Reliability analysis of structural joints in steel lattice tower – experimental and numerical study

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Abstract

The main aim of this paper is a presentation of the results obtained for the stochastic analysis of structural joints. The starting point constituted full-scale pushover test of the 40 m lattice tower. Experimental data served for FE model calibration (entire tower), assignment of steel mechanical properties and results confirmation for structural joint stress analysis. Computational investigation was performed for random wind load. Numerical considerations include in its scope: full dynamic analysis with respect to the determined wind velocity – time function, modelling of two particular tower joints by the shell FE elements and elasto-plastic range (load taken from global analysis), determination of the joints reliability by the FORM and SORM approaches.

Keywords: structural joints, lattice towers, reliability, stochastic finite element method, perturbation technique

1. Introduction

Steel lattice towers are widely used in civil engineering activities like telecommunication [4] and power industry. The issues of design of this specific kind of structures are rather complex and demanding. One of the main problems here is a proper estimation of wind loads and hence a selection of structure individual components that fulfil requirements of Ultimate Limit State. Traditionally lattice towers are analysed by linear static methods and with assuming that all structural members are subjected to axial forces only and deformations are small. As lightweight structures, very sensitive to aeroelastic phenomena (wind dynamic excitations), they require more deeper analyses to describe their physical behavior. In the design process we have to focus on sizing members, select a grade of structural steel and specify components of structural joints [1, 2, 7] i. e. number and class of bolts, thickness of flanges, throat thickness and etc.

The main objective of this paper is to investigate the reliability of two particular joints in exemplary of lattice tower that previously was a subject of full-scale pushover test. Numerical considerations were performed for random wind loading (velocity) via full dynamic analysis (HHT α-method). Reliability indices for selected joints were calculated and discussed for FORM and SORM assumptions.

2. Full-scale test as a starting point

Details about performed full-scale tests are given in [5, 6]. Observations of the tensioned structural joints during and after the experiment allow for conclusion that their reliability level is satisfactory. However, we should take into account the fact that load direction during pushover test was selected to create the compression in one of the tower leg and tension in two others. In further computational simulations the wind load direction was rotated (180°) consequent – one leg is tensioned and two other compressed. In Fig. 1 there are presented tensioned joints after experiment without any damages or failures.

Figure 1: Tensioned joints after performed full-scale test.

3. Governing equations

Numerical analysis of the equations of motion integration allow to obtain the structural response in form of displacements, stresses, strains and etc. at selected time moments. In numerical example we have used the Least Square Method to solve the problem – to obtain a function that describes the wind velocity - axial forces in tower legs dependency. The HHT manner equation of motion may be defined here as:

$$\mathbf{M}\ddot{\mathbf{q}}_{n+1}^{(i)} + (1+\alpha_{HHT})\mathbf{C}\dot{\mathbf{q}}_{n+1}^{(i)} - \alpha_{HHT}\mathbf{C}\dot{\mathbf{q}}_{n}^{(i)} + (1+\alpha_{HHT})\mathbf{K}\mathbf{q}_{n+1}^{(i)} - \alpha_{HHT}\mathbf{K}\mathbf{q}_{n}^{(i)} = \mathbf{f}(\tilde{t}_{n+1}), \quad (1)$$

where $\mathbf{q}_n^{(i)}$ for $i = 1,\ldots,n$ is the solution of a deterministic dynamic analysis involving all the constant symmetric matrices $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ as well as the vector of dynamic excitation $\mathbf{f}(t)$, $\alpha_{HHT} \in (-1/3; 0)$.

4. Computational analysis

Entire tower FE model has been prepared in the civil engineering software Autodesk ROBOT Structural Analysis v.2015. Model has been built with the use of 396 3D linear beam finite elements connected in 278 nodal points. Additionally, the geometrical imperfections have been added to the legs in two lower tower sections (S-7 and S-6) that have been measured before the experiment. Compatible nodes have been inserted in all the crossings within the X patterns of the tower bracing. Also an application of the elastic supports (connections with the foundation) was added. Model includes additionally geometrically nonlinear analysis that has been performed (so-called P-Δ analysis) according to the BFGS (Broyden-Fletcher-Goldfarb-Shanno) algorithm.

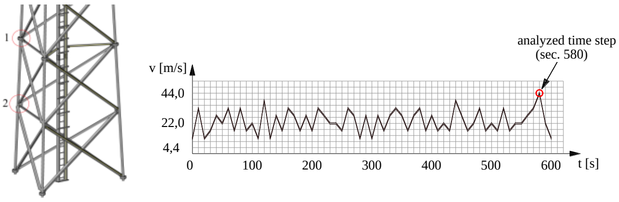

Figure 2: Analyzed joints in the base of the tower (left) and wind velocity – time function considered in the analysis (right).

