ANALYSIS AND DESIGN OF THE SECONDARY AUXILARY TESTING STRUCTURE OF A TOWER TESTING STATION IN PORTUGAL - PART II

Jorge Henriques¹, Fábio Paiva¹, Rui C. Barros¹(*)
¹Department of Civil Engineering (DEC), University of Porto, Porto, Portugal
(*)Email: rcb@fe.up.pt

ABSTRACT

This work comes as Part II, of the work, that describes the analysis and design process of the principal auxiliary testing structure of a tower testing station in Portugal (Trofa). The principal auxiliary structure, as a key element of the testing station, is in this part II, conveniently characterized in terms of the numerical model used, types of analysis (elastic linear and non-linear, buckling analysis) and design methodology according with the Eurocodes part 3 (steel structures). This paper concludes with the difficulties experienced during the design process of the principal auxiliary testing structure.

Keywords: Special Lattice Towers, Linear Analysis, Design, Eurocodes.

INTRODUCTION

As stated in Part I of this two part paper (Henriques, 2015), to enable a horizontal loading on the tower to be tested, auxiliary testing structures are necessary (Paiva, 2013). This part II, focus entirely in the secondary auxiliary testing structure. The numerical model is shown in Figure 1. The structure was modelled in Autodesk Robot Structural Analysis 2014.

Fig. 1 - Secondary Auxiliary Testing Structure Phase 1 (Left) and Phase 2 (Right)
The structure was designed to satisfy two phases. The first phase (Figure 1), the structure has 60 m tall, in the final phase (phase 2) the structure achieves a total of 100 m height.

The secondary auxiliary testing tower can be described as structure formed by the association of the association of two frames. Each structural member of the vertical truss is a built-up members composed of angle sections. The structure is then conveniently anchored to several reinforced concrete foundations, each to the base built-up member type. All structural elements are in galvanised steel (type S355) and painted after the mounting.

A huge number of combinations for all the action were considered (self-weight, temperature, wind, cable loads), according with the Eurocode 0 (EN 1990, 2002). In the next step, through linear static analysis the structure was calculated.

For the design of the testing structure, many parts of Eurocode 3 were used, like part Eurocode 3-1-1, 3-1-5, 3-1-8, 3-1-11 and 3-3-1 (EN 1993-1-1, 2005; EN 1993-1-5, 2006; EN 1993-1-8, 2006; EN 1993-1-11, 2006 and EN 1993-3-1, 2006).

**NUMERICAL MODEL**

The carrying structure, as mentioned, is made of a trussed framework, whose elements, mainly based on single L angles are joined by bolted connections, constituting each a built-up beam-column. The built-up members are realised by means of cross-section arrangements (Figure 2), type L (for the main corner legs, diagonal and horizontal members), DL-arrangement (some bar in the intersections between structural members, like a) and b) element types). In the OZX plane, the direction where cable are applied, the association of the different type of elements constitute a global vertical truss, which provided sufficient stiffness and resistance for the structure. It can also be said, that if the cable loads are applied only through the plane ZX, the structure behave linearly.

In Fig. the main connections between the many built-up members are identified, beginning in detail A and finishing in detail I. The details of each connections are shown in Table to Table, for an illustrative clarification. The connections in all the details results basically from an overlapping of angle members in each intersection (by the built-up members) which are then bolted at fixed pitch. Additionally steel plates are welded to some bars in the connection, with the purpose of increasing node stiffness, reduce stress concentration between elements and to provide greater stability to all adjoining bars.
Fig. 2 – Vertical truss (formed by built-up members) and details of the major connections

Table 1 - Details of connections A to C

<table>
<thead>
<tr>
<th>Detail A</th>
<th>Detail B</th>
<th>Detail C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar overlapping</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The structural analysis has been carried out by modelling the structure through a FEM model: the complete scheme (final phase) required as much as 7641 structural joints, using 4124 beam elements (for the corner legs and other passing main connections), 40 shell elements.

For the simulations, the overall auxiliary testing structure can be considered as an assembly of self-supporting four-legged steel lattice towers (with majority of angle members) – normally built on ground. A general view of the model geometry is shown in Figure 1. The structure is modelled as linear elastic, three-dimensional frame structures with frame elements for the main legs, diagonal and horizontal members. The supports are assumed to be pinned at the base.
TYPES OF ANALYSIS PERFORMED

Static analysis, linear, of the structure has been carried out using the loads prescribed by the Eurocodes as described in Part I of this paper. Stresses, deformations and overall displacements have been assessed for all the combinations (only a few structural deformed shapes are shown in this work). Four incident incoming wind directions have been taken into consideration, in the next Figure 4 and Figure 5 deformed shapes for wind load in x and y direction are shown.

Fig. 4 - Linear static analysis deformed shape for wind load in +x directions (3D and plan views)

Fig. 5 - Non-linear static analysis deformed shape for wind load in +y directions (3D and plan views)
In Figure 6 the deformed shapes for temperature load (+ and -) are shown.

![Deformed shapes](image)

**Fig. 6 - Non-linear static analysis deformed shape for temperature load + (left) and – (right)**

For the next deformed shapes, a few of the many load combinations, taking the cable load as the leading variable load, are described. The load combinations are defined by Eurocode 0 (paper I). The wind load is drastically reduced during the test of the structures, because the wind velocity was limited to a lower value.

