected to very extreme loading conditions (Figure 2 & 3). Due to the model capabilities, robustness and versatility, the Johnson-Cook model has become a standard in the field of finite element analysis. **Mathematical Formulation of the Johnson-Cook Model:**

The Johnson-Cook constitutive model for the flow stress (σ) of a material is expressed as:

$$\sigma = (a + b\epsilon_p^n)(1 + c \cdot ln\frac{\dot{\epsilon}}{\dot{\epsilon}_0})(1 - (\frac{T - T_r}{T_{melt} - T_r})^m)$$

where:

a) ϵ is the equivalent plastic strain.
b) ϵ˙ is the plastic strain rate.
c) ϵ˙0 is the reference strain rate.
d) T is the homologous temperature
e) A is the yield strength of the material at the reference strain rate and room temperature.
f) B is the hardening modulus.
g) n is the strain hardening exponent.
h) C is the strain rate sensitivity coefficient.
i) m is the thermal softening exponent.

Parameters and Calibration of the Specific Materials:

In order to accurately utilize the Johnson-Cook material model the material-specific parameters such as (A, B, n, C, m, and ϵ˙0) should be calibrated. This calibration is typically done through the series of experiments such as quasi-static tensile test for strain hardening parameters and high-strain-rate test (like the split Hopkinson pressure bar test) for the results of strain rate sensitivity parameters. The thermal softening parameters of the materials are often obtained by conducting the high-temperature tests. The calibration process for the material specific parameters ensures that the JC model accurately reflect the material real-world behaviour under the given different loading conditions.

2.2 Modelling of The High Tensile Steel Wind Turbine Tower

The geometric properties of the wind turbine tower are obtained by careful considerations.

Figure 2 Representation of the Wind Turbine Tower

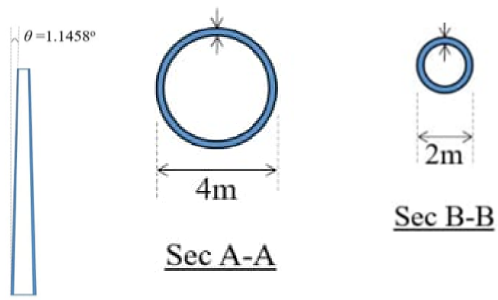

Figure 3 Geometric Dimension of the Wind Turbine Tower

Table 1 Geometric Dimensions of Wind Turbine Tower

S.No	Description	Value	Units
1	Length of the tower	50	Meters
2	Diameter at the sec A-A	4.0	Meters
3	Diameter at the sec B-B	2.0	Meters
4	Angle of inclination	1.1458	Degrees

By adopting the above geometric properties mentioned in the table 1, the wind turbine tower is created. The cylindrical shell structure of the wind turbine tower is modelled with varying diameter typically tapering from the base of the tower to its top and the thickness of the high strength steel is taken as 30 mm keeping it constant throughout the section, representing the typical design specification of the real world wind tower.

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2.3 Defining of Material Properties of the High Strength Steel Wind Turbine Tower

The material property of the High Strength Steel Wind Turbine Tower which is E410W A STEEL of IS2062:2006 is defined by using the Johnson Cook material model parameters. The detailed material property of the above mentioned material is given in the following table (2):

Table 2 Material property of High Strength Steel

S.No	Property	Value	Units
1	Young Modulus	200000	MPa
2	Poisson's ratio	0.3	
3	Density(Tonne/mm^2)	7.85e-09	T/mm^2
4	d1	0.25	
5	d2	4.38	
6	d3	2.68	
7	d4	0	
8	d5	0	
9	A (MPa)	220	MPa
10	B (MPa)	579	MPa
11	n	0.431	
12	Tmelt (k)	1573	K
13	Ttransition (k)	298	K
14	m	1.03	
15	C	0.017	
16	strain rate	1	

2.4 Defining Blast Loads and Assigning the Nacelle Load

In this Research work, two cases are considered for defining the blast loads for the material which is,

- **Case 1:** The blast load is considered to take place at the base of the wind turbine tower.
- **Case 2:** The blast load is considered to take place at the top of the wind turbine tower where nacelle of the wind turbine is located.

