Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 3154-3162

ECCOMAS Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

TUBULAR STEEL LATTICE TELECOMMUNICATION TOWERS, SUBJECTED TO WIND LOADING AND VORTEX SHEDDING

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Keywords: lattice steel towers, wind vortex induced vibrations.

Abstract. *The main goal of this work was to evaluate the response of the diagonals members of steel lattice towers with circular cross-sections under the wind load determined according to the current regulation EN1991-1-4. For the purpose of this study a program in VBA using Excel was developed to evaluate the response of lattice steel towers to vortex shedding induced vibrations and possible failure due to fatigue. A design example was dealt with some possible detail.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5635.20402

1. INTRODUCTION

The telecommunication tower design is strongly influenced by the project requirements. For lattice towers it is necessary to analyse the loading effects on its slender members as well as their resistance. One of the crucial analyses is related with the dynamic wind loading, which can lead to local failure of members and may create a chain of consecutive failures. This would lead to the tower structure loss of resistance and stability, leading eventually to global failure. Thus, wind related phenomenon like vortex shedding should and must be considered.

In the worst scenario, vortex shedding can create small medium and large amplitudes resonant vibrations corresponding to oscillations in the transversal direction, which may strongly lead to fatigue problems in some of the tower members.

The vortex shedding occurs in the diagonals of the telecommunication towers essentially because of the forms of their sections [1]. Although it is frequently not considered as a design verification in lattice towers, a considerable number of similar structures suffers failures due to vortex shedding. The non-linearity of the phenomenon, in addition to its complexity creates difficulties in its approach and study analysis. The aim of this work was to optimize the analysis of the vortex shedding on steel diagonals of lattice towers using a simple program to predict the potential elements at risk. Consequently, for the known diagonals that may experience some induced vibration problems, the final goal of this work is to further develop a method of minimizing the damage, which will be detailed in a letter research work. The results obtained may be useful for future projects and for lattice tower designs.

2. VORTEX SHEDDING

For bluff bodies, i.e., less aerodynamic, the wind action creates transversal vibrations due to vortex shedding [2]. This phenomenon is defined as the moment in which the flow of a fluid around an element creates an alternation of low pressures zones in its vicinity. This alternation causes the perpendicular vibration regarding the wind load direction [3]. As the fluid flow velocity reaches the critical velocity of the contact element, the dynamic force created by the shedding leads to higher vibrations (normal to the flow) in the zones where the dynamic force is more felt on the element perimeter [4]. Same as to say, it creates resonant vibration.

2.1 Lock-in

When the frequency of the vortex shedding and the natural frequency of the slender element are equal, the Lock-in is said to be created. In this instant, the element is subjected to higher vibrations, and its natural frequency controls the shedding [5] [6]. It is difficult to characterize the element response when the vortex shedding frequency value is far from the element frequency (the response type is random). This is way it is considered the scenario where the vibrations are of higher order in resonance. To simplify the analysis and calculations, it is considered a singular value of frequency where Lock-in occurs, but it is well established that in fact it occurs in a range of velocities of fluid flow (representing the frequencies) [4]. Thus, the following equation is used in the analysis:

$$V_{crit} = \frac{f_n D}{St} \tag{1.1}$$

3. VORTEX SHEDDING EVALUATION – EUROCODE EN1991-1-4 (2010)

The current Eurocode establishes that it should be verified two criterions for vortex shedding analysis necessity [7]:

- The ratio between the largest and the smallest dimension in the plane normal to the wind direction is greater than 6;
- The critical wind velocity in the considered mode of vibration, is less than 1.25 times the average wind velocity, at the cross-sectional level where the vortex shedding is triggered.

$$v_{crit,i} < 1{,}25 \cdot v_m \tag{2.1}$$

The average velocity is calculated using the equations and the conditions expressed in EN1991-1-4, for a giving base velocity and height (from the ground). For the case of lattice towers elements, the critical velocity is given for the first mode of vibration, since it's considered the mode that governs.

$$v_{crit,1} = \frac{b.n_{1,y}}{S_t} \tag{2.2}$$

Where b is the cross-section diameter, $n_{1,y}$ the frequency of the element for mode 1 and S_t the Strouhal number, defined as a parameter that relates the vibrational forces and forces of inertia (body forces). For this study, the value of St is 0.18, for circular tubes.
For the vortex shedding calculations, the Eurocode presents two methods of analysis to calculate the maximum deflection. Calculating the maximum deflection, the resultant effect is given by:

$$F_w(s) = m(s) \cdot (2 \cdot \pi \cdot n_{i,y})^2 \cdot \phi_{i,y}(s) \cdot y_{F,máx} \tag{2.3}$$

Methods 1 and 2 are detailed in Appendix E of EN1991-1-4 [7]. It is necessary to determine another parameter to identify the type of flow [8], designated as Reynolds number, which influences the effect of the vortex shedding.

$$R_e(v_{crit}) = \frac{b \cdot v_{crit}}{\nu} \tag{2.4}$$

For the current code, the Reynolds number is used to determine the lift coefficient (for lateral movement) which is used in the deflection formula for method 1. Moreover, it is also used for the variables defined in Method 2.

