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Full-scale tests to measure stresses and vertical displacements in an 18.34 m-diameter agricultural steel silo roof

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ABSTRACT

The large-diameter, metallic, cylindrical silos used in agroindustry require in many cases some type of structure in their uppermost section so that roof panels can be secured in place. These structures often take the form of a lattice of radial and circular beams. The calculation models used in the design of these lattices assume the existence of certain behaviours that are not usually verified experimentally. In the present work, a 3-D beam model was used to predict the stresses and vertical displacements of a metal silo roof structure measuring 18.34 m in diameter. To check the validity of the model, these stress and vertical displacement values were experimentally verified at full scale. The instrumentation required to obtain these values in such a large structure is complex and costly. In this study, slings were used to apply load at 54 points in the roof structure, monitored by the use of dynamometers. The vertical displacements and strains suffered by the structure were recorded using fleximeters and strain gauges respectively. The experimental assays showed that the 3-D beam model did not contemplate the true rigidity of the joints between the tension plates and the radial beams at their point of contact with the vertical silo wall. The model therefore required adjustment in order to predict the measured results. The results show the need to use conservative models in the design of these structures.
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1. Introduction

Silos have been used as storage facilities in the agroindustrial, mining, chemical and pharmaceutical industries since the end of the 19th century. Cylindrical silos made of steel are probably the most commonly used in the agroindustrial sector.

The enormous increase in computing power achieved since the last third of the 20th century has greatly facilitated the use of numerical methods for analysing the mechanical behaviour of these structures (Jofriet et al., 1977; Eibl and Haüssler, 1984; Ooi and Rotter, 1990; Meng et al., 1997; Briassoulis, 2000; Guaita et al., 2003; Vidal et al., 2006; Gallego et al., 2010; González-Montellano et al., 2012). Such studies have significantly improved our knowledge regarding the behaviour of silos and their different components (Ayuga, 2008).

Numerical models allow the stresses and displacements in any structure to be predicted. All that needs to be known are the dimensions involved, the construction materials to be used, the cross-sections of the beams used, the design of the joints, and the constrains applied to the model. However, it is difficult for numerical models to reliably reproduce the behaviour of the final structure; nor can they contemplate small deviations from the design owing to construction works. Such is often the case with silos when the roof structure attaches to the separately-installed wall sheeting.

The need for efficient, economically competitive silos means engineers are faced with structural challenges that would be best examined experimentally *in situ*. The literature, however, contains few reports of full scale experiments on metallic structures with the aim of assessing the resistance of their different elements to deformation when under loads (Foutch et al., 1987; Nielsen, 1998; Kim et al., 2003; Teng et al., 2005; Härtl et al., 2008; Xue and Liu, 2009; Ramirez et al., 2010a,b,c; Pingue et al., 2011; Couto et al., 2012; Yang and Liu, 2012; Ruiz et al., 2012). The reason for their rarity is the cost and complexities involved in setting up the instrumentation. Numerical models are therefore commonly used in the design of such structures, but these are hardly ever validated by checking their predicted results with real ones.

Silo roofs are exposed to the action of wind and snow, and this issue needs to be taken into account in their design (EN 1991-1-3, 2003; EN 1991-1-4, 2005). Their structure must also commonly provide support to rooftop inspection gangways. They must

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therefore behave in such a way as to prevent undesirable stresses on the silo wall, which might result in the denting of the side panels or even their buckling and failure, while allowing all gangways to be held firmly in place (Briassoulis and Pecknold, 1987; Portela and Godoy, 2005; Ayuga, 2008).

The present case study compares the stresses and vertical displacements predicted by a 3-D beam model used to design an 18.34 m-diameter steel silo roof, with those measured in an experimental procedure performed at full scale. The instrumentation required was complex and costly, and required many factors be taken into account, such as the representative selection of the loading points on the roof, the monitoring of the loads transmitted, and the selection of devices capable of measuring the desired variables.

2. Description of the silo roof structure

The silo roof used in the present work had a diameter of 18.34 m. Its 24 radial beams were the main components resisting the loads acting on the roof (Fig. 1). The same beams also provided a surface for the fixing of the covering panels.

A steel plate was used to connect the circular beams to the radial beams only through the web of both beam types, leaving the flanges to rotate freely. This plate was L-shaped, being one side attached to the web of the circular beam and the other side attached to the web of the radial beam. In both cases, bolts were used to connect the plate with the radial or circular beams. So, this type of union was understood as articulated in the 3D-beam model.