In each case the blast load is considered to take place almost on the outer surface of the steel wind turbine tower. The weight of the charges for the blast loads are increased from low to high in a incremental order upto failure. The blast loads are considered to be air blast in the form of TNT charges in increasing order of weights 500 Kgs, 1000 Kgs, 1250 Kgs, 1500 Kgs, 1750Kgs, 2000 Kgs, respectively in accordance with the guidelines set by IS 4991 codal provisions. The standoff distance of the blast will be 0 meters from the surface of the steel pylon of the wind turbine that is the blast loading takes place almost on the outer surface of the steel wind turbine tower. The load of the Nacelle which consists of all the units of the wind turbine such as rotor blades, rotor hub, generator unit, etc; which is carried by the tower of the wind turbine is applied to the wind turbine tower model generated in the form of lumped mass. The initial load of 80 tonnes in the form of lumped mass is applied to the top of the tower of the wind turbine tower model. (Refer Figures 4-10 & Tables 3-8).

3 Results and Discussions

3.1 Results

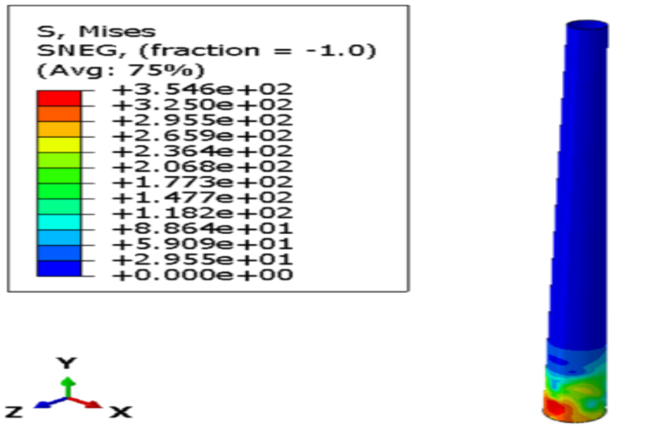

Figure 4 Simulation of High Strength Steel Turbine Tower Subjected to 500kgs Blast Load At the Base

Table 3 Results of High Strength Steel Subjected to 500 Kgs Blast Load At the Base

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	63.682	0.150	2419.744
1	293.638	1.254	970824.06
1.5	330.391	4.621	136312.37
2	348.064	12.383	15269.736
2.5	303.819	23.624	-369409
3	353.640	35.416	-726517
3.5	358.070	43.119	926436.5
4	361.141	46.195	1504174.875
4.5	366.842	52.260	2231459
5	372.308	57.190	2101679.75

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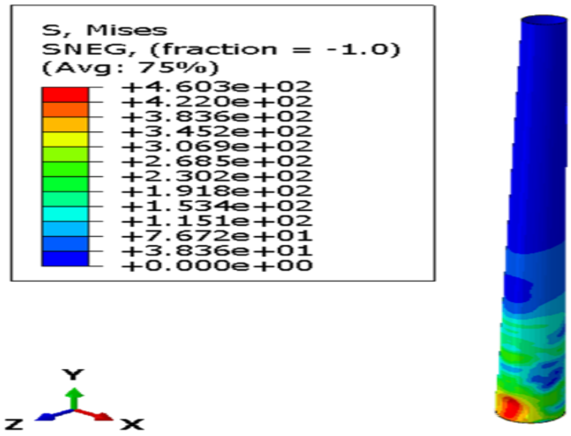


Figure 5 Simulation of High Strength Steel Turbine Tower Subjected to 1000kgs Blast Load At the Base

Table 4 Results of High Strength Steel Subjected to 1000 Kgs Blast Load At the Base

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	176.311	0.129	20600.5
1	318.481	1.556	701751
1.5	364.326	5.827	192443
2	390.026	14.948	174665
2.5	403.384	28.450	-75801.8
3	411.121	43.393	-446978
3.5	419.823	54.804	-260468
4	428.782	59.445	487079
4.5	435.928	67.080	1.71e+06
5	445.181	73.390	2.45e+06

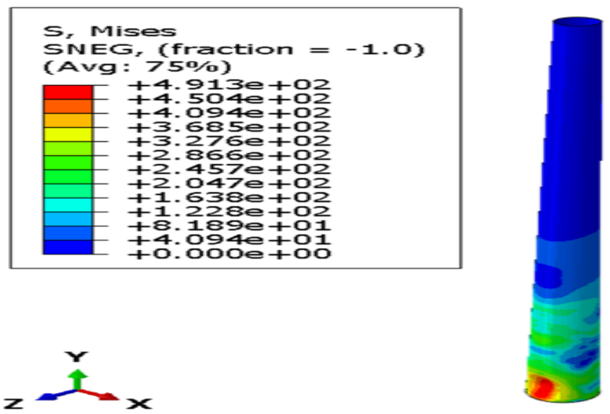


Figure 6 Simulation of High Strength Steel Turbine Tower Subjected to 1250 Kgs Blast Load At the Base

Table 5 Results of High Strength Steel Subjected to 1250 Kgs Blast Load At the Base

