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Technical paper

Static and dynamic approach to the analysis of wind gusts in case of a tower H=110 m*

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ABSTRACT
Steel lattice towers have large application in meteorology, and are regularly exposed to loads difficult to determine reliably, like wind and ice, and especially wind gusts and accompanied structural vibrations. EN 1993-3-1 treats such structures and requires checking of vibrations, but does not supply methodology for it, neither allowed values for deformation and vibrations. The paper presents analysis of a tower 110 m high using the Finite Element Method (FEM), in case of wind gust, for iced and non-iced structure, both statically and dynamically. The results were compared and recommendations for future treatment of such sensitive structures were given.

The meteorological tower structure

The analysed structure is a triangular lattice tower with total height of 110 m, and base length of 4.40 m (Fig. 1). The location of the tower is Vršac, Serbia, a region with severe winds. The structural and load data are taken from the expertise [2].

1 Wind and ice loads on towers

In this analysis, attention is paid to loads dominant for this type of structure: self-weight and wind action. Wind action is often associated with icing, which increases the self-weight and aerodynamic drag. Besides, the wind action itself is a highly stochastic phenomenon. Usually it consists of some steady air stream, known as "wind mean action" (WM), and intermittent wind gusts (WG), which can cause significant vibrations of the structure. Both components are commonly calculated using static analysis, and superimposed.

The standard [4] requires that towers and masts be examined for gust induced vibrations in the wind direction. However, it does not specify the methodology for such checking.

The idea of this investigation was to compare structural behaviour of a realistic sample structure applying two different approaches:

1. Analysis of the load case self-weight + wind mean action + wind gust (G+WM+WG) using FEM static analysis.
2. Analysis of the load case self-weight + wind mean action (G+WM) using static approach, and then applying the wind gust load (WG) on such deformed structure, using FEM dynamic time-history analysis (Specific details of the methodology used for this approach are given in further text).

Both approaches are conducted for ice-free and for iced tower, in order to investigate the influence of icing on the structure. The ice loading was taken from the expertise [2], with adopted ice density of ρ=900 kg/m^3, as the most unfavourable value. Modelling of the iced tower showed significant mass increase. Namely, the structural mass was 18270 kg, mass of the ice 8960 kg, (additional 46%), and total mass 27230 kg. Ice also affects the natural frequency of the structure, altering it from f_1=0.5012 Hz (ice-free) to f_1=0.3869 Hz (iced).

2 FE analysis of the tower

2.1 FE modelling and analysis parameters

The tower structure model is based on the model analysed in [5], and using the standard [1]. The adopted FE mesh was obtained by division of every structural member into eight FE.

The dynamic analyses were conducted for a series of ten load frequency values, ranging from 10 % of the resonant frequency (K = 0.1) up to 100 % of the resonant frequency (K = 1.0), see *Table 2, 3*. The idea was to investigate the influence of different excitation frequencies, including the resonant one, on behaviour of the structure and on its serviceability and strength.

The overall structural damping factor (G) is calculated based on the relationship between the structural damping coefficient (G) and the relative damping (ξ):