4. FATIGUE ANALYSIS

The analysis used in the determination of number of cycles of excitation leading to damage is based on the rules and methods in the regulation EN1993-1-9 [9]. The initiation and crack propagation on a structural element is caused by a cyclic change of stress, this is way the code presents two types of safety verification for damage control: one based on range of equivalent stress in constant amplitude, and accumulative damage verification. The total number of cycles is given by [7]:

$$N = 2 \cdot T \cdot n_y \cdot \varepsilon_0 \cdot \left(\frac{v_{crit}}{v_0}\right)^2 \cdot \exp\left(-\left(\frac{v_{crit}}{v_0}\right)^2\right) \tag{3.1}$$

The number of cycles is a function of the critical velocity v_{crit}, the frequency of vibration n_y, the modal value of the wind velocity taking in account the Weibull distribution v_0, the life spam considered for the structural element T, and factor that describes the range of velocity in which vibrations occur ε_0.

For the equivalent stress in constant amplitude safety verification, the following condition must be verified:

$$\frac{\gamma_{Ff} \cdot \Delta\sigma_{E,2}}{\Delta\sigma_c / \gamma_{Mf}} \leq 1 \tag{3.2}$$

Where the variables related to stresses can be calculated using the formulas here expressed, in addition to using the graph of S-N curves for the resistance stress determination.

$$\Delta\sigma_{E,2} = \lambda \cdot \Delta\sigma_E \tag{3.3}$$

$$\lambda = \left(\frac{N}{2 \cdot 10^6}\right)^{\frac{1}{m}} \tag{3.4}$$

$$\Delta\sigma_E = 2 \cdot \sigma_{Comb.Freq} = 2 \cdot \sigma(\psi_1, \sigma_{máx}) \tag{3.1}$$

$$\sigma_{Comb.Freq} = \frac{\psi_1 \cdot M_{máx}}{I} \cdot \frac{D}{2} = \frac{0{,}2 \cdot M_{máx}}{I} \cdot \frac{D}{2} \tag{3.6}$$

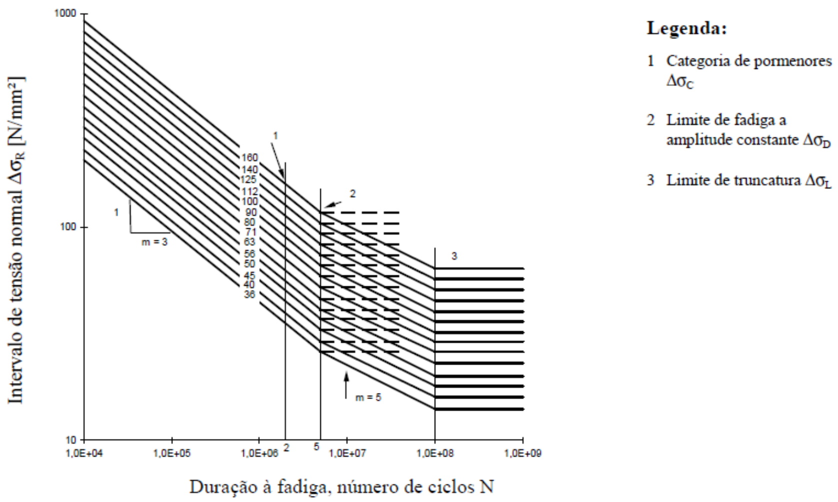

Figure 1 – S-N fatigue resistance curves for nominal stress range [9].

As for the safety verification based on the accumulative damaged, the code obliges that the ratio of the summation of the number of cycles associated to given range of stresses and the number of cycles associate to the resistant stress, must be less than 1.

$$D_d = \sum_i^n \frac{n_{Ei}}{N_{Ri}} \leq 1 \tag{3.7}$$

Furthermore, based on the EN1993-1-9 [9], the number of cycles until damage can be predicted by:

$$N = \frac{\Delta\sigma_C^m \cdot 2 \cdot 10^6}{\Delta\sigma_{Freq}^m} \tag{3.8}$$

Which can be converted to the period T related to it, which is a function of the frequency, the Weibull distribution, and the factor of range of velocities.

5. LATTICE TOWER - ANALYSIS

For this study it was analyzed a 200-meter-tall already designed lattice steel tower (figure 2) with different diagonals per section (depending on the height).