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	220	0.129	20600.5
1	331.926	1.55	701751
1.5	380.777	5.827	192443
2	407.582	14.948	174665
2.5	420.66	28.450	-75801.8
3	432.659	43.393	-446978
3.5	451.994	54.804	-260468
4	467.549	59.445	487079
4.5	477.386	67.080	1.71e+06
5	483.186	73.39	2.45e+06

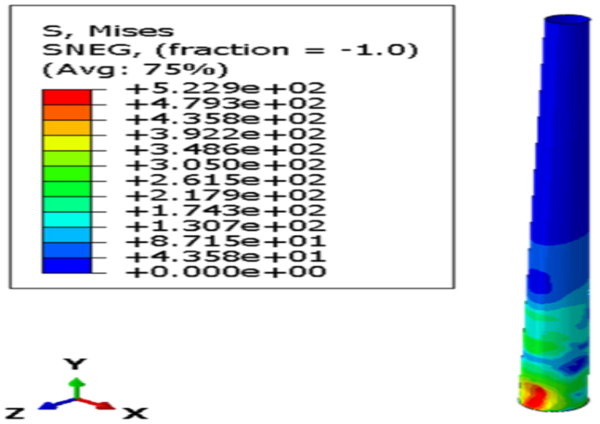


Figure 7 Simulation of High Strength Steel Turbine Tower Subjected to 1500 Kgs Blast Load At the Base

Table 6 Results of High Strength Steel Subjected to 1500 Kgs Blast Load At the Base

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	220	0.0760	1743.42
1	335.452	1.568	987771
1.5	386.83	6.021	240836
2	416.19	15.209	464670
2.5	432.826	28.574	-12038.9
3	446.341	42.295	-234064
3.5	462.877	52.960	486365
4	478.982	57.486	794351
4.5	489.72	64.992	2.22e+06
5	498.461	82.35	2.91e+06

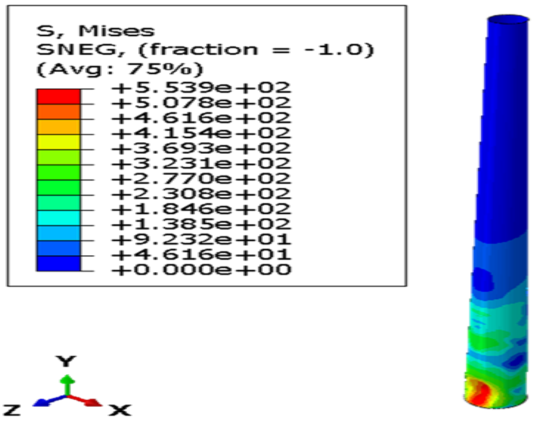


Figure 8 Simulation of High Strength Steel Turbine Tower Subjected to 1750 Kgs Blast Load At the Base

Table 7 Results of High Strength Steel Subjected to 1750 Kgs Blast Load At the Base

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	251.269	3.698	2757.98
1	346.342	17.466	956069
1.5	400.593	31.522	268581
2	430.268	42.202	472173
2.5	445.245	49.994	-17014
3	464.151	60.527	-450092
3.5	487.962	72.484	580754
4	506.512	79.328	742181
4.5	517.777	93.260	2.17e+06
5	523.747	105.684	2.89e+06

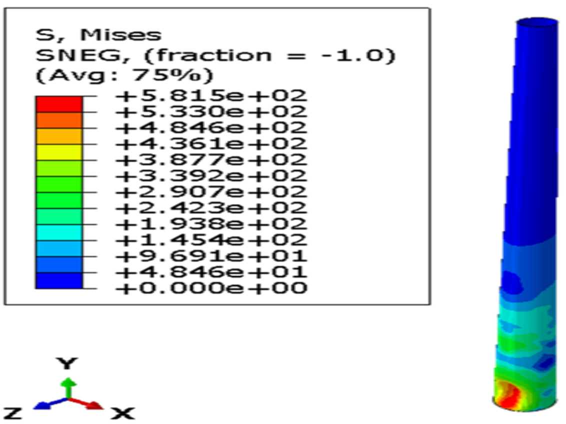
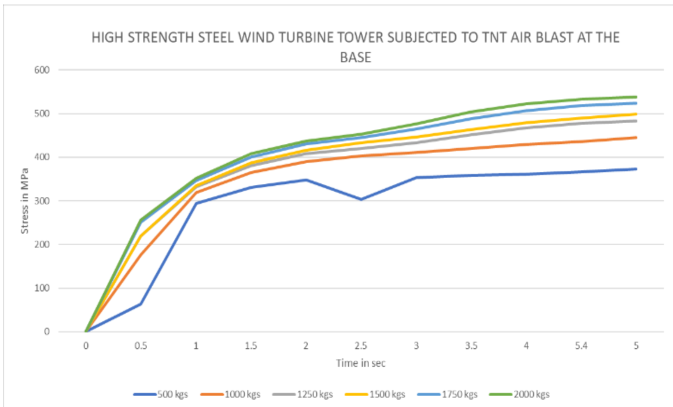