$$\xi = \frac{G}{2} \Rightarrow G = 2\xi \tag{1}$$

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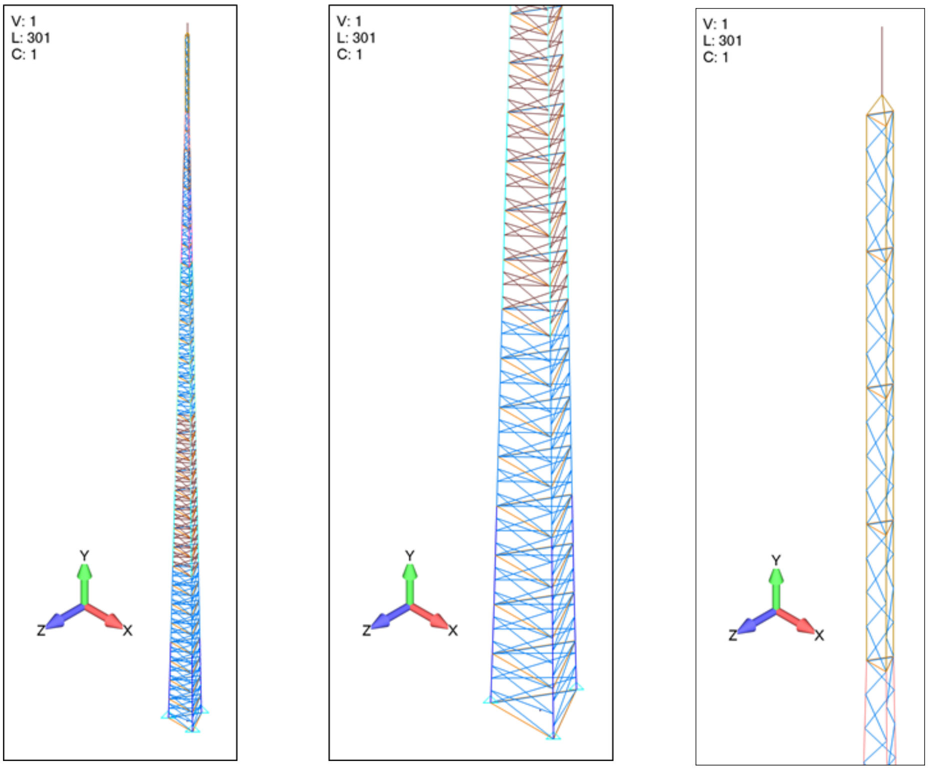

Figure 1. Tower geometry; a) global view; b) bottom part - detail; c) top part - detail

Based on the equation (1) and adopted relative damping ξ = 0.05, recommended for steel structures, the overall structural damping factor is calculated as G = 0.10. The system damping frequency (denoted as *W3* in [6]) was adopted based on the frequency of the 1st mode of oscillation, that is, W3 = 0.5013 Hz (ice-free tower), and W3 = 0.3869 Hz (iced tower).

As mentioned, the main idea was to superimpose the dynamic action of the wind gust on the tower structure that is already statically deformed by the basic load case (G+WM). For that purpose, a set of two load functions were created. The first function, simulating static G+WM action was defined as time-dependent, using bilinear function. According to this, the load rises linearly from zero to full value in a relatively short period, t=5 s, and from then on holds this steady value. The time interval between t_1=5 s and t_2=20 s is intended for damping of the oscillations which unavoidably arise by applying this part of the load. Consequently, the G+WM load function is formally a dynamic one, although its action on the structure has static character. For the purpose of clarity, we denoted it as quasi-static (Table 3, 4). The second function that simulates the gust wind action is a sine function, and has a zero value from t_0=0 s to t_2=20 s. At t_2=20 s starts the sine function and lasts for one oscillation period (T_c). Lasting time of this period varies depending on the excitation frequency of the wind gust, which was varied as described above. After one sine period, the wind gust function takes zero value in order to enable damping of the structure, and it ends at t_3=60 s. The complete loading process is presented on diagrams in Figures 2 and 3.

