On the response of steel lattice telecommunication masts under environmental actions and seismic loading

E. Efthymiou[1], D. N. Kaziolas[2] & C.C. Baniotopoulos[1]
[1]*Institute of Metal Structures, Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece*

[2]*Technological Educational Institute of Kavala, Drama, Greece*

In the present paper the response of steel telecommunication masts under the influence of environmental actions and seismic loading is investigated. As flexible structures, they are highly sensitive to the effect of wind and ice, while earthquakes can be important as well, according to the modern codes for earthquake resistance structures. In the framework of a recent research activity, a large number of lattice steel masts on the ground of four different typologies were studied taking into account both the impact of the environmental effects, i.e. wind and ice loading, and seismic actions on their structural behaviour and all their special geometrical structural features. Emphasis was given to the evaluation of the wind loading on the steel masts, since the accurate computation of the wind loading is very important due to the fact that wind appears in most cases to be the most critical loading. The analysis has been carried out according to the contemporary relevant codes by means of innovative software, whereas all parameters of the study are presented and thoroughly described. In the last part of the paper, useful conclusions are presented regarding the performance of the structural members for each one of the four types of the steel masts under investigation.

1 INTRODUCTION

1.1 *On the steel lattice masts*

Steel lattice masts belong to the category of steel tower structures which are used in telecommunications, as well as in energy transmission infrastructure, where they can also carry cable guys. These special structures are constructed in such a way that the most efficient and economic use of material is achieved through the use of an open lattice system. In this way, the accomplishment of lightweight structures with high structural capacity is succeeded and at the same time the modularity of construction is achieved. As these structures have to be often placed in spots of maximum visibility, the choice of hill or mountain peaks for their erection is obvious. Lattice masts can be transported in relatively small modules making easier to cope with difficult terrain and their construction is characterized by less demands in labor requirements.

Regarding the steel lattice telecommunication masts, these are self-supporting structures and they can be found on the ground or on buildings carrying antennas at several heights of the tower. They carry reflectors or antennas and in every tower there are working floors constructed at different levels of the mast according to the type of the mast, in order to provide climbing access for inspections and maintenance operations. Inside the structure a ladder is constructed, while special systems are configured in order to stabilize the cables which connect the reflectors and antennas with the telecommunication network (Stathopoulos & Baniotopoulos 2007).

Masts cross-sections are typically square, rectangular or rarely triangular and their height varies from 6m to over 50m. In view of morphology, steel lattice masts can have a vertical, a truncated cone system, or a combination of the two systems where truncated cone base continues beyond of a specific height level as a prism, see Figure 1. The columns-legs of the mast are braced by means of main bracing of type X,K,V which transmits the shear forces to the foundation and at the same time provides stability against the horizontal seismic forces and the wind loading, while the secondary bracing reduces the member's effective buckling length (Owens & Knowles 1994). There is also a plan bracing usually in a rhomboid formulation which is introduced mainly in cases where the length of the horizontal face members becomes large enough in order to provide transverse stability (Cook 2007).