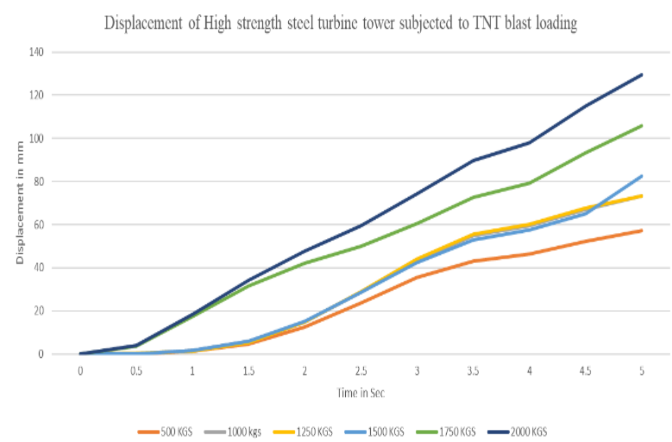
Figure 9 Simulation of High Strength Steel Turbine Tower Subjected to 2000 Kgs Blast Load At the Base

Table 8 Results of High Strength Steel Subjected to 2000 Kgs Blast Load At the Base

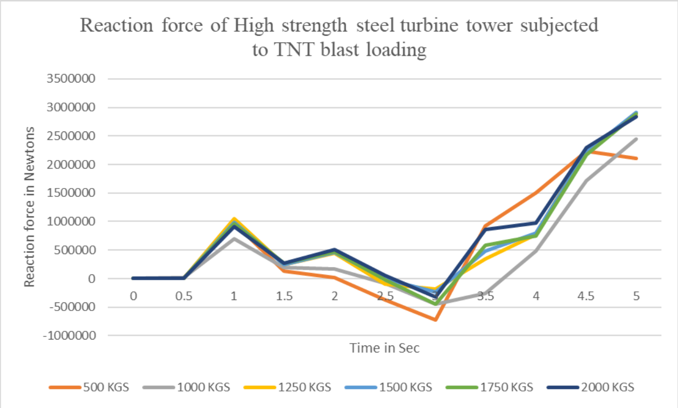
Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	256.248	3.845	4185.92
1	352.373	18.491	912453
1.5	407.75	34.102	271976
2	437.115	47.502	505616
2.5	452.974	59.650	50751.7
3	477.033	74.206	-325018
3.5	503.644	89.581	858132
4	522.797	97.998	977204
4.5	533.279	115.036	2.29e+06
5	538.47	129.487	2.84e+06



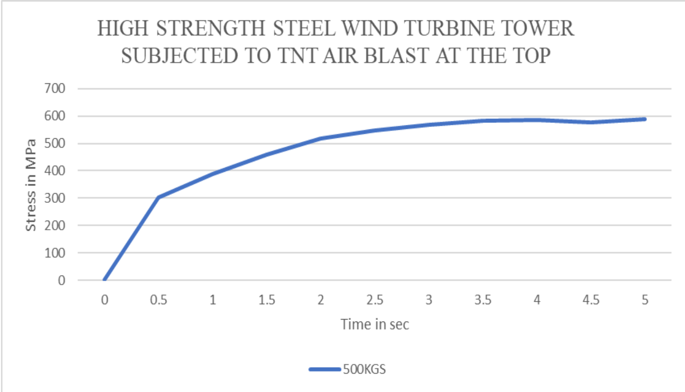
Graph 1 Von Mises Stress of High Strength Steel Wind Turbine Subjected to Blast Loading at The Base of the Tower



Graph 2 Displacement of High Strength Steel Wind Turbine Subjected to Blast Loading at The Base of the Tower



Graph 3 Reaction Force of High Strength Steel Wind Turbine Subjected to Blast Loading at The Base



Graph 4 Von Mises Stress of High Strength Steel Wind Turbine Subjected to Blast Loading at The Top

