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Numerical analysis of influence of intermediate stiffeners setting on the stability behaviour of thin-walled steel tank shell

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ABSTRACT

Cylindrical bolted steel tanks with H/D∼1 can be made from very thin steel courses the thickness of which is determined by tension. The important issue is to stiffen the whole shell with intermediate stiffeners to prevent from stability loss in situations when the tank is empty and exposed to a strong wind. The FEM package Abaqus with nonlinear Riks algorithm was used for analysis. A parametric study programmed in python, internal Abaqus language was conducted to establish the influence of number and position of intermediate stiffeners on buckling resistance of the tank. After calculating nearly one thousands tasks, results were gathered with python script and compared with classic design recommendations proposed in Eurocode 3, DIN 18 800 Part 4 and AWWA D103-09. Simplified analytical approaches present in current standards are rather conservative and one may want to look for more sophisticated methods of analysis of tank shells presented in this paper for more economical design of such structures. From the comparison of the results obtained with different numerical strategies such as linear buckling analysis (LBA), geometrically nonlinear analysis of perfect (GNA) and imperfect (GNIA) structure a necessity of taking into account imperfections in GNA arises. Otherwise a capacity of the shell structure may be overestimated even over the value obtained from LBA.

1. Introduction

Amongst thin-walled tanks with a ratio H/D usually not exceeding unity one can distinguish welded tanks for storage of oil, petrol or other dangerous chemicals, and bolted tanks for water storage sealed with a special inner membrane. Former tanks must be made from thicker courses because of corrosion and minimal thickness conditions required for the proper welding process. In case of latter tanks, their walls are thin because they are usually made from galvanized or factory coated steel which prevents the structure from corrosion. Tank walls require stiffening rings in order to enhance their stability behaviour. Stiffening the thin shell with only a top ring is usually not sufficient in case of bolted tanks and intermediate stiffeners are necessary. Moreover, the stability check becomes more complicated when the thickness of consecutive shell courses of tank wall is stepped. In standards [1–3], analytical methods are proposed to determine spacing of intermediate stiffeners through the replacement of stepped tank wall by an equivalent shell of the thickness being uniform throughout its theoretical length. Although this approach is conservative, it is widespread in design of typical tanks for non-dangerous liquids. Eurocode [1] refers also to other more advanced approaches that are recommended for tanks of a higher consequence class, e.g. for storing dangerous materials. These approaches require the application of linear stability and nonlinear finite element methods indicated by abbreviations LBA and GNA, GNIA, GMNIA, respectively, that are being able to trace the buckling and postbuckling behaviour of stiffened thin-walled tank shells.

The buckling and post-critical behaviour of tank structures have been a subject of many research papers. Calladine [4] tried to summarize a history of understanding the imperfection-sensitivity in the buckling of shell structures. Basic concepts of nowadays idea of shell buckling is formulated therein. More discussion on imperfections effect on wind loaded cylindrical shells can be found in [5]. In first paper, not only the effect of nonlinear geometry was taken into account but also plastic properties of the shell material. Always in such analysis the fundamental issue is an assumption of wind load distribution. This problem can be solved by wind tunnel investigations which allow to establish wind pressure distribution around circumference. Portela and Godoy conducted such research for tanks with dome roofs [6] and conical roof [7]. The obtained wind distribution was applied in a vast number of numerical simulations. Tests carried on steel and PVC specimens with wind-like pressure distribution and followed by subsequent numerical analysis in order to establish the post-buckling strength were presented in paper [8]. There were also

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recommendations for an economic postbuckling strength design strategy given by the authors. Some analytical attempt of establishing simplified lower-bound buckling loads under wind pressures were presented in [9]. The reduced energy methods was implemented to evaluate a lower-bound for critical wind pressures and the results were compared with the static nonlinear analysis carried out on the same models. More general unsymmetrical load cases and their influence on design procedures against buckling are discussed in [10]. In this paper the results of parametric study were presented to show the influence of the circumferential speed of the pressure strip on the structural behaviour. Important issue concerning risk of buckling of steel tanks under construction is discussed in [11]. Shell structures are usually designed by considering their final form, what does not prove stability on each stage of building process. Collapse of the industrial cylindrical tank under moderate winds was analysed. Geometrically nonlinear finite element modelling of the tank was carried out, in which the shell was modelled in detail giving tank failure at the building process stage as in real case. It has been proven a need to apply more sophisticated material models and FEM formulations in designing of the thin-walled tanks. Another field of research, which should not be neglected in designing, is axial compression resistance of tanks and its postbuckling behaviour as discussed in [12,13]. Aspects of practical calculations for stepwise variable wall thickness were presented in details in papers [14,15]. These papers describe a new method of determining the critical buckling resistance of such shells and demonstrate the manner in which it can be used to produce rapid and moreover safe assessments of cylindrical shells with a wide range of patterns of wall thickness changes. Finally, the effect of stiffening elements on stability of tank shell was researched in [8] in case of wind load and moment of inertia of top ring while in [16] in case of harmonic settlement.