Section number	Diagonals	
S	**Tube elements**	**Steel Grade**
1	Øx168,3x3,0	355
2	Øx168,3x3,0	355
3	Øx168,3x3,0	355
4	Øx168,3x3,0	355
5	Øx139,7x3,0	355
6	Øx139,7x3,0	355
7	Øx139,7x3,0	355
8	Øx139,7x3,0	355
9	Øx114,3x3,0	355
10	Øx114,3x3,0	355
11	Øx101,6x3,0	355
12	Øx76,1x3,0	355
13	Øx60,3x3,0	355
14	Øx60,3x3,0	355
15	Øx76,1x4,0	355
16	Øx76,1x4,0	355
17	Øx76,1x4,0	355
18	Lx40x40x4	355
19	Lx40x40x4	355
20	Lx40x40x4	355

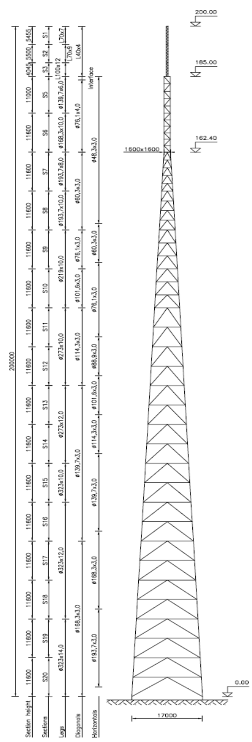

Figure 2 – Lattice tower geometry and diagonals sections.

To automate the process of analysis, it has been developed a program in VBA Excel for evaluation of both vibration induced by vortex shedding due to wind load, and the fatigue analysis for the lateral vibrations in the diagonals.

The program relies on the user input, and it is developed to work with a structural evaluation software, like Robot Structural Analysis from Autodesk. The user must provide all data required to run the program in excel. The program overview is simple and easy to use, with steps such that the user can follow the regulation guidelines (Figure 3).

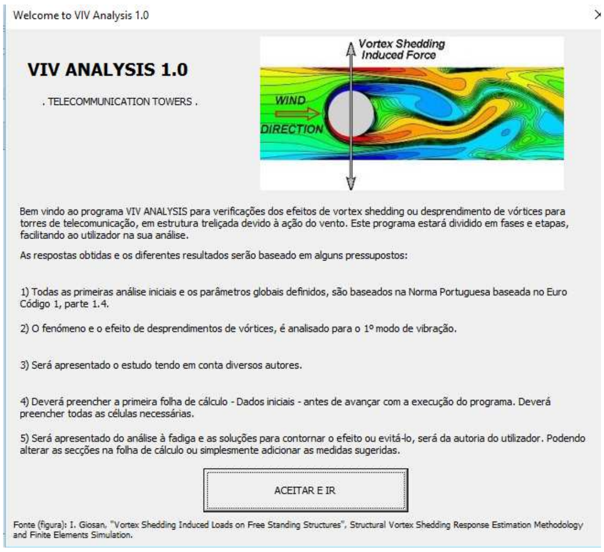

Figure 3 – Overview of the program (Vortex Induce Vibration Analysis) [10].

The output of the program will be all the variables necessary for vortex shedding evaluation, including potential diagonals at risk, and the results of fatigue safety verifications (Figure 4). Besides, the user can also choose to see the proposed measures of lateral vibration mitigation. This setup corresponds to adding steel fins of certain length (defined at the program) on the mid span of the element. It is used an equation based on an approximation of the alpha factor equation for reduction of the lift coefficient used in the Eurocode [11].

$$\alpha = \left(1 - \frac{l_s}{L}\right)^{9 - \frac{d}{22}} \tag{4.1}$$

With the output information, it is possible to adapt the members if it is necessary, or if it fails the safety verifications.

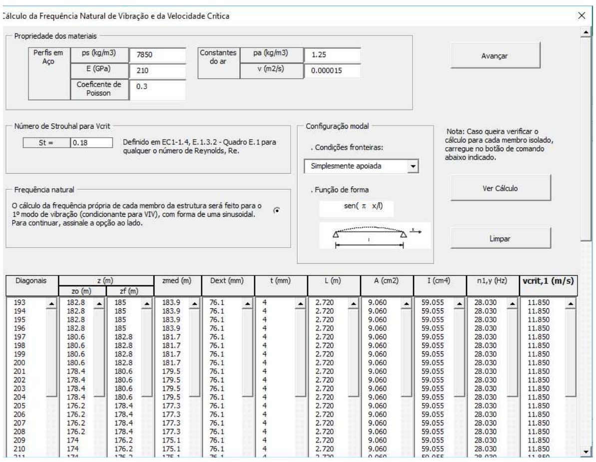

Figure 4 – Output example – determination of the diagonals critical velocities.