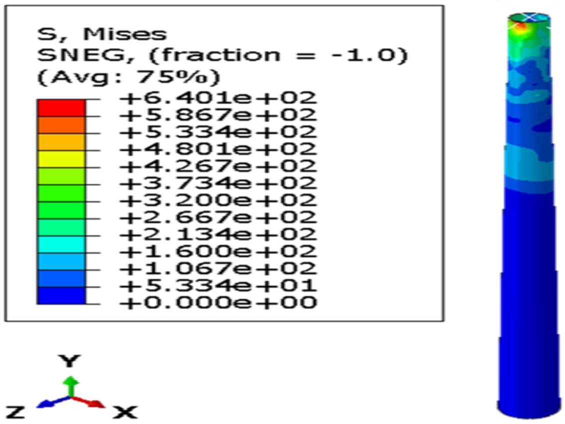
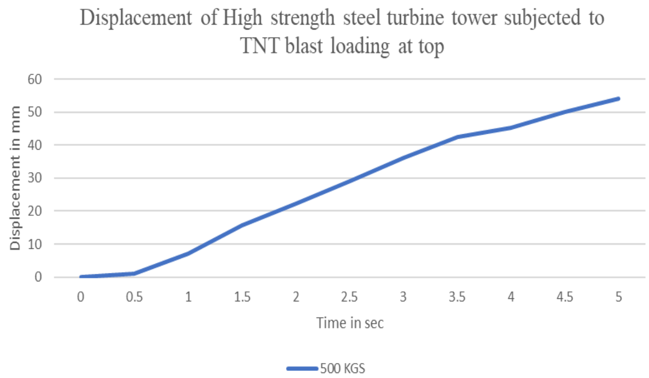


Figure 10 Simulation of High Strength Steel Turbine Tower Subjected to 500 Kgs Blast Load At Top



Graph 5 Displacement of High Strength Steel Wind Turbine Subjected to Blast Loading at The Top

Table 9 Results of High Strength Steel Subjected to 500 Kgs Blast Load At the Top of the Tower

Time in sec	Stress in Mpa	Displacement in mm	Reaction force in N
0	0	0	0
0.5	301.696	0.932	2419.744
1	387.323	7.198	970824.062
1.5	458.398	15.810	136312.375
2	519.033	22.237	15269.736
2.5	546.256	29.138	-369409
3	568.262	36.189	-726517
3.5	582.983	42.540	926436.5
4	587.054	45.409	1504174.875
4.5	576.777	50.211	2.23e+06
5	589.421	54.141	2.10e+06

3.2 Discussion

From the obtained simulation results of high strength steel wind tubine tower subjected to blast loading, the following are noted:

a) The maximum Von mises stress of High Strength Steel wind turbine tower subjected to blast loading of maximum charge of 2000 kgs is 538.47 MPa at the base of the tower.
b) The maximum Von mises stress of High Strength Steel wind turbine tower subjected to blast loading at the top of the tower for the minimum charge of 500 Kgs is 589.42 MPa which proves fatal to the structure at such charges.
c) The maximum displacement captured on the high strength steel wind turbine tower subjected to blast loading of maximum charge of 2000 kgs at the base of the tower is 129.49 mm.

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d) The maximum displacement captured on the High Strength Steel wind turbine tower subjected to blast loading of 500Kgs charge at the top of the tower is 54.14 mm.
e) The maximum reaction force notice on the high strength steel wind turbine tower subjected to blast load is 2890 KN at the charge of 1750 kgs.

Conclusion

The captured results of simulations of the High Strength Steel wind turbine tower which is subjected to the blast loads demonstrated insights into the structural response of the wind tower under extreme conditions. Results are shown in graph 1 to 5. The wind turbine tower when subjected to the blast loads withstood Von Mises stresses up to 1500 kgs of charge at the base successfully. However, for the successive charges of 1750 kgs and 2000 kgs, the stresses developed in the wind turbine tower exceeded the material's yield strength of the modelled wind turbine tower possibly leading to the structural failure. Additionally, the tower exhibited excessive displacement, particularly at the charge of 2000 kgs demonstrating 129.49 mm of displacement which surpasses the prescribed limitation of the displacement of wind turbine tower by the international guidelines IEC 61400 standard. At the top of the tower, the structure demonstrated vulnerability under a relatively low blast load charge of 500 kgs capturing Von Mises stress reaching 589.42 MPa indicating failure. These results of wind turbine tower models subjected to blast loading trigger the limitations of High-strength steel wind turbine towers in accidental prone environments, especially in regions of high-risk zone. Therefore, from this research study it is evident that the High strength steel tower provides substantial strength under moderate loads of blast forces but the performance diminishes significantly when subjected to higher blast loads particularly at the base and top sections of the wind turbine tower when foundation and nacelle is located respectively. The study suggest that in zones of high risk where blast loads are a concern, alternative designs, reinforcement strategies and hybrid models must be considered to incorporate to ensure the safety and compliance with structural standards.

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