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Structural Analysis of a New Generation of Guyed Telecom Mast with a Wind Turbine

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ABSTRACT

This work focuses on the structural analysis and response of an innovative design of a guyed mast for the telecom industry in which the power is supplied mainly by attaching a wind turbine on the top. For this purpose a numerical model based on the finite element method (FEM) was developed. The FEM model was validated with experiments conducted on one modular section of the mast, which was loaded in torsion. The model showed good agreement with the experimental results and revealed that failure in the modular section loaded in torsion is governed by non-linear buckling. The entire 57 m guyed mast structure was then modeled using the validated modeling procedure with applied loads corresponding to wind conditions resembling typical African landscape. The design wind loads were determined according to the Telecommunications Industry Association (TIA-22-G-1). Several structural design criteria were stipulated and the current design of the mast met all the requirements with a good margin of safety and hence making it a suitable product for the African market.

Keywords: *Guyed Masts, Telecom, Antenna Towers, Wind Loads, Finite Element Modeling, Structural Analysis.*

1. INTRODUCTION

The telecom industry has grown and evolved at an incredible pace for the last 20 years and dramatically changing the way people communicate. This rapid growth has created continues technology development and challenges for enabling environmental friendly and cost effective telecommunication. The demand on environmentally friendly solutions e.g. clean-tech solutions in the telecom industry have resulted in new innovative design of telecom guyed masts. One of these promising products is the E-Site® shown in figure 1, which is provided by the Sweden based company Flexenclosure AB. The innovative concept with this new telecom enclosure is the attachment of a wind turbine at the very top of the mast providing its antennas with prime source of energy generated from solar and wind. The power generated from these energy sources are stored in a battery bank in the terminal base station Diriflex™ located on ground and a back-up source is provided for secure operation at all times. The E-Site® solution is ideal for remote locations and rural areas with no reliable access to the electricity grids. However, the wind turbine with its weight of 500 kg will have imposed considerable load on the mast structure statically by its dead load and dynamically once it is in service.

Guyed antenna masts are frequently used within the telecommunication industry and are exposed to several types of loads e.g. dynamic and static loads due to wind. In some cases this can lead to loss of signal due to the displacement and rotations of the antennas and in some cases lead to permanent deformation or failure. Several studies have been conducted in order to study the structural and dynamic behavior of guyed antenna mast under variety of loading conditions. Ben Kahla [1-2] investigated the geometric nonlinear dynamic response of a guyed tower when a sudden rupture of one arbitrarily selected guy occurred. The dynamic effects of the wind were neglected, and the tower was subjected to a static wind pressure. Natural frequencies and periods of vibration of the structure are determined for the intact and damaged structure.

Madugula et al [3] modelled the dynamic response of guyed mast by using truss elements in one model and beam-column elements in another model. The resulting natural frequencies for the two modelling approaches agreed well with each other which also were validated by experimental results. The same methodology was applied in the evaluation of the dynamic response for antenna towers in Madugula et al [4-5] where six different tower designs where considered subjected to a variety of load combinations involving dead, wind and ice loads.

Harikrishna et al [6] carried out full scale measurements of the structural response of a 50 m guyed mast under wind load and comparison is made with current design practice. Hensley et al [7] carried out 3D analysis on a 120 m guyed mast considering seismic excitation in order to design guyed masts against earthquakes.

The objective of the current study is to perform a structural analysis of the telecom mast E-Site® to assure its suitability for service in a specific geographic location. The geographic locations that where considered were landscapes corresponding to the savannahs of Tanzania and Kenya. The wind conditions in these locations make the E-Site® an ideal solution but subjects the structure and the wind turbine to high loads. The developed finite element procedure will serve as design tool for future constructions and evaluations of E-site® solutions at arbitrary landscapes.

2. APPROACH

The telecom mast consists mainly of lattice structured modules compiled in a way to meet height and design specifications whereas the exact E-Site® configuration is determined by local climate conditions for the given market. In the current investigation a 57 m guyed E-Site® is analyzed suitable for markets such as Tanzania and Kenya. The wind loads were established according to the Telecommunications Industry Association, TIA-222-G-1 [4], which is an American structural standard for antenna supporting structures. The wind loads were determined for a specific exposure category, topographic category and structure classification.