In this paper the water tank of stepped wall thickness segments described in [17] is considered. In the recalled paper, the Eurocode's analytical method to determine spacing of intermediate stiffeners was discussed and the proper mesh size of tank structure was developed through the linear elastic analysis of numerical models with different mesh sizes. The fine mesh fulfilling the sufficient convergence of numerical models to the analytical solution based on the shell differential equilibrium equation presented in [18] is used hereafter. A parametric study based on stability LBA and nonlinear GNIA analyses is presented in order to establish the influence of number and position of intermediate stiffeners on buckling resistance of tank shell.

2. FEM model of considered thin-walled steel tank

2.1. Geometry

A geometry of a typical bolted tank considered in [17] was modelled in finite element method package Abaqus [19]. Courses of the tank shell are made from steel sheets 2.5 m × 1.2 m and 2.5 m × 0.6 m, and connected with use of bolts. The thickness of tank courses was established as a result of resistance checks of bolted connections and tension shell weakened by bolt openings. Summary of designed thickness is presented in Fig. 1. The tank has an almost flat roof rested on four Z section rafters pinned to the top ring. Rafters are arranged in one direction, so that in case of wind blowing in perpendicular direction to the axes of rafters their stiffness is negligibly low. Therefore in the finite element method model the roof structure was neglected and equivalent load was applied on the edge of the shell.

Base ring was modelled through boundary conditions restraining displacement in radial and axial direction. The top ring and intermediate stiffeners were modelled as beam elements with equal leg angles section 60 × 6. Due to technological reasons, intermediate stiffeners may only be installed in the same place where horizontal bolted connections are located. The typical distance between these connections is 1.2 m or 0.6 m when shorter sheet is used, cf. Fig. 1.

2.2. Loads in FEM computations

In order to reduce number of independent variables in parametric analysis, design loads were assumed according to Eurocodes for typical climate conditions observed in Central and East-Central Europe (in Poland these conditions cover 90% area of the country). Characteristic dead loads including self-weight of roof 0.22 kN/m^2 and isolation coverage 0.10 kN/m^2 were taken with the load factor of 1.15 to produce their design values [20]. Characteristic snow load of 0.72 kN/m^2 [21] was taken with a coefficient of 0.75 describing the representative design value when snow is treated as an accompanying action. The design wind load as the leading load was calculated with the load factor of 1.5. The base wind velocity was taken as 22 m/s. Terrain category II is assumed which means a terrain with low vegetation and isolated obstacles. Due to the fact that situation when the tank is empty is a transient design situation, which lasts more than three months a year, a base wind velocity was reduced by c_{prob} coefficient, meeting the case of return period equal to 5 years according to [22]. Consequently, a characteristic peak velocity pressure concerning exposure factor results in the characteristic value of 0.53 kN/m^2 and the design value of 0.80 kN/m^2. The wind action on an almost flat roof is giving mainly suction which is confirmed by standards [23] and research conducted in a wind tunnel by Portela and Godoy [6,7]. Due to the favourable effects of wind suction on the roof, it is neglected in the following parametric study. Formula (1) for external wind pressure coefficient around the circumference of the shell without stiffeners is taken according to appendix C of Eurocode [2]. The pressure distribution coefficient with respect to the θ angle is shown in Fig. 2.

$$C_p = -0.54+0.16\frac{D}{H}+\left(0.28+0.04\frac{D}{H}\right)\cos\,\theta+\left(1.04-0.20\frac{D}{H}\right)\cos\,2\theta+ \\ +\left(0.36-0.05\frac{D}{H}\right)\cos\,3\theta-\left(0.14-0.05\frac{D}{H}\right)\cos\,4\theta \quad (1)$$

Similar formula was obtained as a result of experiments conducted in wind tunnel by Portela and Godoy [6,7], see for example Fig. 4 in work [7], where the mean pressure coefficient of tanks with conical roof obtained for different aspect ratios were presented. It is expected that the presence of intermediate stiffeners will affect the wind flow and as a result wind pressure pattern but since there is no experimental data on that matter it is assumed in this study that pressure distribution according to formula (1) is sufficient enough.

2.3. Material properties

The sheets of tank shell are made from galvanized steel S350 GD class according to Eurocodes with yield stress equal to 350 MPa and intermediate stiffeners are made from steel with yield stress equal to 320 MPa. In finite strain analysis (GNA and GNIA) using Abaqus a St. Venant–Kirchhoff (SVK) [24] material is used for the description of steel properties. The stored energy function (SEF) in case of SVK material model is defined by the following function:

$$W(\mathbf{E})=\frac{1}{2}\left[\lambda_o(\mathrm{tr}\mathbf{E})^2+2\mu_o\mathrm{tr}\mathbf{E}^2\right], \quad (2)$$

where constants λ_o and μ_o are identical like in small deformation theory (Lame constants) and depend on technical constants