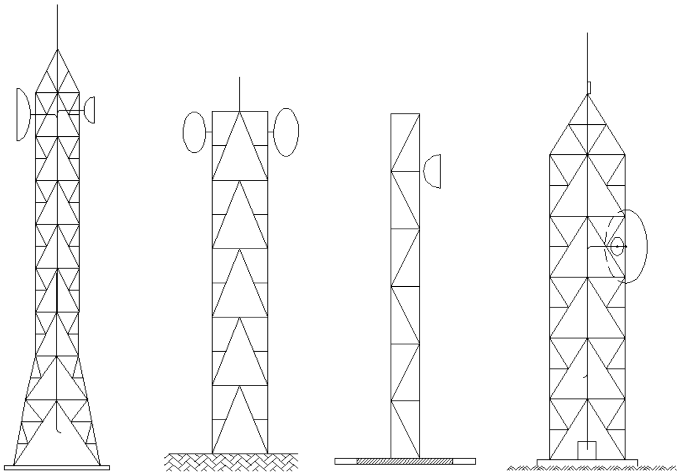


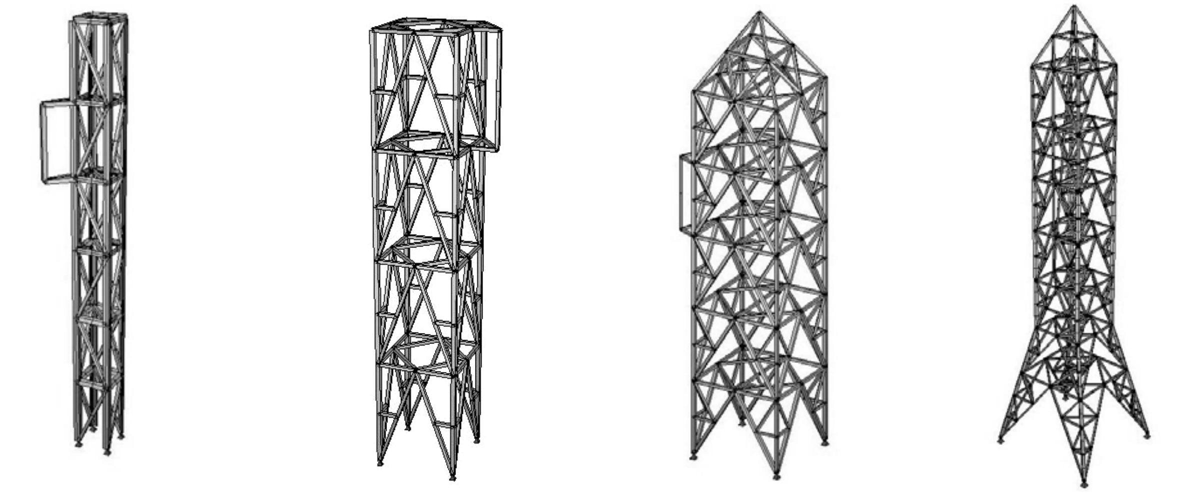
Figure 1. Morphology of steel lattice masts

As far as the cross-sections of the members of the mast is concerned, these are mostly angle sections L, single or double for the legs, while for the horizontal face members, as well as the other elements of the mast, the cross sections L and U are used. In cases where the stresses are low enough to allow relatively simple connections, tubular legs and bracings can be also an economic solution, since masts with tubular members may be less than half the weight of angle towers because of the reduced wind load on circular sections. The disadvantage of this solution is that the extra cost of the tube and the more complicated connection details often exceed the saving of steel weight and foundations.

1.2 *Description of the structures under investigation*

Regarding the existing steel lattice masts of the Greek telecommunications network, a large number of these tower structures which was built in the 1970s-1980s, are characterized by versatility and variety of constructional arrangement (Hatzinikolis et al. 2008). In the last years, the continuous changes and additions in the normative framework of actions on the masts, the installation new antennas and reflectors, in combination with the new provisions of the codes for earthquake resistance structures created the need for investigating the existing telecommunication network (Dasiou et al. 2008, Vayas et al. 2005, Tsitlakidou et al. 2005). Several types of steel lattice telecommunication masts were investigated according to the contemporary relevant codes.

The present paper deals with the study of the four most commonly used types of steel lattice telecommunication towers located on ground and focuses on their behaviour especially regarding the influence of the environmental actions and the seismic loading on their structural capacity. Four characteristic examples of self-supporting steel lattice telecommunication masts located on ground each one with base dimensions of 0.50m x 0.50m, 1.40m x1.40m, 2.50m x 2.50m and 4.30m x 4.00m, are studied. All parameters of the analysis are described and the behavioral aspects of the structures especially under the influence of environmental actions and seismic loading are described. These four types of telecommunication masts have different cross sections and arrangement, the height varies from 6m to 18m, while the number and the size of the reflectors also differ. All special features of the material, the used bolts and the local conditions were incorporated in the simulation models, see Figure 2.



a) Mast 0.50x0.50 b) Mast 1.40x1.40 c) Mast 2.50x2.50 d) Mast 4.00x4.30

Figure 2. Simulation of the four types of masts located on the ground

2 ACTIONS ON THE MASTS

The permanent loads on the steel lattice masts included the self-weight of the structure, the climbing ladder, the reflectors and finally the accessible working floors. For the imposed loads, the calculation was realized considering the possible imposed loads for the ladder and the working floors accordingly.

