On the structural response of steel telecommunication lattice masts for wind loading and combined effects

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Keywords: Steel lattice masts, wind loadings, structural codes, combined effects

ABSTRACT

In the last years, a lot of new issues have been arisen regarding the structural behaviour of steel lattice masts which are used either for telecommunication needs or as systems to transfer energy. As environmental effects are becoming more severe and the earthquake phenomenon is taken into account in a more detailed way according to the modern codes for earthquake resistance structures, the thorough investigation of the performance of these structures becomes imperative. In addition, since these two industries become strategic and growing in today’s economy, their structural safety and stability is considered vital. In some cases the financial and social consequences caused by a possible collapse of this kind of structures are considered as damaging as those caused by the collapse of traditionally significant infrastructure, such as bridges. The present paper aims at investigating the structural response of these special structures subjected to the influence of wind loading, as well as the combination of wind loading and ice. For the purpose of the herein presented research activity, 6 types of steel masts have been analysed, namely 4 masts located on the ground and 2 masts located on buildings. The study was carried out by means of innovative software in order to introduce the wind actions as thoroughly as possible and simulation models have been configured for the masts under investigation incorporating all special geographical...
parameters and structural arrangements. The influence of the wind action on the structural behaviour of the lattice masts is highlighted through the results, whereas deformation configuration for all the masts have been developed. In the last part of the paper, conclusive remarks concerning the structural performance behaviour of each of the six types of steel telecommunication masts under the influence of wind actions, as well as the combined environmental effects have been extracted.

1. **ON THE STEEL LATTICE TELECOMMUNICATION MASTS**

1.1 **General**

Steel masts belong to the category of those special steel tower structures which are used in the telecommunication field for telephone and data transmission, as well as in energy transmission infrastructure where they usually carry cable guys. Steel masts are often flexible and light structures and their common, cost effective practice is using an open lattice, lightweight but adequately stiff system, since a lattice morphology requires only half as much material as a free-standing tubular one with similar stiffness. In addition, the lattice system enables the modularity of construction so that the masts can be transported in relatively small modules making easier to cope with difficult terrain and thus requiring less labor demands.

As in many cases, steel lattice telecommunication masts have to be often placed in spots of maximum visibility, the choice of hill or mountain peaks for their erection is obvious. They are self-supporting structures, their height varies from 5m to over 50m and they can be found located either on the ground or on the top of buildings when needed in the urban environment (Fig.1).

![Figure 1: Steel lattice telecommunication masts located on i) ground ii) buildings](image)

According to the type of the mast and the telecommunication needs, they carry dish reflectors or aerials-antennas at several heights of the structure, whereas in every tower there are platforms at different levels of the mast according to the type of the mast, in order to enable inspections and maintenance operations. Inside the structure a ladder is constructed to provide climbing access, while special systems are configured in order to stabilize the feeders which connect the reflectors and antennas with the telecommunication network (Stathopoulos & Baniotopoulos 2007).
1.2 Morphology of the telecommunication masts

Steel lattice masts are tower structures of triangular, square or rectangular plan form which in the structural design of these structures is conventionally taken as the section of the mast. In view of morphology, steel lattice masts 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 2. The legs (columns) of the mast are braced by means of main bracing of type X,K,V which transmit 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 introduced mainly in cases where the length of the horizontal face members becomes large enough in order to provide transverse stability (Cook 2007) (Fig. 2).

As far as the cross-sections of the members of the mast concern, these are usually 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 offer appear to be 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.

![Figure 2: Types of steel lattice masts and the respective bracings forms](image)

2. ACTIONS ON STEEL LATTICE MASTS

2.1 Permanent actions, imposed loadings and earthquake loading

The basic loads that are considered in the design of a steel telecommunication lattice tower are the dead loads of all the elements, the imposed live loads, the environmental loads and the earthquake action. Regarding the permanent actions on the steel mast, these include the dead load of the structure
(the self-weight), the ladder, the several dish reflectors of different diameters that a mast carries and the working platform, located at specific heights of the structure, according to the type of the mast. As far as the imposed live loading is concerned, the calculation takes into account the variable loads of the ladder and the working platform. Regarding the seismic loading, it can be particularly important in structures with high masses at the top.

2.2 Environmental actions: Wind and ice loading

As steel lattice masts are flexible structures, they are primarily affected by the environmental loading. This way the effect of wind and ice consist the primary loading of these structures, especially at high altitude (Simiu & Scanlan1996, Vayas et al. 2005). According to the current regulative norms, wind effects on steel masts can be considered either on the basis of DIN 4131 or by implementing the provisions of Eurocode1 in combination with Eurocode 3 (CEN 2005).