The key issue was to investigate whether certain design criteria were met or not when a wind turbine is placed on top of the 57 m guyed telecom mast. The wind turbine will contribute with a weight load and will be exposed to the wind pressure which will affect the structure. Moreover, it will in severe running conditions expose the structure with torsion and bending torques. Appurtenances such as antennas were mounted on the telecom mast which will be exposed to the wind pressure. The latticed structure will also be exposed to the wind pressure. Consequently the structure will be exposed to the wind load and the dead loads which it has to withstand. The design criteria are in accordance with TIA-222-G-1 [4] and are of two kinds. The first is a structural stress criterion and states that the stresses in the structure should not exceed a certain limit, i.e. the material yield strength or ultimate rupture strength. The second is a serviceability requirement and is based in structural deformation. It states that deflections and displacements at any location of the mast should not exceed a certain limit.

3. FINITE ELEMENT MODEL

The modules of the E-Site® were implemented in the FEM model in a parameterized manner such that all the major dimensions could be changed independently. For this purpose the commercial FEM package ANSYS [5] was used. Each module was programmed in a separate macro and is called from a main file which generates the entire E-Site® structure. The schematic sketch in figure 2 shows how the model is built up. In this way the entire E-Site® is build up with the different modules from bottom to top in a sequential order according to a list of standardized modules. For the leg members, the horizontal rods connecting the legs and the diagonal rods three dimensional beam elements with six degrees of freedom at each node are used. The degrees of freedom are three translational and three rotational. Similarly, three dimensional beam elements were used for modeling the guy attachments and the torsion attachment shown in figure 3. In all structural members the elastic properties for steel is used; Young's modulus E = 210 GPa and Poisson's ratio ν = 0.3.

For the guys special tension-only link elements are used which resembles real cables with vanishing stiffness when loaded in compression. In table 1 the guys supporting the mast at the different height levels are listed along with their ultimate rupture force Fu, cross sectional area A and the guy stiffness E_g = 166 GPa. It shall be mentioned here that the modulus of elasticity for guys is a structural property rather than a constant material property. It can vary for different guy dimensions, manufacturing methods and environment. In order to determine the exact elastic properties one need to test the specific guy. This is out of the scope in this investigation.

The guys are initially stretched with a force corresponding to 10% of their ultimate rupture force. If linear elastic conditions are assumed in the guys then the initial strain in the link element can be calculated as

$$\varepsilon = \lambda \frac{F_u}{E_g A} \qquad (1)$$

where the constant λ is the initial stretching factor of the guys. Hence for all calculations a constant λ = 0.1 was used. The link elements were created between the guy attachments and the ground at a radius of 30 m corresponding to the E-Site® ground radius. In order to incorporate the gravity loads for the antennas and the wind turbine, mass elements were used. The antennas and wind turbine were considered as point masses and mass elements were placed at these locations as can be seen in figure 3. The entire structure was anchored to the ground, which corresponds to fixing the structure to a concrete foundation.

The loads are of three types: wind loads, gravity loads and service loads taking into account the loads induced from the wind turbine. The loads are applied, a static analysis is performed and relevant results are extracted from the solution in the post-processing step. Below follows the method of determination and application of the wind loads.

4. DETERMINING THE LOADS

The forces and moments which will represent the design load case will serve as input for the FE model in order to predict deformations and safety factors for structural stresses. The loads are determined according to the American structural standard for antenna supporting structures [4] and product specification for E-Site®. The design load case is presented below:

Basic wind speed: 40 m/s
Exposure Category: C
Topographic Category: 1
Structure Class: II
Height to turbine hub: ≤ 60 m
Height to top of antenna: ≤ 60 m above ground – behind rotor.
Effective projected areas: Antennas: – 4 m2 at 4 m below hub
4 m2 at 7 m below hub
Cables: – 0.30 m2/m
K750: – 0.28 m2/m
Turbine: – 11 m2

Exposure category C corresponds to open terrain with scattered obstructions having heights generally less than 9.1 m. This category includes flat, open country, grasslands and shorelines in hurricane prone regions. Topology category 1 corresponds to no abrupt changes in general topography, e.g. flat or rolling terrain, and thus no wind speed-up consideration shall be required. Structural class II corresponds to structures that due to height, use or location represent a substantial hazard to human life and damage to property in the event of failure and/or used for services that may be provided by other means.

As mentioned earlier, the loads that affect the E-Site® structure with the wind turbine are of three types. The first is due to the actual wind pressure, which gives rise to a distributed force in the direction of the wind and varies with height above ground level, which is denoted F_x'. Figure 4(a) shows the different loads on the structure. Based on the conditions given above the distributed force F_x' is plotted in figure 4(b). The wind load is factored with 1.6 according to chapter 2.3.2 in TIA such that the structure should withstand a combination of factored loads.