2.1 *The environmental action of wind*

As slender and flexible structures, steel lattice masts, are vulnerable to the effect of wind loading which is the main environmental action. In the present study, two sets of codes have been initially implemented, Eurocode 3 and DIN 4131 (prEN 1993-3-1 2005, DIN 4131 1991). Due to the common practice in Greece and since the Eurocode part regarding masts, EC3-Part 3-1, is compatible with DIN, the assessment of the wind loading has been performed on the basis of DIN 4131. The forces of wind loading on the reflectors and the accordingly transferred forces and moments on the masts have been calculated using the special software *Antwind* and the velocity of the wind has been calculated separately for each case. The definition of the wind loading for every mast included the calculation of the wind pressure q at the specific level, the reference area A (the projected area of the structure normal to the wind), the dynamic coefficient ϕ_B and the aerodynamic loading coefficient c_f. Thus, the wind loading on each reference area is calculated by means of the following formula:

$$\mathrm{W}=c_f \cdot \phi_B \cdot q \cdot A \tag{1}$$

Whenever the height of the tower does not exceed 50m, a constant value of the wind pressure q is taken into account which is equal to:

$$q = 0.75 \cdot \left(1+\frac{h}{100}\right) \cdot q_o \tag{2}$$

,whereas h is the height of the mast and q_o is the basic wind pressure.
The vibrations induced by the wind flow are taken into account by means of a dynamic coefficient ϕ_B which is equal to

$$\phi_B = \phi_{B0} \cdot n \tag{3}$$

, where ϕ_{B0} is a function of he fundamental period of vibration and the logarithmic damping coefficient of the tower, while n is the size coefficient which in the case under investigation is equal to 1. The aerodynamic coefficient c_f is a function of the wind (perpendicular or inclined action) and is defined as $c_f = c_{f0} \cdot \psi$. The values for c_{f0} and ψ are derived from the relevant nomograms from DIN 4131, as a function of the slenderness λ and the ratio of the covered area over the overall area of the side face of the mast which is defined as the solidity ratio ϕ.
The slenderness of the tower is given by means of the relations:

$$\lambda = 0.7h/b, \quad \text{for h > 50m} \tag{4}$$

$$\lambda = h/b, \quad \text{for h < 150m} \tag{5}$$

, whereas *h* is the height of the tower above ground and *b* is the breadth of the tower at *h/2* (*b* is measured perpendicularly to the wind direction). For intermediate *h* values, linear interpolation may be used. In the case of wind combined with the ice, the value of the wind pressure is calculated as 75% of the initial value.

2.2 *The environmental action of ice*

The effect of ice is calculated by increasing the cross-section of all the structural elements by 1cm to 10cm, depending on the exact altitude that the mast is erected, as well as increasing the section of the reflectors, see Figure 3. This way, the distributed load is applied along the members of the structure proportionally to the thickness of the element and the unit weight of the ice, 7kN/m^3 (DIN1055 2002). However, for simplification purposes the reference areas are increased by 2α, whereas α is the thickness of the layer of the snow (0.06m). In the case of wind combined with the ice, the value of the wind pressure is calculated as 75% of the initial value.

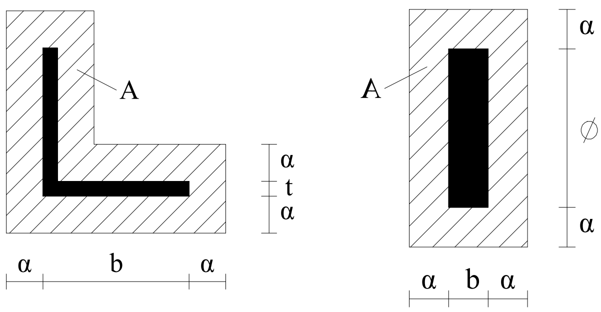


Figure 3. Ice loading on angle section and reflector

2.3 *Seismic loading*

Regarding the seismic action, it can be significant as well, especially for structures which have parts with high mass concentrations. For the earthquake loading, a dynamic spectrum analysis of the masts was performed according to code for earthquake resistance structures EAK 2000, taking into account the particularities of each region (Earthquake Planning and Protection Organization 2000). Each mast exhibits a different design spectrum depending on the geographic location, meaning a different zone of earthquake hazard (zones I, II, III) and is equal to:

$$\Phi_d(T) = \frac{n \cdot A \cdot g \cdot \gamma_I \cdot \theta \cdot \beta_o}{q} \tag{6}$$

, whereas γ_I is the importance factor, θ is the foundation factor and n is the correctional damping factor. In the present study, a behavior factor of q=1 is considered for the reassurance of the desirable elastic response of the mast, for reasons of extra safety, while for simplifying reasons a soil category B is applied and all the temperature and aero elastic phenomena effects are disregarded.

