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Alongwind load effects on free-standing lattice towers

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ABSTRACT

Free-standing lattice towers are structures used for various purposes such as radio and television broadcasting, electric power and microwave transmission, meteorological measurements, wind energy production and so on. Due to their properties, they are mainly sensitive to wind loads. A longstanding discussion on the wind loading effects on this structural type has been carried out in the literature. This paper investigates the alongwind load effects on free-standing lattice towers by introducing specific influence functions of displacements, shear forces, bending moments and axial forces in leg elements. Such influence functions are first derived, calibrated and validated for the most typical structural types, then they are used within the framework of the gust effect factor technique. Comparative studies with reference to both the traditional use of cantilever beam approaches and finite element methods point out the role of the bracing pattern and, more precisely, of the level of the crossing of diagonals in tower panels. All the applications developed here refer to real structures with different properties. Results are interpreted and compared with those provided by previous studies on this structural type. Engineering and design issues are discussed focusing on the most critical aspects concerning dynamic wind loads.

1. Introduction

Free-standing lattice towers are structures used for various purposes such as radio and television broadcasting, electric power and microwave transmission, meteorological measurements, wind energy production and so on. In Romania, such structures are used extensively by the local mobile network operators which have recently started collaborating on the infrastructure by using joint telecommunication towers; their importance is testified by the circumstance that, due to recent technological changes, many of these towers needed to be mounted with additional equipment resulting in an increase of the wind-exposed surface. Consequently, they required rehabilitation in order to satisfy the safety issues resulting from the load increase. Another important aspect is related to the most recent change of the Romanian wind code (CR 1-1-4, 2012) which prompted insurance companies to ask for expert evaluation of the towers in order to properly evaluate their insurance value.

Due to their properties, free-standing lattice towers are mainly sensitive to wind loads that produce both shear forces and bending moments. Shear forces are resisted by web members whereas bending moments give rise to axial forces resisted by leg members. Leg members may be arranged either in a square or in equilateral triangular shape with typical cross-sections including single angles, tubes, solid rounds as well as built-up cross-sections with two angles in cruciform section or back to back. Commonly used bracing patterns of web members are single diagonal bracings (N), cross bracings (X, XB, XBX), K bracings, V bracings, arch bracings, W bracings, etc. (Dalban et al., 1976; Punmia et al., 1998; Madugula, 2001; Eurocode 3, 2006) as shown in Fig. 1. Secondary bracing may be provided in order to stabilize legs.

The response of lattice towers to wind loads is typically evaluated by dividing the tower into a number of panels, of approximately equal length, and applying the loads in the nodal points at the interface of subsequent panels. All members are assumed to be hinged at joints, the loads being resisted only by internal axial forces. Leg members are loaded in compression due to gravity loads and in tension and compression due to wind loads whereas bracing members work either solely in tension or in alternating tension and compression, depending on the bracing pattern. Plan (horizontal) bracings may be provided at the level of the crossing of diagonals to subdivide the primary vertical bracing system. These are redundant members used to reduce the buckling length of the horizontal members as well as to provide transverse stability. Structural analyses are usually carried out by Finite Element Methods (FEM), by simplified cantilever beam approaches, or by suitably mixing these two evaluation techniques.

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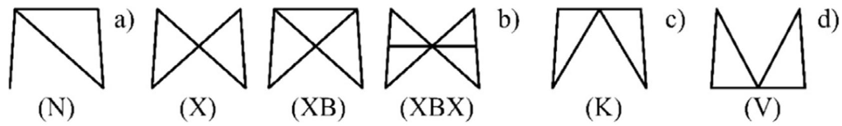

Fig. 1. Bracing patterns: (a) single diagonal bracing; (b) cross bracing; (c) K bracing; (d) V bracing.

Alongwind loads on cantilever vertical structures, and in particular on free-standing lattice towers, are classically evaluated by the method introduced by Davenport (1961, 1967). He expressed the maximum alongwind displacement as the product of the mean static displacement by a non-dimensional coefficient, the gust response factor (GRF), that takes into account only the first flexural mode of vibration. Accordingly, he defined the equivalent static force (ESF) as the force that statically applied on the structure causes the maximum displacement. Exploiting structural linearity, the ESF is the product of the mean static force by the GRF. By this method a unique load pattern provides all the desired wind load effects. An application of the GRF technique to a free-standing lattice tower has been reported by Lungu and Ghiocel (1982). Closed form solutions (CFS) of the GRF have been developed by Solari (1982, 1983, 1993a, 1993b).