Moreover, appurtenances such as antennas and the wind turbine will also be exposed to the wind due to their project area in the wind direction and thus they will be subjected to forces in the direction of the x-axis as shown in figure 4(a). These forces are point loads at different heights and are denoted F_x^{a1} and F_x^{a2} for the antennas and F_x^{t} for the wind turbine. The point loads are determined with accordance to TIA-222-G multiplied with a load factor of 1.6. Below, EPA stands for effective projected area:

F_x^{a1} = 6.45 kN at z = 53 m above ground level with a EPA = 4 m^2 (antenna 1)

F_x^{a2} = 6.37 kN at z = 50 m above ground level with a EPA = 4 m^2 (antenna 1)

F_x^{t} = 18.21 kN at z = 60 m above ground level with a EPA = 11 m^2 (wind turbine)

The second type of loads is gravity loads which arise due to the weight of the E-Site® lattice structure mast, the guys that support the mast and the appurtenances such as the antennas and the wind turbine. The third type of loads is service loads which arise when the wind turbine is in operation. The torque M_x shown in figure 4(a) arises in the rotor of the wind turbine due to the generation of power and the eventual emergency braking of the rotor at shut down of the wind turbine. This torque was estimated to M_x = 3.0 kNm based on correspondence and data delivered from wind turbine manufacturer. The torque M_z corresponds to the twisting of the structure and is estimated to 7 kNm.

5. VALIDATION OF THE MODEL

A torsion test was performed on a modular flatpack section as shown in figure 5(a). The section was rigidly mounted between two plates and was tested by applying a torque on one end keeping the outer end fixed. The displacement due to the twisting of two rigid plate ends was monitored using four extensometers as shown in figure 5(b). The torsion test of the modular flatpack was modeled with FEM as shown in figure 6, which was rigidly supported to the ground at the bottom and a torque was applied to rigid beam elements at the top. In figure 6(a) the deformed configuration of the structure after application of the torque is shown and as can be seen, ultimate failure is a consequence of buckling of a diagonal rod which is well captured by the FEM model.

The comparison between the model and test serves as a validation of the FEM model and hence several modeling aspects were considered in the modeling procedure in order to reveal some important structural phenomenon of the test. In figure 6(b) the mechanical response torque versus twist measured as the average of the LVDT displacements from the test and the FEM model is shown. The black dashed-dotted line corresponds to a pure linear elastic material behavior characterized by Young´s modulus E = 210 GPa and Poisson's ration ν = 0.3. The red solid line corresponds to elastic material behavior with large deformation analysis technique allowing for non-linear buckling. The black solid line corresponds to elastic-plastic material behavior allowing for plastic yielding of the members in the structure and large deformation analysis technique allowing for non-linear buckling. It is interesting to note that the two last mentioned approaches give minor difference in the mechanical response. This reveals that buckling of the diagonal rod is preceded by plastic yielding in the diagonal rod. This is realized when comparing the stress in the diagonal rod (σ_{max} = 367 MPa) obtained from the FEM results at the instance of buckling, which exceeds the allowable material yield strength (σ_Y = 355 MPa).

Qualitative good agreement between the FEM results and the test results are found as shown in figure 6(b). The FEM model predicts ultimate failure by local non-linear buckling at a torque of M_{FEM} = 51.5 kNm whereas testing gives ultimate failure at M_{EXP} = 44.9 kNm. The difference in the mechanical response between the FEM and test results is due to various reasons. A main reason is that the details of the flatpack section such as fasteners, bolts and welds are not modelled explicitly. These features can reduce the overall stiffness of the section as a consequence of i.e. loosely tightened bolts or not rigidly fixed testing fixtures.

6. SERVICEABILITY REQUIREMENTS AND DESIGN CRITERIA

In order to assess the serviceability and safety of the E-Site® structure by means of the finite element results certain design criteria need to be met. Four different design criteria and serviceability requirements are stipulated.

6.1 Serviceability Requirements – Criterion 1

These requirements are modified versions of the serviceability requirements in the TIA-222-G standard chapter 2.8.2 [4]. It is stated that the deformations under service loads at any point on the structure shall not exceed:

- A rotation of 4 degrees about the vertical axis (twist about z-axis) or any horizontal axis (sway about x- or y-axis) of the structure.

$$\max(\theta_x, \theta_y, \theta_z) < 4° \tag{2}$$

- A maximum horizontal displacement of 3% of the height of the structure. Thus, the horizontal displacement in x- and y-axis (u_x and u_y) shall not exceed 1710 mm.

$$\max(u_x, u_y) < 1710 \text{ mm} \tag{3}$$

According to TIA 2.8.3 [8] these serviceability requirements shall be met for the service loads including the effect of the wind turbine. The design load case in this evaluation is the actual wind load factored by 1.6 shown in figure 4(a). Hence, if the serviceability requirements are met for the design loads case then it is assured that they are met for the service loads.