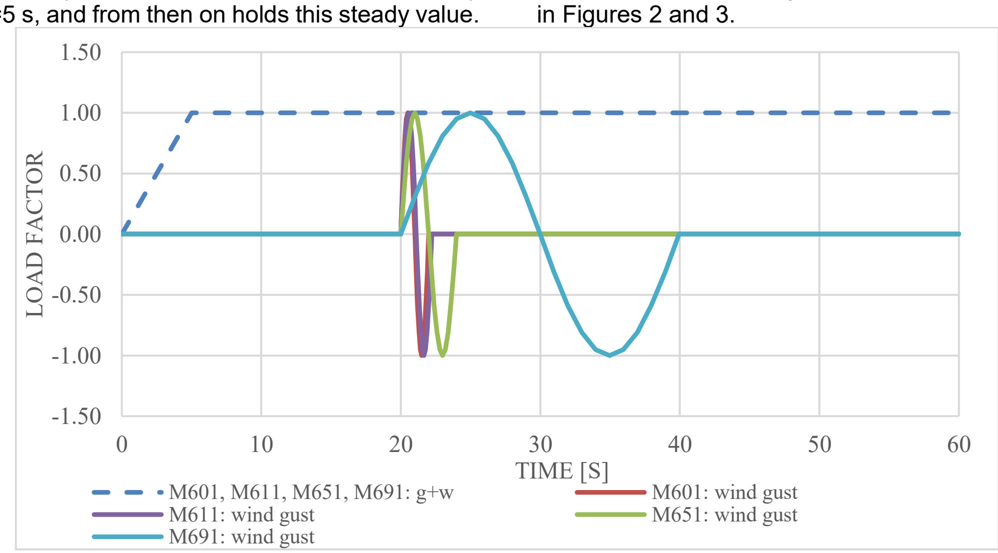

Figure 2. Ice-free tower: load factor vs. time

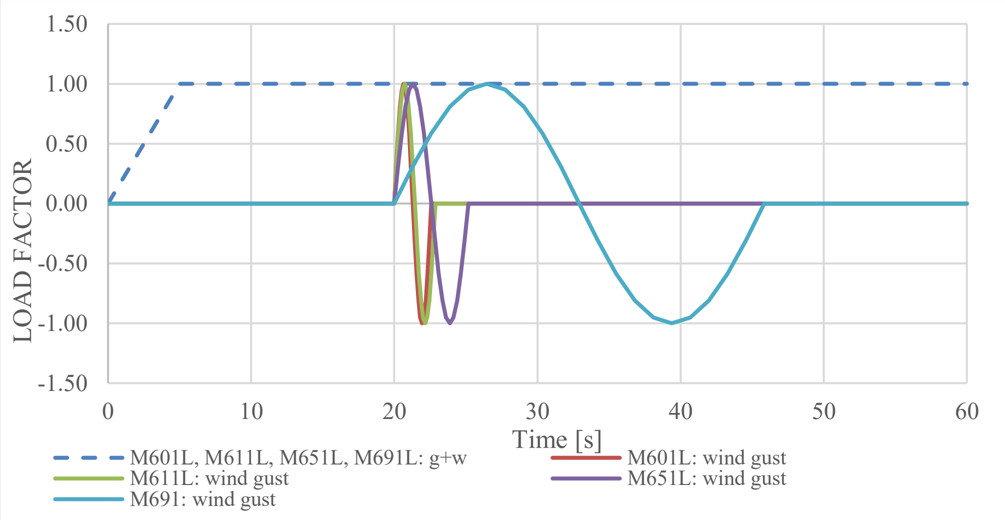

Figure 3. Iced tower: load factor vs. time

2.2 FEM analysis results and discussion

The structural displacements of the top of the tower in the wind direction (Z) were selected as main serviceability value, and the max. and min. stresses were taken as strength check data.

Characteristic input and output analysis data are presented in the Tables 1 and 2 and on diagrams in Fig. 4 and 5.

Table 1. Ice-free tower – static and dynamic analysis; f_1=0.5013 Hz; G=0.1; W_3=0.5013 Hz

Model	Load freq. factor K [-]	Total load duration ts [s]	No. of steps n [-]	Zmax [m]	Smax [MPa]	Smin [MPa]
M601	1.00	60	600	6.203	211	-412
M611	0.90	60	600	**6.345**	**219**	**-426**
M621	0.80	60	600	6.293	217	-423
M631	0.70	60	600	5.735	197	-383
M641	0.60	60	600	4.970	162	-316
M651	0.50	60	600	4.907	157	-307
M661	0.40	60	600	4.740	150	-292
M671	0.30	60	600	4.432	138	-270
M681	0.20	60	600	3.918	121	-238
M691	0.10	60	600	3.887	120	-235
M600	G+WM	STATIC	1	**2.176**	**79**	**-157**
M600	G+WM+WG	STATIC	1	**3.816**	**135**	**-263**

G= Self-weight; WM= Wind mean value; WG= Wind gust

Table 2. Iced tower – static and dynamic analysis; f_1=0.3869 Hz; G=0.1; W_3=0.3869Hz

Model	Load freq. factor K [-]	Total load duration ts [s]	No. of steps n [-]	Zmax [m]	Smax [MPa]	Smin [MPa]
M601L	1.00	60	600	7.810	277	-542
M611L	0.90	60	600	**7.970**	**286**	**-559**
M621L	0.80	60	600	7.893	284	-555
M631L	0.70	60	600	7.337	262	-514
M641L	0.60	60	600	6.532	223	-437
M651L	0.50	60	600	6.452	217	-427
M661L	0.40	60	600	6.267	209	-411
M671L	0.30	60	600	5.931	196	-387
M681L	0.20	60	600	5.398	179	-353
M691L	0.10	60	600	5.393	178	-350
M600L	G+WM	STATIC	1	**3.624**	**143**	**-285**
M600L	G+WM+WG	STATIC	1	**5.266**	**202**	**-389**