As DIN 4131 dictates, in order to define the wind loading, it is necessary to calculate 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 $B_\phi$ and the aerodynamic loading coefficient $f_c$ (DIN 1991). Thus, the wind loading on each reference area is calculated by means of the following formula:

$$W = f_c \cdot B_\phi \cdot q \cdot A$$  \hspace{1cm} (1)

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

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

where $h$ 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 $B_\phi$ which is equal to

$$B_\phi = B_{\phi_0} \cdot n ,$$ \hspace{1cm} (3)

where $B_{\phi_0}$ is a function of the 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 $f_c$ is a function of the wind (perpendicular or inclined action) and is defined as $f_c = c_{f_0} \cdot \psi$. The values for $c_{f_0}$ and $\psi$ are derived from the relevant nomograms from DIN 4131, as a function of the slenderness $\lambda$ 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 $\phi$.

The slenderness of the tower is given by means of the relations:

$$\lambda = 0.7h/b , \text{ for } h > 50m$$ \hspace{1cm} (4)

$$\lambda = h/b , \text{ for } h < 150m ,$$ \hspace{1cm} (5)

whereas $h$ is the height of the tower above ground and $b$ is the width of the tower at $h/2$ ($b$ is measured perpendicularly to the wind direction). For intermediate $h$ values, linear interpolation may be used.

Regarding the Eurocode provisions, the mast is divided into a series of sections, where a section comprises several identical or nearly identical panels. When determining the projected area of the structure, the projections of bracing members in faces parallel to the wind direction, as well in plan and hip bracing are omitted. The structure is divided into a sufficient number of sections to enable the wind loading to be adequately modeled for the global structural analysis.

According to Eurocode 1, the wind force is equal to:

$$F_w = c_s c_d \sum c_f q_p(z_i) A_{ref} ,$$ \hspace{1cm} (6)
where \( c_f \) is the force coefficient for the structure or structure element, \( A_{ref} \) is the reference area of the structure or structural element, \( q_p(z_e) \) is the peak velocity pressure at reference height \( z_e \) and \( c_s c_d \) is the structural factor which takes into account the effect of wind actions from the non-simultaneous occurrence of peak wind pressures on the surface together with the effect of the vibrations of the structure due to the turbulence.

The Eurocode framework provides analytical expressions for evaluating the wind drag of square or equilateral triangular lattice structures. The total wind force coefficient \( c_f \) in the direction of the wind over a section of the structure should be taken as

\[
\sum c_f = c_{f,S} + c_{f,A}
\]

(7)

Where \( c_{f,S} \) is the wind force coefficient of the bare structure section, calculated by using the solidity ratio \( \phi \), appropriate to the bare structure, and \( c_{f,A} \) is the wind force coefficient of the ancillaries. In cases, where the projected areas of ancillaries on each face are within 10% of each other, they are considered as appropriate structural members.

For a lattice mast of square or equilateral triangular plan form, having equal area on each face, the total wind force coefficient \( c_f \) of a section in the direction of the wind:

\[
c_{f,S} = K_o c_{f,S,0},
\]

(8)

where \( c_{f,S,0} \) is the overall normal drag (pressure) coefficient of a section \( j \) without end-effects and \( K_o \) is the wind incidence factor which has different calculation expressions for square masts and for triangular structures.

Regarding the peak velocity pressure, it is depended from the mean wind velocity. This parameter is the 10-minute mean wind velocity at a specified height above ground appropriate for the exposure of the site under consideration. The mean wind velocity \( v_m(z) \) at a height \( z \) above the terrain depends on the terrain roughness and orography and on the basic wind velocity \( v_b \) and is determined using the following expression:

\[
v_m(z) = c_r(z) c_o(z) v_b,
\]

(9)

where \( c_r(z) \) is the roughness factor, \( c_o(z) \) is the orography factor, which are usually taken as 1.0. It is noteworthy that the value of \( c_o \) is defined in the National Annex of each country. If the orography is accounted for in the basic wind velocity the recommended value is 1.0. In addition, design charts or tables for \( v_m(z) \) may be given should be considered. The influence of neighboring structures on the wind velocity should be considered (CEN 2004).

The basic wind velocity \( v_b \) is equal to:

\[
v_b = c_{dir} c_{season} v_{b,0}
\]

(10)

In this expression \( v_{b,0} \) is the fundamental value of the basic wind velocity which is different for every country, \( c_{dir} \) is the directional factor and \( c_{season} \) is the season factor. The recommended value for the both last factors is equal to 1.0, but there are values for every country in the National Annex.

The Eurocode regulative framework provides analytical expressions for the calculation of the roughness factor at a height \( z \), which accounts for the variability of the mean wind velocity at the site of the structure due to the height above ground level or the ground roughness of the terrain upwind of the structure in the wind direction considered.