6.2 Structural Stresses – Criterion 2

The design criteria based on the structural stresses states that the stresses in any members shall not exceed the allowable stress for that member. For the case of the members of the E-Site® structure the allowable stress is taken as the yield strength of the diagonal and horizontal rods 355 MPa, whereas the yield strength of the leg members of the structure is 460 MPa. The ultimate failure strength for the diagonal and horizontal rods is 500 MPa and for the leg members 540 MPa. As was discussed earlier, initial yielding of a member is a precursor for non-linear buckling failure, which motivates the use of this criterion. According to this design criterion the safety factor against initial yielding shall be greater than 1.0 in order to assure a safe design.

In a similar way a design criterion based on the stress in the guys can be formulated. Here the maximum stress in any of the pre-stretched guys shall not exceed the ultimate rupture strength 1370 MPa during service loads.

7. RESULTS

All the FEM results in this section are for the E-Site® 57 m structure with all the modules modeled and an initial stretch of the guys in equation (1) with $\lambda = 0.1$ corresponding to 10% of their ultimate rupture force. Since the main objective is to analyze the effect of a wind turbine on the serviceability and integrity of the mast two different scenarios where considered. Both the scenarios, i.e. Case 1 and Case 2, consider the actual design wind loads and gravity loads as shown in figure 4(a). However Case 1 is without a wind turbine and Case 2 is with a wind turbine. Consequently a comparative study can be done between Case 1 and Case 2 to understand the effect of the wind turbine.

a. Serviceability Requirements

In figure 7 the displacements and rotations throughout the entire E-Site® structure are shown for Case 1 (without wind turbine) and Case 2 (with wind turbine). The displacements are denoted u_x , u_y and u_z whereas the rotations are denoted θ_x , θ_y and θ_z which correspond to the three coordinate axes of the global coordinate system with the origin at the ground level as shown in figure 4(a). The dotted lines in figure 6 indicate the locations of the antennas. Figure 6(b) shows the rotations for Case 1, indicating that the maximum rotation occurs about the z-axis and is -0.87 degrees (green line) corresponding to a twist of 0.87 degrees about the z-axis. In Figure 6(d) the rotation for Case 2 is shown indicating that the maximum rotation occurs about y-axis with 1.27 degrees (blue line) and about the z-axis with about 1.14 degrees (green line), which correspond to a sway and a twist respectively. Thus the wind turbine will induce sway deformation mode on the structure, however the maximum rotation for both the load cases (Case 1 and 2) is below the limit value of 4 degrees and hence the structure fulfils the serviceability requirement in equation (2)

Similarly, in figure 6(a) and (c) the displacement for Case 1 and 2 are shown indicating that the maximum displacement occuring in the x-direction is 35 mm for Case 1 (without wind turbine) whereas the maximum displacement is 260 mm for Case 2 (with wind turbine). The maximum displacement of the both the cases are below the limit value of 1710 mm and hence the serviceability requirement in equation (2) is also met.

b. Stresses in the Structure

In figure 8 the results for Case 1 and Case 2 are illustrated showing the minimum compressive and maximum tensile stresses in the structure occurring at the height of 52 m (Level 3).

For Case 1 (without wind turbine) the highest compressive structural stress is -124 MPa and occurs at the top part at the torsion attachment. This is mainly due to the wind forces F_x^{a1} and F_x^{a2} at the two antennas which are placed above and below the torsion attachment. Also a high compressive stress of -107 MPa is found at the bottom part of the mast at the flatpack with man hole which is a compressive bending stress.

For Case 2 (with wind turbine) similar results are shown for. As in the previous case the highest structural stress occurs at the top part above the torsion attachment in the leg member of the flatpack and is -401 MPa. This is most likely due to the service loads and wind loads (F_x^t and M_x) associated with the wind turbine, which will impose a bending mode on the leg member giving rise to the high compressive stress. However, the yield strength of the leg member is higher than for the diagonal and horizontal rods, which implies a higher allowable stress in the leg members when determining the safety factor against yielding. Hence, whether compressive and tensile stress both Case 1 and 2 give safety factor large than 1 against yield and therefore fulfill the structural stress criterion.