3 ANALYSIS AND RESULTS

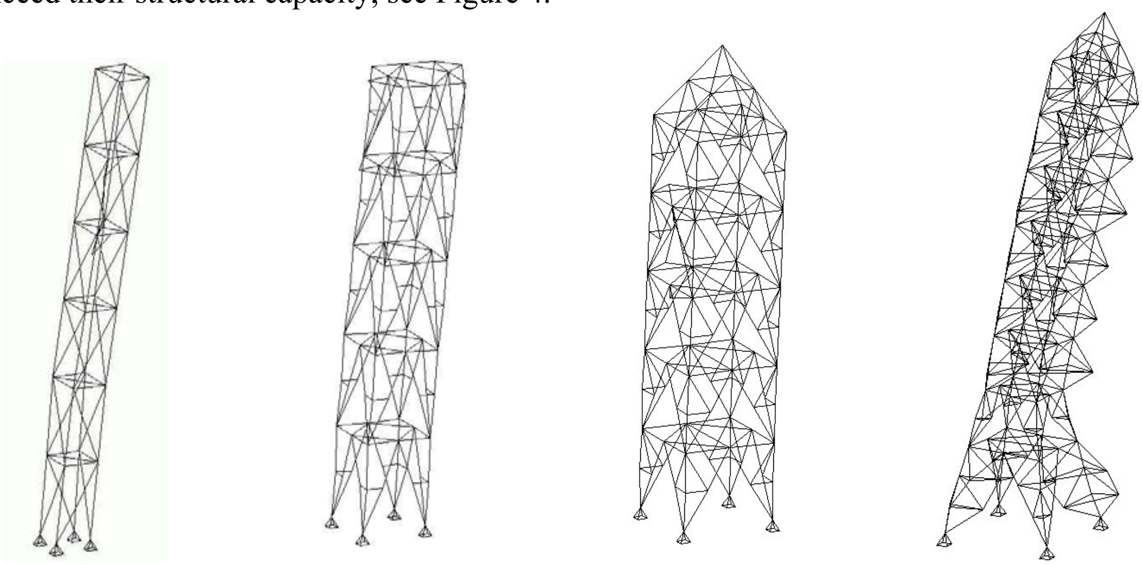
For each mast, the internal forces were calculated for all the basic loading combinations, according to the code provisions, while the wind loading was considered with the most possibly accurate way, i.e. changing the wind action direction every 15^o (prEN 1993-1-1 2002, EN 1990 2002). In Table 1, the basic loading combinations for which the analysis was conducted are shown:

Table 1. Load combinations

1	$1.35G+1.5Q$
2	$1.35G+1.5W_0$
3	$1.35G+1.5W_0+0.9Q$
4	$1.35G+1.5W_{0S}+1.5S$
5	$1.35G+1.5W_{0S}+1.5S+0.9Q$
6	$1.35G+1.5S+0.9Q$
7	$G+0.3S+0.3Q\pm E$

All members of the masts, i.e. the legs, the horizontal face members, the main, secondary and plan bracing were checked by means of the provisions of Eurocode 3 (prEN 1993-1-1 2002). Regarding the masts with a base dimension of 0.50m x 0.50m, no overstress was noted in the vast majority except the ones with a height of 8m or 10m whose members carry antennas and big diameter reflectors. In many masts of sections of 1.40m x 1.40m, 2.50m x 2.50m και 4.30 x 4.00m many members showed overstress, especially the higher ones. In particular, as the height increases, the lower part of the legs exhibits inadequacy, while the members used for the plan horizontal bracing and the working floors are subjected to significant bending stresses. In the case where the replacement of the members is not possible, then strengthening interventions are proposed such as construction of diaphragms aiming to restrain of the out-of-plane motion (reduction in the out-of-plane buckling length) or the addition of horizontal or diagonal members (in plan view).

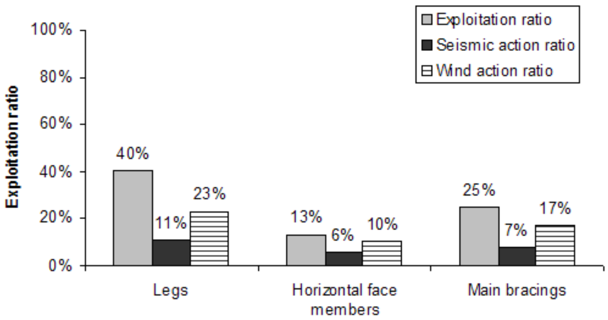
The analysis showed that masts are very vulnerable to the combined effect of wind and ice. The wind pressure by itself produces significant forces and results to high capacity ratios on the members, but combined with the ice loading, it causes the maximum displacements and many members exceed their structural capacity, see Figure 4.