On the other hand, the radial beams were deemed to be rigidly joined to the ring stiffener placed at top of the structure. For this type of union, steel plates are also used to connect the ring stiffener to the radial beams by using bolts. In this case, the steel plate is joined both to the web and flanges of the radial beam, thus forcing the radial beam and ring stiffener to maintain the angle formed by both elements, even if the structure is loaded. This is the reason why this type of union was supposed to be rigid in the 3-D beam model.

Finally, at the lower part of the structure, the radial beams were joined among them by means of tension plates (Fig. 2). In this case, bolts placed only at the web of the radial beams were used to join this element to the tension plates. So, the flanges of the radial beams can freely move with respect to the tension plate, and then the angle formed by both elements can vary. This is the reason why the union of tension plates to the radial beams was supposed to be articulated in the 3-D beam model. Detailed views of the joints between the different elements of the roof structure are shown in Fig. 3.

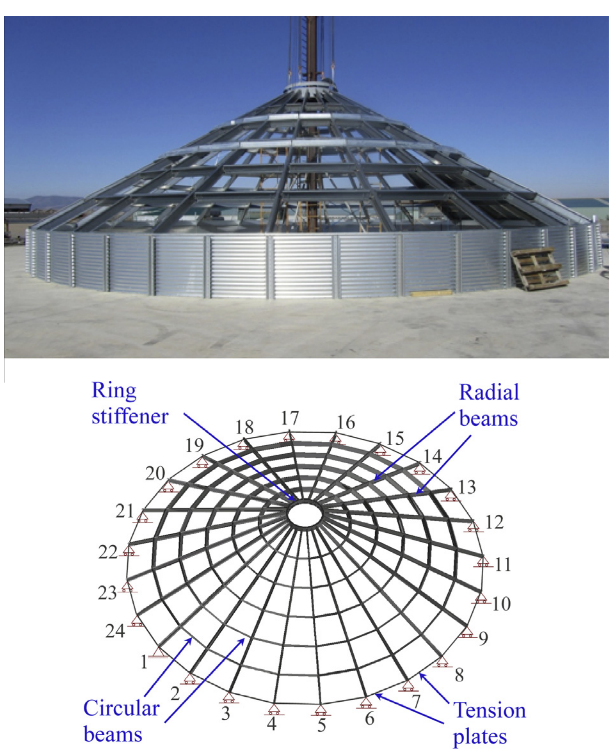

Fig. 1. Structure of the silo roof used in the present work.

3. The 3D-beam model

A 3D-beam model (PowerFrame software [BuildSoft]) was used to predict the behaviour of the silo roof under load. The model was based on the displacement method, and contemplated the following (Fig. 1):

- Radial beams and circular beams with a Sigma profile (height 250 mm, thickness 3 mm).
- A top ring stiffener with an European Standard Channel UPN-300 profile.
- 18 cm-high, 3 mm-thick steel tension plates joining the radial beams at their lower part, close to the vertical wall sheet.
- Constrains contemplated only at the exterior perimeter nodes.

Material properties, dimensions and cross sections of the beams of the real structure were introduced in detail in the 3-D beam model. Only an assumption was made concerning the lower support of the radial beams. These beams rested directly on vertical stiffeners of the side wall panels, therefore only vertical displacement at these nodes were impeded in this model, by using constrains applied at the exterior perimeter nodes.

According to the mounting of the structure described in Section 2.1, the joints between the radial and circular beams were deemed to be articulated, as were those between the tension plates and the radial beams, while the joints between the radial beams and the ring stiffener were considered to be rigid.

Concerning the stiffness of the tension plate, this was calibrated by a numerical trial and error approach in order to account for the real behaviour of this element as it was mounted.

4. Test procedure

4.1. Load application system

Loads were applied to the roof structure via the use of slings set at 54 points (Fig. 4). The slings were fixed at one end to a concrete floor slab using bolts (Fig. 5); the other end was wrapped over and anchored to the joints between the radial and circular beams. Equal loads were applied simultaneously to the loading points in increments of 1 kN, up to a maximum of 7.2 kN (approximately 80% of the load the roof could resist) using the ratcheting system on each of the slings. This was performed by staff members of SYMAGA, there was one person operating one sling system. The assay was repeated seven times and means were calculated for the variables measured.

The loads applied were monitored using dynamometers, the strains were measured with strain gauges, and the vertical displacement experienced by the roof was recorded using cable-actuated position sensors (fleximeters). The strains measured can be converted into stresses multiplying their values by the steel modulus of elasticity. All these pieces of equipment and the procedures followed are described in Section 4.2.

4.2. Instrumentation

4.2.1. Dynamometers

Eight dynamometers were installed on slings attached to the radial beams to measure the loads applied (Fig. 6). These

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