According to the detailed procedure described in Eurocode 1, the structural factor \( c_s c_d \) is equal to:

\[
c_s c_d = \frac{1 + 2 k_p i_v(z_e) \sqrt{B^2 + R^2}}{1 + 7 i_v(z_e)},
\]

(11)

where \( z_e \) is the reference height, \( k_p \) is the peak factor defined as the ratio of the maximum value of
the fluctuating part of the response to its standard deviation, $I_\nu$ is the turbulence intensity, $B^2$ is the background factor and is the resonance response factor, allowing for turbulence in resonance with the vibration mode.

2.3 Ice loading

The effect of ice is introduced in the design of lattice masts 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 ((DIN 2002, CEN 2004). This way, the distributed load is applied along all structural members, components of ladders, ancillaries etc. proportionally to the thickness of the element and the unit weight of the ice, 7kN/m³.

![Figure 3: i) Iced conditions on steel telecommunication lattice mast ii) Influence of ice on angle cross-sections](image)

2.4 Combined effects

In determining the wind force under iced conditions, the projected areas of structural elements and ancillaries should be increased to take due account the thickness of ice. In this case, the wind resistance of a structure and ancillaries under iced conditions for each element of the structure, ancillary parts and guys should be taken as coated on all sides by ice with a thickness of that given in Annex C. According to relevant codes, where the gap between components not iced is less than 75mm, this should be assumed to be completely filled by ice under icing conditions, whereas the force coefficients of individual members are obtained from the respective provisions.

3. STUDY OF THE STEEL LATTICE MASTS: ANALYSIS AND RESULTS

In the last years, the changes and additions in the normative framework of actions on the masts, the installation new dish reflectors and antennas in combination with the new provisions of the codes for earthquake resistance structures, especially in countries like Greece where seismic risk is high, created the need for investigating the existing telecommunication network in new perspective (Dasiou et al. 2008, Vayas et al. 2005, Tsitlakidou et al. 2005). The steel lattice masts under
investigation cover a big part of the steel telecommunication mast industry of Greece, where a large number of these tower structures which was built in the decades 1970s-1980s, are characterized by a variety of constructional arrangement (Hatzinikolis et al. 2008).

The present paper deals with the study of the four most commonly used types of steel lattice telecommunication towers located on ground as well as with two masts located on top on buildings, and focuses on their behaviour especially regarding the influence of the environmental actions and the combined effects 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 x 1.40m, 2.50m x 2.50m and 4.30m x 4.00m, are studied. The study also included two types of masts located on the top of buildings in an urban environment with sections 3.00m x 4.80m and 4.00m x 6.40m. Each mast has different cross sections, while the number and the size of the dish-reflectors and aerials also differ. In Table I, the sections of the main members of the structures, namely the legs, the horizontal face members are shown with respect to the dimension of each mast.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Legs</th>
<th>Horizontal face members</th>
<th>Main bracings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50m x 0.50m</td>
<td>L80x8</td>
<td>L70x7</td>
<td>L45x5</td>
</tr>
<tr>
<td>1.40m x 1.40m</td>
<td>L80x10</td>
<td>L60x6</td>
<td>L60x6</td>
</tr>
<tr>
<td>2.50m x 2.50m</td>
<td>L80x10</td>
<td>L70x7</td>
<td>L60x6</td>
</tr>
<tr>
<td>4.30m x 4.00m</td>
<td>L120x12, L110x10</td>
<td>L70x7</td>
<td>L60x6</td>
</tr>
<tr>
<td>3.00m x 4.80m</td>
<td>L100x10</td>
<td>L70x7, L80x8</td>
<td>L70x7</td>
</tr>
<tr>
<td>4.00m x 6.40m</td>
<td>L150x15, L110x10</td>
<td>L70x7</td>
<td>L70x7</td>
</tr>
</tbody>
</table>

Table I: Cross-sections of the steel masts under investigation

The mast with dimension 0.50mx0.50m has height equal to 6m, while the 1.40x1.40 mast is 8m tall. In the case of the 2.50m x 2.50m mast the height is h=12m, while the mast of 4.30x4.00 has height equal to h=18m. As far as the masts that are located on the top of buildings is concerned, their height is 12m for 3.00m x 4.80m mast and h=15m in the case of the mast with base dimension 4.00x6.40, whereas an additional parameter in the analysis is the height of the buildings, which is equal to 10m and 17.65m respectively. All special features of the material, the used bolts, as well as the geometrical parameters and local conditions were incorporated in the simulation models, see Figure 4.
The basic loads considered in the study of the masts were the dead loads of all the elements, the imposed live loads, the environmental loads and the earthquake action. Regarding the permanent actions on the steel mast, these included the dead load of the structure (the cross-sections used), the ladders, the antennas and the platforms. As far as the imposed live loading is concerned, the calculation was carried out taking into account the variable loads of the staircase and the working deck.