In table 2 the safety factor against failure in the guy wires at the three different attachment levels are given for Case 1 and 2. The safety factor is defined as the ratio between ultimate strength of the guys (1370 MPa) and the maximum stress in the guys. One can note that the safety factor in the guys attached to the guy attachments at level 1 and 2 increases when the wind turbine is present. This is due to that the presence of the wind turbine exerts a gravity load through the E-Site® structure resulting in a relaxation in the pre-stretched guys. However, the stress in the guys attached to the torsion attachment at level 3 increases when the wind turbine is present. This is due to the service loads and wind loads (F_x^t, M_x and M_z) associated with the wind turbine, which will result in an increase of the tensile stress in the guy at this level. A decrease in the magnitude of the pre-stretch of the guy wires attached to level 3 would increase the safety factor at this level.

8. CONCLUSIONS

In the current study a FEM modeling approach is proposed for structural analysis of E-Site® guyed telecommunication mast, which was validated with structural test. The model consists of a number of scripted macros in ANSYS which can be used for further analysis on guyed masts with different configurations and under different wind conditions. A method for determining the design loads including wind loads affecting the guyed mast is proposed based on the Telecommunications Industry Association (TIA-22-G-1), which is implemented in the FEM model.

Design criteria based on serviceability, deformations and structural stresses were stipulated which the guyed mast is required to satisfy. For the specific design load case considered corresponding to climate conditions in Tanzania and Kenya all the design criteria were met. Based on the results from this study the E-Site® telecom mast is suitable for places with climate conditions similar to Tanzania and Kenya.

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Figure 1. Guyed antenna mast for telecommunication, E-Site®.

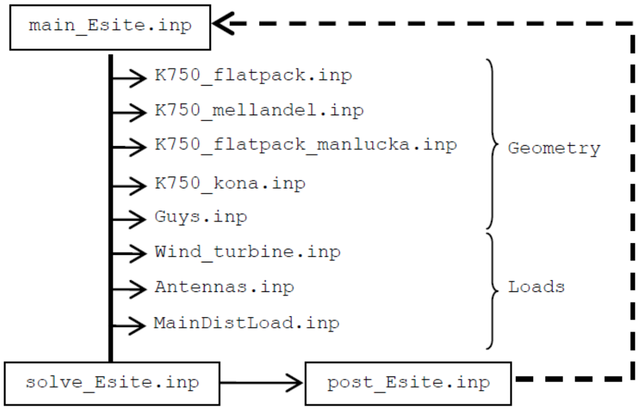

Figure 2. A schematic sketch over the macros and Input-files building up the FEM model

Table 1. Properties of the Guys

Level	F_u [kN]	E_g [GPa]	A [mm^2]
1 (18 m)	71	166	52
2 (36 m)	93	166	68
3 (52 m)	143	166	105