**Table 4 - Partial factors on actions for the ultimate limit states for persistent design situations, for the case where the load cable 1a is the leading variable action**

<table>
<thead>
<tr>
<th>Leading load- Cable load 1a</th>
<th>Permanent actions</th>
<th>Wind load</th>
<th>Temperature load</th>
<th>Cable load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 145</td>
<td>1,10</td>
<td>0,03</td>
<td>0,84 Temperature+</td>
<td>2,0</td>
</tr>
<tr>
<td>Combination 753</td>
<td>1,10</td>
<td>0,03</td>
<td>0,84 Temperature+</td>
<td>2,0</td>
</tr>
<tr>
<td>Combination 1140</td>
<td>1,10</td>
<td>0,03</td>
<td>0,84 Temperature-</td>
<td>2,0</td>
</tr>
</tbody>
</table>
A buckling analysis has been performed to assess the safety degree of the structure towards the instability phenomena, looking for a certain number of critical modes up to the instability of one or more members in the structure. The classical linear stability analysis is based on the imposition of the following condition:

\[ \det (K_e + \lambda K_g) = 0 \]

where \( K_e \) is the stiffness tangent matrix of the structure, while \( K_g \) is the geometric stiffness matrix as a function of the stress state. From the above linear eigenvalue problem, the critical load external factors and the corresponding critical modes are achieved. The method of block subspace iteration is used to solve the generalized eigenproblem. The method of block subspace iteration consists in simultaneous iterations of a vector in subspace with a determined dimension. Each vector for which the process of convergence has been performed is removed from the working subspace and a new start vector is added in its place. Orthogonality of the vectors is assured in each iterative step (Robot Structural Analysis, 2014).

The stability analysis has pointed out for the first critical mode, a critical mode related with bar (local instability mode). For the critical mode 2 the bar also suffer local instability. Table 8 -resume the critical parameters found for the configurations with diagonal wind load, for the critical combination. These critical parameters correspond to local instability of the bars. The partial factors on actions for the critical combination, correspond to the values indicated in Table 5.
Table 5 - Partial factors on actions for the ultimate limit states for persistent design situations, for the case where the wind load is the leading variable action

<table>
<thead>
<tr>
<th>Leading load- Wind load</th>
<th>Permanent actions</th>
<th>Wind load</th>
<th>Temperature load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 1160</td>
<td>1,10</td>
<td>1,4</td>
<td>0,84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind in y direction</td>
<td>Temperature+</td>
</tr>
</tbody>
</table>

Table 6 - Critical modes and critical loads factor of the buckling analysis

<table>
<thead>
<tr>
<th>Nº critical mode</th>
<th>Load factor Combination 10557</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,17</td>
</tr>
<tr>
<td>2</td>
<td>3,17</td>
</tr>
<tr>
<td>3</td>
<td>3,28</td>
</tr>
<tr>
<td>4</td>
<td>3,28</td>
</tr>
<tr>
<td>5</td>
<td>3,35</td>
</tr>
</tbody>
</table>

DESIGN METHODOLOGY ACCORDING WITH EUROCODE 3

Structural members may be present as individual members or as part of the planar sub-assemblage of a structure. Individual members are rarely encountered in practice. They interact with the other members of the structure only in the case that they are loaded by them or transfer their support reaction to them. Therefore, normally all members build part of the overall structure, and a great number of them are beam– columns which are loaded by axial forces and bending moments at the same time. The borderline cases are columns that are loaded by axial forces only and beams that are loaded by bending moments only (Lindner, 2000).

The ultimate states of the members were verified according with the Eurocode 3-1-1, 3-1-5 and 3-1-8. For that the following resistance were checked against the internal forces:

- resistance of cross-sections;
- resistance of members to instability assessed by member checks;
- resistance of joints;

A significant percentage of the angle bars of the built-up members were classified as section 3 and 4 class. Class 4 cross-section demands the calculation of the effective cross-sections properties (area and section modulus), for that Eurocode 3-1-5 was required.

Particular attention was paid to the realization and to the criterions of verification of the connections between the main structural elements (corner legs and diagonal elements). Many structural connections were analyzed, in order to guarantee safety, reliability and durability, by means of approaches defined Eurocode 3-1-8. These connections are designed under the
condition that they are able to transfer the maximum forces determined by the structural analysis. Particular attention was also paid to the major nodes identified in Figure 3, principally the connection between the steel panels and the bars. The overlapping bolted bars that constitute the connection between built-up members, as shown in Table 1, were carefully studied.

CONCLUSIONS

The part II of this work, completes the analysis and design process undertaken in part I. Regarding part I of this work, the main difficulties felted, were due to the wind load quantification, basically the complex surrounding topography of the structure and its geometry generated situations that were not strictly within the scope of the code. Therefore some simplification were needed for the assessment of the wind load.

Moreover the global stability analysis showed how the structural reliability is suitably assured with regard to variable loads (wind, cable and temperature loads). Only local modes of instability were detected in the first 100 buckling modes.

Probably, the major difficulty faced during the design, was the large amount of time taken to verify the resistance of the numerous cross sections (cross-section class 3 and 4) and the buckling resistance of each member as defined in Eurocode 3-1-1. Finally, specific attention has been focused in joint design of the main elements. The connection of the corner legs has been designed to guarantee the continuity of the cross-section. The others joints were verified to comply with the requirements stated in Eurocode 3-1-8.

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REFERENCES