For the purposes of this research, the determination of the wind loads was carried out on the basis of DIN 4131, which provides the methodology for all the relevant calculations. It should be noted here that DIN 4131 being a complete and extensively tested group of rules gives very similar results to EC1, while it is generally compatible with the Eurocodes applied later in the analysis (Efthymiou & Baniotopoulos 2008).

Regarding the effect of ice and for simplification purposes, it was taken into account by increasing the cross-section of all the structural elements by two times 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. As far as the seismic analysis of the structures is concerned, it was based on a Spectral Response Analysis, which was performed according to the Codes, taking into account the special regional characteristics of the specific mast (EPPO 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:

$$\Phi_d(T) = \frac{n \cdot A \cdot g \cdot \gamma_1 \cdot \theta \cdot \beta_0}{q},$$

whereas $\gamma_1$ is the importance factor, $\theta$ 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 simplification reasons a soil category B is applied and all the temperature and aero elastic phenomena effects are disregarded. In the case of the steel masts located on buildings, the wind velocity changes as the height is increasing by the height of the building, whereas the introduction of the earthquake loading is changing according to the codified provisions.

The basic load combinations for which the internal forces and moments were calculated are shown in Table II.

<table>
<thead>
<tr>
<th>A/A</th>
<th>Load Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.35G+1.5Q</td>
</tr>
<tr>
<td>2</td>
<td>1.35G+1.5W_0</td>
</tr>
<tr>
<td>3</td>
<td>1.35G+1.5W_0+0.9Q</td>
</tr>
<tr>
<td>4</td>
<td>1.35G+1.5W_0s+1.5S</td>
</tr>
<tr>
<td>5</td>
<td>1.35G+1.5W_0s+1.5S+0.9Q</td>
</tr>
<tr>
<td>6</td>
<td>1.35G+1.5S+0.9Q</td>
</tr>
<tr>
<td>7</td>
<td>G+0.3S+0.3Q±E</td>
</tr>
</tbody>
</table>

Table II: Basic loading combinations

For each mast, the internal forces and moments were calculated and the members of every mast, i.e. the legs, the horizontal face members, the main, secondary and plan bracing were checked by means of the provisions of Eurocode 3 (CEN 2002).

The results had shown that in all types of masts, the most severe action is the combination of wind with ice loading. In Figure 5 the exploitation ratios, namely the resistance ratio along with the wind actions for each type of mast are shown. The combined effect of wind and ice is the critical loading condition which in many cases it led to exceeding the strength of the steel mast members. Based on the analyses at hand, it is stated that wind action can be considered as the primary environmental action that has to be taken into consideration in the design of the steel lattice masts.
In addition, as the height increases, the lower part of the legs exhibits inadequacy, while the members used for the plan horizontal bracing and the platforms 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 the out-of-plane motion (reduction in the out-of-plane buckling length) or the addition of horizontal or diagonal members (in plan view).

Regarding the seismic loads, although the isolated seismic case is not a critical one, the dynamic analysis shows that the seismic combination gives rise to high stresses that reach the capacity limits. 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 on the ground with sections 2.50x2.50, 4.30x4.00 and the mast located on buildings.

With respect to the deformations developing at the top of the steel lattice masts, in Figure 6 the maximum values of the horizontal displacements are depicted. It is observed that the maximum displacements have been caused due to the combined effect of wind and ice and as the height of the mast increases, the displacements increase.

![Horizontal displacement Ux(mm)](image1)

![Horizontal displacement Uy(mm)](image2)

Figure 6: Maximum horizontal displacement at the top of each mast

Note that in the previous diagrams, rather strong variation in the respective displacements is observed due to the different distributions of aerials and reflectors.

4. CONCLUSIVE REMARKS

Nowadays, a well-established framework of recommendations and codes is available for the design of steel lattice telecommunication masts 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.

The analysis showed that the predominant loads of steel lattice masts are the wind and the ice, as well as their combination. As slender structures, the masts are especially sensitive to the wind and their structural behaviour is strongly affected by the environmental actions. The wind pressure 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. Ice on a mast causes additional weight and this changes the dynamic behaviour as well as it can increase the wind drag of the lattice structure in a dramatic way.
ACKNOWLEDGEMENTS

The authors would like to thank Ass. Professor Dr. Civil Engineer E. Koltsakis for the development of the innovative analysis software “Istos” that was used in the study of the masts for the evaluation of the wind in a very automatic and detailed manner. Parts of the herein described research work has been performed within the framework of the project “Assessment, Ranking and Reduction of the Seismic Risk of the National Telecommunications Network”, supported by the Greek General Secretariat of Research and Technology and the National Telecommunication Organization of Greece (OTE).

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