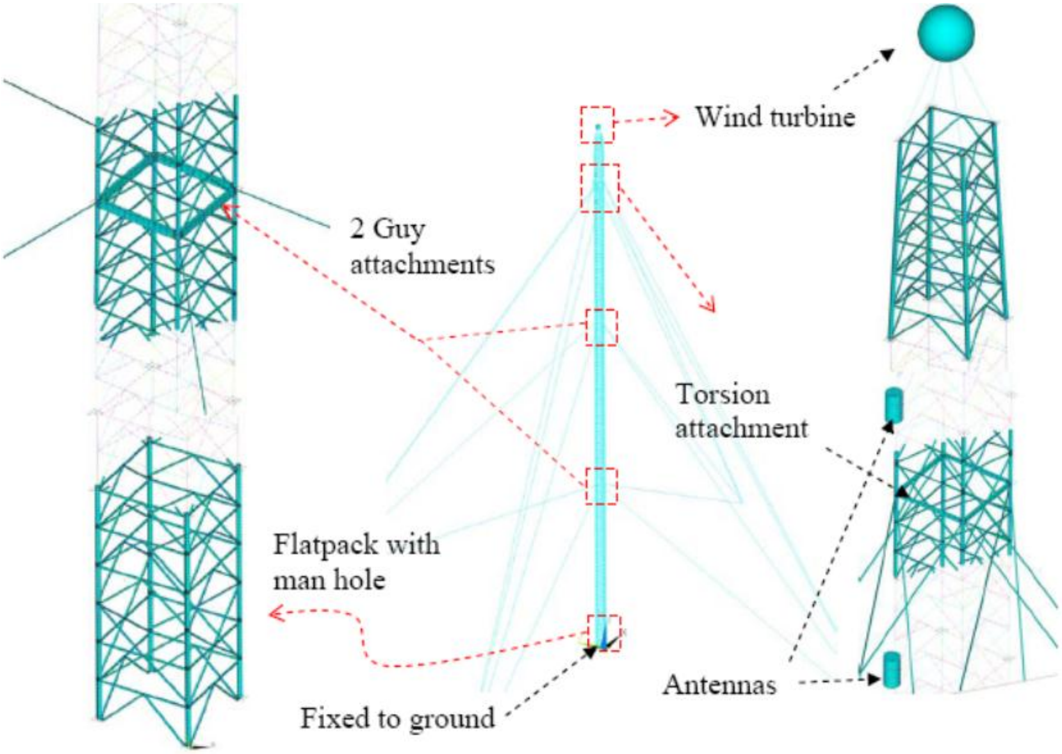

Figure 3: Illustration of the different modules of the guyed mast E-Site® 57 m

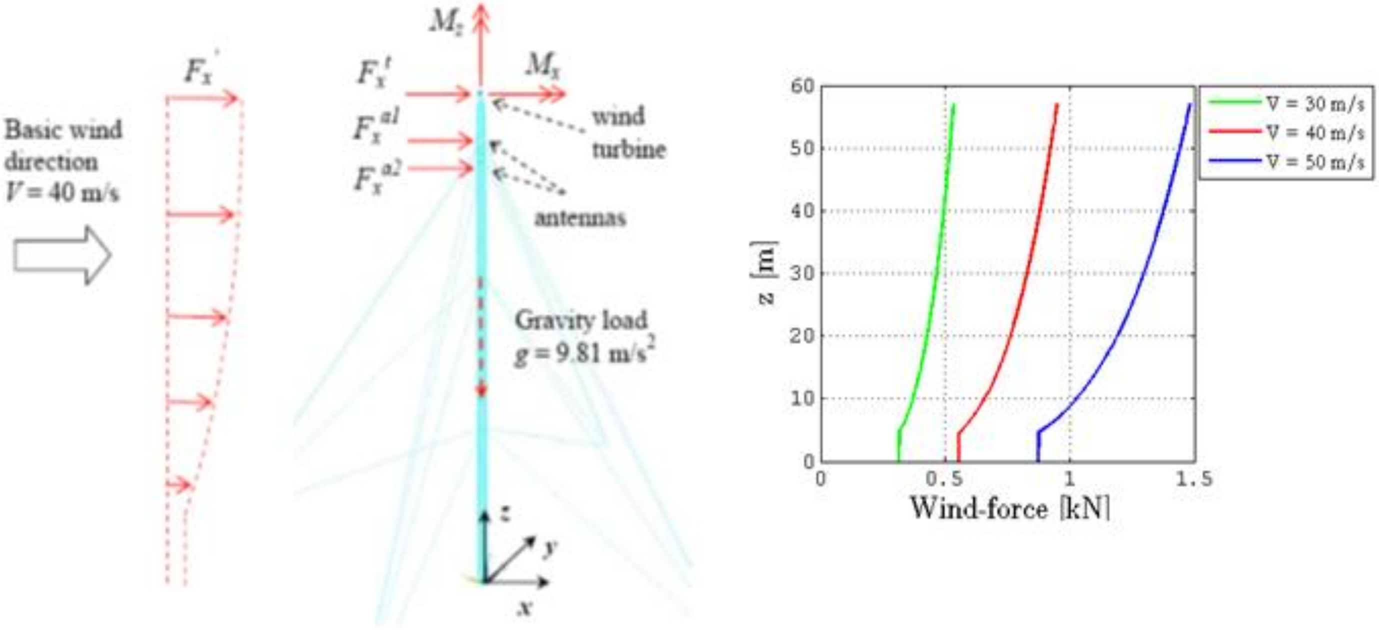

Figure 4: (a) Schematic representation of the forces and moments imposed on the E-Site structure with the wind turbine and (b) distributed factored wind load Fx´ for different basic wind speeds as function of z height above ground.

Figure 5: (a) Experimental setup: Flatpack section fixed to a rigid plate
(b) Experimental setup: extensometer measuring the rotational displacement.