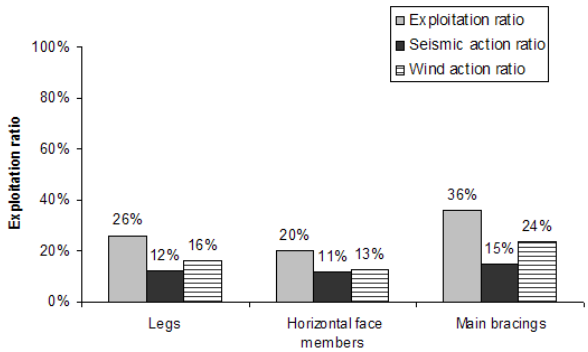
a) Mast 0.50x0.50 b) Mast 1.40x1.40 c) Mast 2.50x2.50 d) Mast 4.00x4.30

Figure 4. Deformed masts- Combination of wind and ice

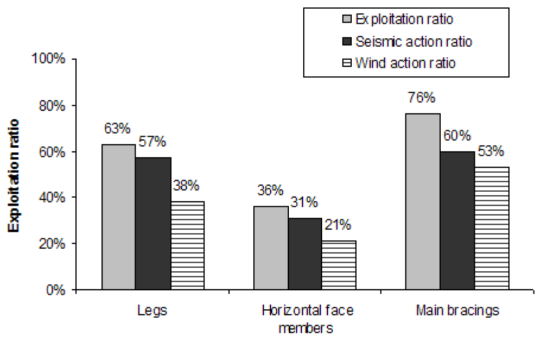
Concerning the maximum displacements at the top of the masts, these have been caused due to the combined effect of wind and ice in all analyzed cases and as the height of the mast increases, the displacements also increase. There was also a rather strong variation in the respective displacements observed due to the different distributions of aerials and dish reflectors. In addition, the size of antennas and reflectors in relation to the cross-sections of each mast, as well as their installation height play a significant role in the response of the members. In many masts, the legs and horizontal members, where these discrete ancillary items are installed, failed. For this reason, special emphasis must be shown to the number and the size of the reflectors a telecommunication mast can carry, as well issues on the strengthening of the mast in these areas.
Regarding the seismic loads, although the isolated seismic case is not critical, the dynamic analysis shows that the seismic combination G+0.3(Q+S) as well as the combination 0.3xx+yy+0.3zz and xx+0.3yy+0.3zz give rise to high stresses that reach the capacity limits. In Figure 5 the exploitation ratios, the resistance ratio along with the seismic and wind actions for each type of mast are shown. In case of masts with small relative height, the performance of the structures is not affected. However, as the height increases, the seismic combinations cause more and more negative consequences, especially in cases of the main bracings of the masts with sections 2.50x2.50, 4.30x4.00.



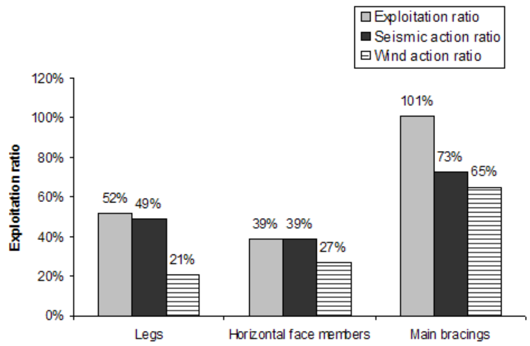
a) Mast 0.50x0.50- Height 6m



b) Mast 1.40x1.40 – Height 8m



c) Mast 2.50x2.50- Height 12m



d) Mast 4.30x4.00 – Height 17m

Figure 5. Type of steel masts and exploitation ratios

4 CONCLUSIVE REMARKS

Steel lattice telecommunication masts being slender and flexible, are subjected primarily to the environmental actions of wind and ice. Nowadays, a well-established framework of recommendations and codes is available for the design of these structures, in order to assess the wind forces in detail so that the respective mast to be able to withstand the critical situations. This way, such structures

can be analyzed and designed in an effective and safe way, whereas their peculiarities can be dealt in a correct way.
According to the assessment of a sample of steel lattice telecommunication masts, the members of the masts with sections 0.50m x 0.50m overcome their structural capacity when they carry reflectors of big diameter. Concerning the 1.40m x 1.40m, 2.50m x 2.50m και 4.30m x 4.00m structures, they are vulnerable to the combination of wind and ice loading, where it proved to be the most often cause of failure. Regarding the influence of seismic action, for masts with sections 0.50m x 0.50m and 1.40m x 1.40m which have relative small height, it is not critical to the performance of the structures. However, as the height and dimension of the section increases, the seismic combinations cause more and more negative consequences, especially regarding the main bracings and the lower part of the legs.

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