G= Self-weight; WM= Wind mean value; WG= Wind gust

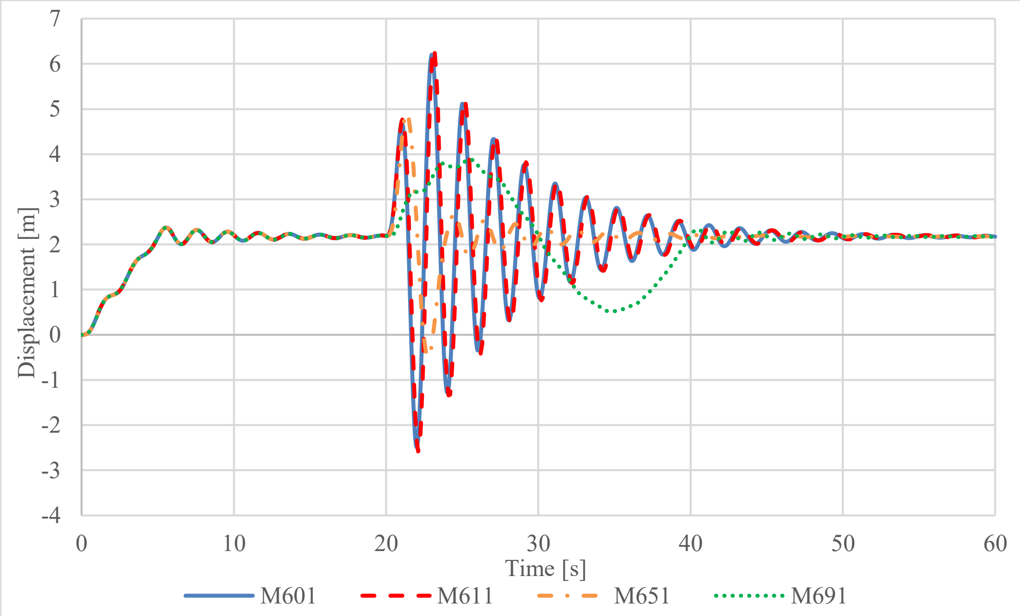

Figure 4. Ice-free tower: displacements of the top of the tower

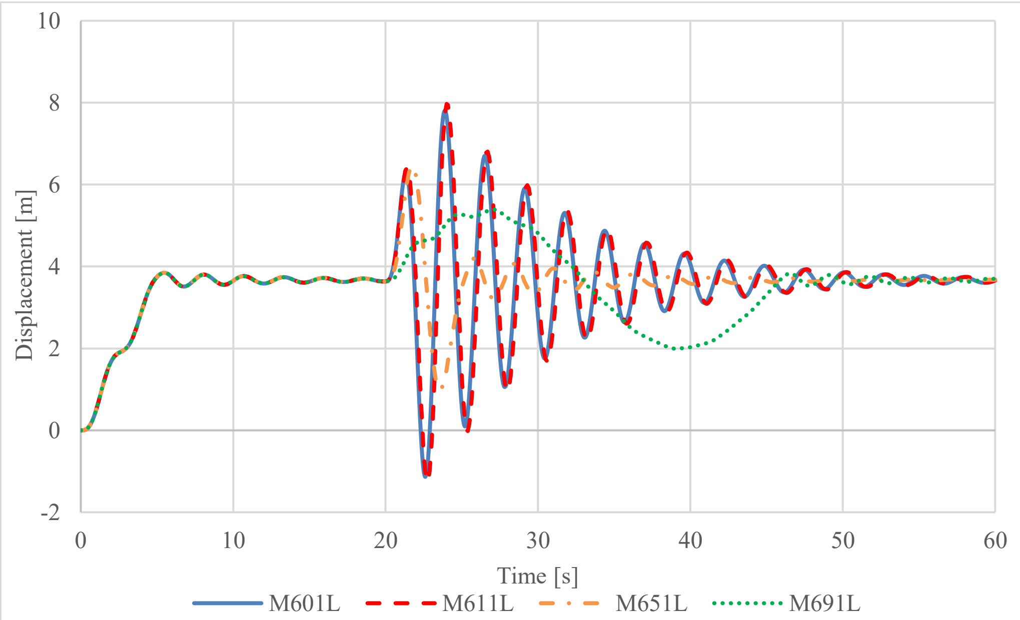

Figure 5. Iced tower: displacements of the top of the tower

Based on the obtained analysis results presented in tables 1 and 2 and in figures 4 and 5 a comparison was done, separately for the ice-free and the iced tower (Table 3 and 4). For comparison extreme values of displacements and stresses were taken. The load case G+WM, analysed statically, was adopted as a starting point, and its results were declared as 100 % value. In the second step, the wind gust was added, and this load case (G+WM+WG) was again analysed statically. The third step in fact represents the focal point of this paper. Here the wind gust was analysed using dynamic time-history analysis.

Table 3. Ice-free tower – comparison of results

Load and analysis method	Zmax [m]	Zmax [%]	Smax [MPa]	Smax [%]	Smin [MPa]	Smin [%]
G+WM (STATIC)	2.176	**100**	79	**100**	-157	**100**
G+WM+WG (STATIC)	3.816	**175**	135	**171**	-263	**168**
G+WM(QUASI-STATIC) + WG(DYNAMIC)	6.345	**192**	219	**277**	-426	**271**

Table 4. Iced tower – comparison of results

Load and analysis method	**Zmax [m]**	**Zmax [%]**	**Smax [MPa]**	**Smax [%]**	**Smin [MPa]**	**Smin [%]**
G+WM (STATIC)	3.624	**100**	143	**100**	-285	**100**
G+WM+WG (STATIC)	5.266	**145**	202	**141**	-389	**136**
G+WM (QUASI-STATIC) + WG (DYNAMIC)	7.970	**220**	286	**200**	-559	**196**

The first observation is that wind gust, even taken as a static load, increases all relevant output data, e.g., displacements rise for 75 % (ice-free tower) and 45 % (iced tower). The stresses were also significantly higher (see Table 3 and 4). That points to a strong recommendation that such high and slender structures should be obligatory checked under gust action, according to the standards [3].

However, the third analysis step, with the dynamic approach to gust action shows further considerable increase in displacements and stresses. This poses a very important question: is static analysis of wind actions satisfying for towers and similar structures? The obtained results obviously show that the answer is – no. Here must be noticed that Tables 3 and 4 present the most unfavourable results, which arise at frequencies of the gust excitation close to the resonant ones. But, a close look into the output data given in Tables 1 and 2 shows that displacements start to rise even if the gust excitation is only 10 % of the resonant frequency, compared to the static approach to gust action.