Numerical modelling of structural joints was performed using IDEA StatiCa commercial system. Particular members of joints were divided into plates. Four noded shell elements were used with six degrees of freedom in every node: 3 translations t (u_x, u_y, u_z) and 3 rotations (φ_x, φ_y, φ_z). Deformations of the element has been didvided into membrane and flexural components. The nonlinear elasto-plastic stage of the material was taken into account. The mechanical parameters were taken from the experimental tensile tests as: expected values of the Young modulus equal to 205.11 GPa with standard deviation equal to 2.78 GPa. Expected value of the yield strength – 286.37 MPa and corresponding standard deviation – 16.02 MPa. Internal forces were applied with the values taken directly from global (entire tower) dynamic analysis for the second 580 – where the values of the wind velocity is the highest. Equivalent stresses for particular members of joints are presented in Fig. 3. As we can observe and what coincide with the experimental observations, tensioned node that connects two sections of the tower is the critical one with magnitude of the stresses close to the yield strength of the structural steel.

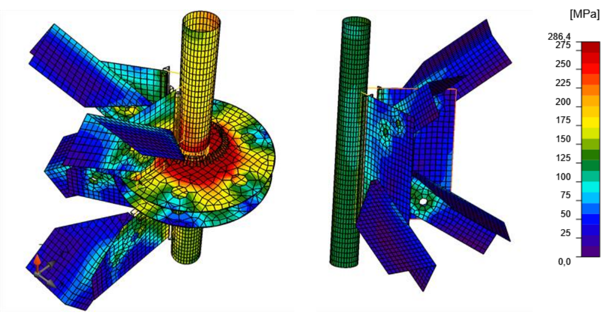

Figure 3: Equivalent stresses for joint nr 1(left) and nr 2 (right).

Wind velocity *v* treated as Gaussian random variable was a parameter in stochastic calculations. Stochastic perturbation technique [3] was implemented to obtain the basic first four probabilistic characteristics (all equations defined in computer algebra system MAPLE v. 2016) of the observed parameters (stresses) and this is done with the use of the 8th order stochastic perturbation method. The main goal of the performed numerical tests was to obtain the reliability indices in FORM and SORM approaches in function of the input coefficient of variation $\alpha(v)$ – the graphs presenting these results are given in Fig. 4.

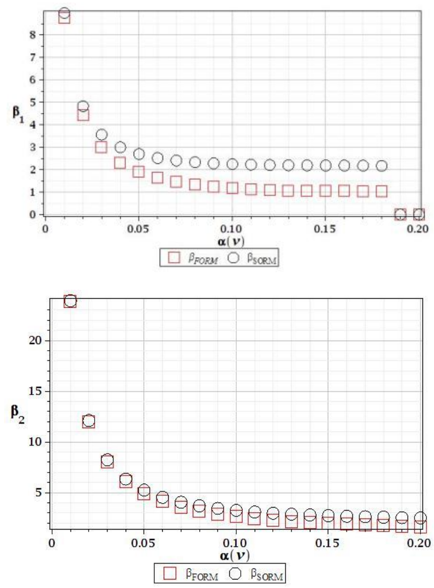

Figure 4: Reliability indices FORM and SORM for joint nr 1 (top) and no 2 (bottom).

We can draw the following conclusions: - reliability level is higher for joint no 2, - advantage of using elasto-plastic FE analysis allow to observe that for $\alpha(v)$=0.18 β_1=0 what is impossible to catch in elastic stage only, - differences in reliabilities are visible for particular calculation approaches, especially for more loaded joint (no1) where SORM based values are higher about 1.0, - in some cases that difference can define the joint as a safe one or not.

References

[1] Bučmys, Ž. and Daniūnas A., Component method in the strength evaluation of cold-formed steel joints, *Procedia Engineering*, 172, pp. 143-148, 2017.

[2] Hou, C. and Han L.H, Analytical behaviour of CFDST chord to CHS brace composite K-joints, *Journal of Constructional Steel Research*, 128, pp. 618-632, 2017.

[3] Kamiński, M., The Stochastic Perturbation Method for Computational Mechanics, Chichester, Wiley, 2013.

[4] Smith, B.W., *Communication structures*, London, Thomas Telford Publishing, 2007.

[5] Szafran J., An experimental investigation into mechanism of a full-scale 40 m high steel telecommunication tower, *Engineering Failure Analysis*, 54, pp. 131-145, 2015.

[6] Szafran J. and Rykaluk K., A full-scale experiment of a lattice telecommunication tower under breaking load, *Journal of Constructional Steel Research*, 120, pp. 160-175, 2016.

[7] Zhao, M.S., Lee, C.K. and Chiew, S.P., Tensile behaviour of high performance structural steel T-stub joints, *Journal of Constructional Steel Research*, 122, pp. 316-325, 2016.