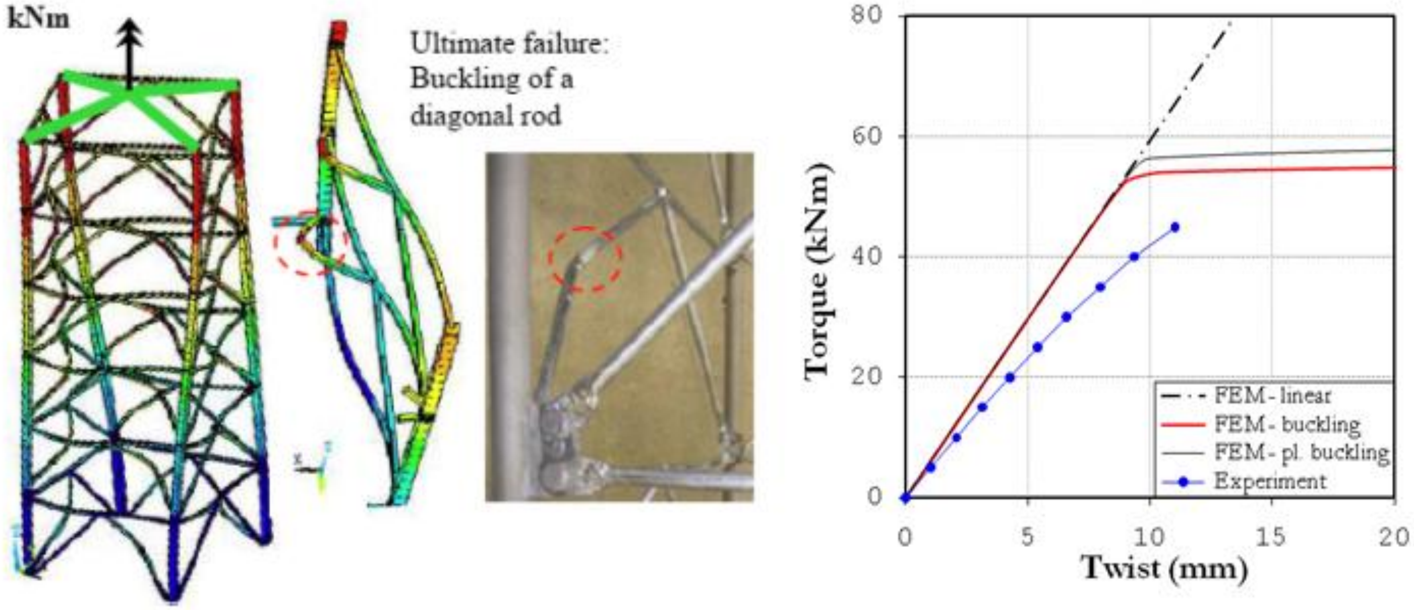

Figure 6: (a) The FEM model of the torsion test showing the deformed section after it is subjected to a torque leading to failure by buckling of a diagonal rod and (b) showing comparison of torque versus deformation between the FEM and the experimental results. The deformation is measured as the average displacement obtained from the extensometers and the FEM model.