The results of the dynamic analysis are expected, but with one unexpected anomaly – the maximal displacements do not occur for the excitation frequency (K=1.0), but for a little lower value (K=0.9). This can be ascribed to some numerical error of the software, and certainly indicates that smaller frequency increments around resonance should be applied in the analysis, which will be the subject of the further investigations.

General view on the analysis results, especially the stresses, show that the selected structure could not satisfy criteria for safety and strength. Regardless of that, it was used for demonstration purposes of the importance of appropriate structural analysis method. Also, it must be noted that all analyses were done as linear, meaning that stability problems were nor treated. By all means, including of nonlinearity would be the next step of this research. It is reasonable to expect that noticed differences between the static and dynamic approach be even higher.

3 Conclusions

Based on the presented research, the following conclusions are drawn:

- Towers, masts, and similar structures are exposed to severe meteorological loads, and the most critical are wind, ice, and wind gust;
- Eurocode standards provide checking of towers and masts on wind gust induced vibrations in the wind direction, but do not supply concrete procedures for this;
- In this paper is developed an FEM model and load functions that enable a dynamic analysis of the wind gust, combined with the static action related to self-weight of the structure and wind mean action;
- The proposed method showed that application of dynamic analysis of the wind gust is strongly justified, because it showed significantly higher values of displacements and stresses compared to static wind gust analysis, mostly in the resonant domain, but also out of it;
- The FEM and application of advanced engineering software are a powerful tool for more reliable analysis of sensitive classes of structures like towers and masts, and make the approximate methods like the quasi-static method unjustified.

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