Research from the 90's derived from noting that the ESF, as conceived by Davenport (1961, 1967), usually furnishes correct estimates of maximum displacements, but may lead to poor evaluations of other load effects. Kasperski (1992) developed the Load Response Correlation (LRC) technique, a method by means of which the quasi-static part of the ESF is the most probable load pattern for each specified load effect. Holmes (1994, 1996a, 1996b) applied this concept to derive effective wind load distributions and a CFS for the maximum displacements, bending moments and shear forces at any level of a free-standing lattice tower. Other authors applied analogous methods to various structural types (Davenport, 1995; Zhou and Kareem, 2001; Holmes, 2002), sometimes deriving a CFS. The common aspect of all these approaches is a clear separation among the static, quasi-static and resonant parts of the response: the first and the second ones are evaluated by influence function technique, thus taking all modes of vibration into account; the third one retains the contribution of only the first flexural mode.

In parallel, Piccardo and Solari (1998a, 2000) evaluated the alongwind, crosswind and torsional (3-D) response of slender structures and structural elements in closed form by the 3-D GRF technique, a method that generalizes the Davenport's GRF to the 3-D case. Starting from this framework, a CFS of the most relevant wind load effects at any level of a cantilever slender vertical structure, namely displacements, bending moments and shear forces, was also derived through a non-dimensional coefficient, the 3-D Gust Effect Factor (GEF) (Piccardo and Solari, 2002; Solari and Repetto, 2002), which extends the 3-D GRF through the Generalized Equivalent Spectrum Technique (Piccardo and Solari, 1998b). General methods for determining the ESF were discussed by Repetto and Solari (2004).

This paper investigates the alongwind load effects on free-standing lattice towers by introducing specific influence functions of displacements, shear forces, bending moments and axial forces in leg elements. Such influence functions are first derived, calibrated and validated for the most typical structural types, then they are used in the framework of the GEF technique. Comparative studies with reference to both the traditional use of cantilever beam approaches and FEM analyses point out the role of the bracing pattern and, more precisely, of the level crossing of diagonals in tower panels. All the applications developed here refer to real structures with different properties. The results obtained are interpreted and compared with those provided by previous studies on this structural type (Ballio et al., 1992; Holmes, 1994, 1996a, 1996b; Glanville and Kwok, 1995; Harikrishna et al., 1999; Lou et al., 2000; Loredo-Souza and Davenport, 2003). Engineering and design issues are discussed focusing on the most critical aspects concerning free-standing lattice towers subjected to dynamic wind loads.

Section 2 illustrates the wind velocity model used herein. Section 3 recalls the fundamentals of the GEF technique as applied to cantilever beams in order to evaluate alongwind load effects. Section 4 describes the most typical geometrical configurations adopted for free-standing lattice towers as well as their dynamic and aerodynamic parameters. Section 5 introduces new specific definitions and expressions for the influence functions of this structural type, discussing their role with reference to both static and dynamic evaluations. Section 6 analyses the wind-induced response of the lattice towers described in Section 4, comparing the use of different approaches. Conclusions and some prospects are drawn in Section 7.

2. Alongwind velocity

Let us consider a Cartesian reference system x, y, z with origin at O on a flat homogeneous terrain; z is the vertical axis directed upwards; x and y are horizontal axes orthogonal to z. The wind velocity is expressed by the relationship:

$$u(z;\, t) = \bar{u}(z) + u'(z;\, t) \tag{1}$$

where z is the height above ground, t is the time, $\bar{u}$ is the mean wind velocity aligned with x, u' is the zero-mean longitudinal turbulence component, treated as a stationary Gaussian random process. Since this paper aims at investigating the alongwind response, the lateral and vertical turbulence components are here disregarded (Solari and Piccardo, 2001; Solari and Tubino, 2002). The atmosphere is dealt with as neutrally stratified. The applications developed in Section 6 adopts a wind model coherent with the Eurocode 1 (2005).

Accordingly, the mean wind velocity profile is defined as:

$$\bar{u}(z) = \frac{1}{\kappa} u_* \ \ln\ \frac{z}{z_0} = \bar{u}_{ref} k_r \ \ln\ \frac{z}{z_0} \tag{2}$$

where κ is the Kármán constant, u_* is the shear velocity, z_0 is the roughness length, $\bar{u}_{ref}$ is the reference mean wind velocity (i.e. the mean wind velocity at 10 m height on a flat homogeneous terrain with roughness length $z_{0,ref}=0.05$ m and 50 years return period), $k_r = 0.189\left(z_0/z_{0,ref}\right)^{0.07}$.

The longitudinal turbulence component u' is defined by its cross-power spectral density (CPSD):

$$S_{uu}\left(z, z';\, n\right) = \sqrt{S_u(z;\, n) S_u\left(z';\, n\right)}\ Coh_u\left(z, z';\, n\right) \tag{3}$$

where z' is a height above ground, n is the frequency; S_u and Coh_u are, respectively, the power spectral density (PSD) and the coherence function of u':

$$\frac{nS_u(z,\, n)}{\sigma_u^2} = \frac{6.868 n L_u(z)/\bar{u}(z)}{\left[1 + 10.302 n L_u(z)/\bar{u}(z)\right]^{5/3}} \tag{4}$$