6. RESULTS

It is considered now one single element from the all structure, of the ones in the sections at risk of failure due to fatigue caused by vortex shedding. Using the program developed, the results for the diagonal 588 of section S15 are shown in table 1 and 2.

Table 1 – Properties of diagonal 588 S15.

Data	
z (mid section height)	66,7m
Exterior diameter	139,7mm
Thickness	3mm
Span	7,981m
Cross-sectional area	12,884cm^2
Inertia	301,090cm^4
Young's modulus	210GPa
Volumetric weight	7850kg/m^3
Frequency of vibration (mode I)	6,167 Hz

Table 2 – Lateral deflection due to vortex shedding and the resultant stress, given by the Eurocode.

	Method 1		**Method 2, considering turbulence effects**		**Método 2, not considering turbulence effects**	
Results of the parameters using the base values of table 8.4 EN1991-1-4	-	-	Kv	0,583	-	-
	-	-	Ka	1,166	Ka	2
	clat	0,70	Cc	0,02	Cc	0,02
	Kw	0,16	al	0,4	al	0,4
	K	0,10	kp	2,004	kp	1,490
ymáx (m)	$3{,}99 \cdot 10^{-3}$		$4{,}45 \cdot 10^{-2}$		$5{,}92 \cdot 10^{-2}$	
σmáx (MPa)	14,233		158,917		211,428	

These results were used for the fatigue safety verification, and as shown in table 3 the element fails the condition of safety in method 2.

Table 3 – Fatigue safety verification, based on the equivalent stress in constant amplitude.

Equivalent stress in constant amplitude safety verification		
Method	**2, considering turbulence effects**	**2, not considering turbulence effects**
vcrít (m/s)	4,786	4,786
vm (m/s)	36,915	36,915
N	$8{,}17 \cdot 10^8$	$8{,}17 \cdot 10^8$
$\Delta\sigma_c$ (MPa)	71	
$\Delta\sigma_{E,2}$ (MPa)	211,584	281,498
$\frac{\gamma_{Ff} \cdot \Delta\sigma_{E,2}}{\Delta\sigma_c / \gamma_{Mf}}$	3,43	4,56

Table 4 – Results for the diagonal 588 of S15 related to failure prediction due to lateral vibrations.

Method	2, considering turbulence	2, not considering turbulence
v_{crit} (m/s)	4,786	4,786
N_c	$2 \cdot 10^6$	$2 \cdot 10^6$
$\Delta\sigma_c$ (MPa)	71	
$\Delta\sigma_{Freq}$ (MPa)	63,57	84,5712
m (curve slope)	3	3
N (Resistant cycles)	$1{,}832 \cdot 10^6$	$7{,}781 \cdot 10^5$
Damage prediction	**41,5 days**	**17,6 days**

As shown in table 4, not only the diagonal fails the safety check for fatigue analysis due to vibration in the lateral direction, but it can also be assumed that the members of this same section will fail in a short period. It is not possible to confirm that all members will fail in the time range calculated, but an alert notice is given for the design process.

For the entire structure the sections in blue can be defined as potential risk zones (figure 5).

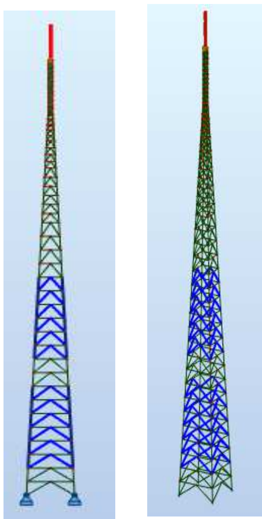

Figure 5 – Output example – determination of the diagonals critical velocities.

7. CONCLUSIONS

The second method of lateral vibration analysis for vortex shedding due to wind load presented in the Eurocode has a better approximation to similar cases where structural elements have failed. This is the reason way it is given special attention throughout the calculations of fatigue failure verifications. The risk of failure of the tower structural elements due to fatigue is as expected because for slender members in lower heights in which the wind turbulence is more felt, the promptness for transversal excitation is higher. Therefore, it should be taking into account adding bracing to the diagonals. The special software program in VBA using Excel that was developed for the purpose of this study, has great potential to be adapted to numerous scenarios and new features could be added for more complex cases. It is a valuable tool in accelerating the decision process and wind verifications.

ACKNOWLEDGEMENTS

Although the co-authors are respectively collaborator and Member of Construct Research Unit at FEUP, present lack of funds disabled Construct direct support of this R&D. So the authors solely acknowledge at the present moment the financial support received directly through the cost centre of the second co-author, and associated with his overheads from past R&D multiple activities and consultancy services.

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