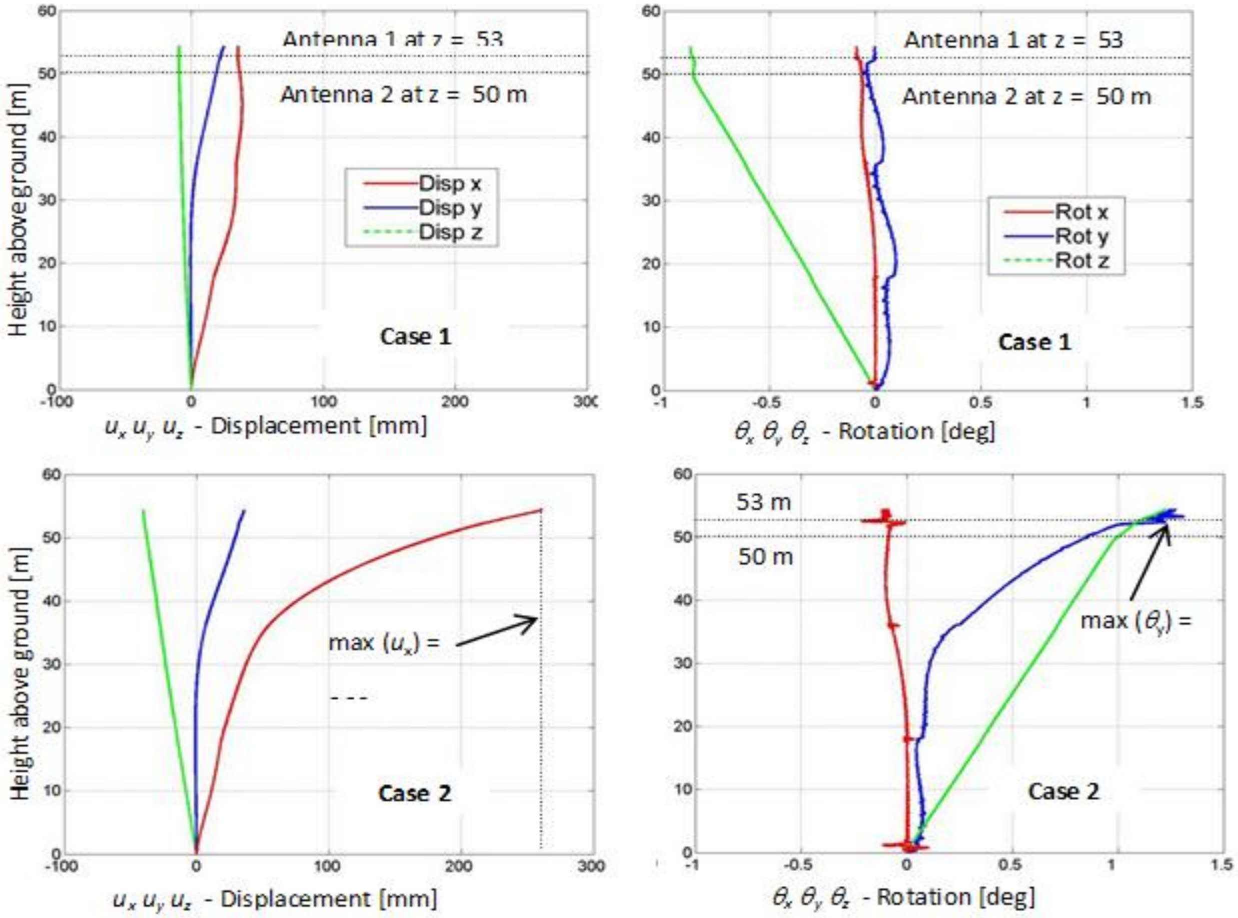

Figure 7: FEM results showing the displacements and rotations throughout the entire E-Site® structure for Case 1 (*without* wind turbine) and Case 2 (*with* wind turbine) due to wind conditions. The dotted lines indicate the location of the antennas

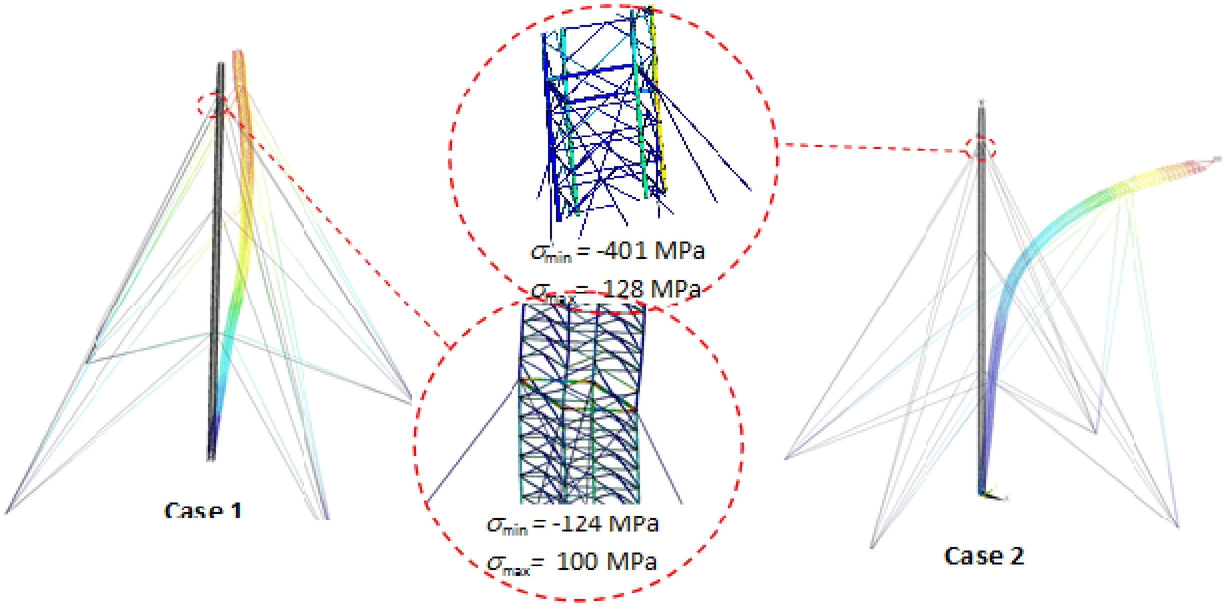

Figure 8: Deformation of the E-Site® mast and level of stresses in the top member for Case 1 (without wind turbine) and for Case 2 (with wind turbine). The deformation scale is 100 X

Table 2: Safety factors against material yielding for Case 1 and Case 2

	Bottom	Guy att. 1	Guy att. 2	Torsion att.
Case 1	3.3	4.8	5.7	2.8
Case 2	1.3	1.7	1.4	1.1