Thin-Walled Structures 96 (2015) 11–28

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Numerical methods for the design of cylindrical steel shells with unreinforced or reinforced cutouts

Christoforos A. Dimopoulos *, Charis J. Gantes

Institute of Steel Structures, School of Civil Engineering, National Technical University of Athens, Greece

ARTICLE INFO

Article history:
Received 10 October 2012
Accepted 28 July 2015
Available online 6 August 2015

Keywords:
Cylindrical steel shells
Cutout
Stiffening
Design
EN1993
Nonlinear numerical analysis

ABSTRACT

The effectiveness of the numerical methods GMNIA and MNA/LBA proposed in EN1993-1.6 for the design of steel shells is studied for cylindrical steel shells with an unreinforced or reinforced rectangular cutout chamfered elliptically at the four ends and for the corresponding shells without cutout. Moreover, another design method proposed in the literature and denoted here as MNA/GNA, which is based on a modified slenderness, is also evaluated. GMNIA is considered as the most reliable analysis type, provided that a judicious choice of shape and amplitude of initial imperfections is made. Thus, GMNIA results are used as basis for comparison, except for shells without cutout where the EN1993-1.6 normative strengths could serve the same purpose as well. For shells without cutout it is found that the modified slenderness gives similar results to the corresponding results of the conventional slenderness definition. In the case of unreinforced cutout the modified slenderness gives better results, thus the use of MNA/GNA is recommended. However, in the case of reinforced cutout the GMNIA results are approximated better by employing the conventional slenderness, thus MNA/LBA is more appropriate.

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1. Introduction

Efforts for proposing design rules for shell structures, and mainly for cylindrical or conical shells that are encountered more frequently in civil engineering practice, have begun many years ago. The first design codes were probably published in 1980 (DASt-Richtlinie 013 [1] and ECCS [2]), followed by DIN 18800-4 [3] and DASt-Richtlinie 017 [4]. The more recent and advanced design code is EN1993-1.6 [5]. A distinguished feature introduced in DASt-Richtlinie 017 and adopted also by EN1993-1.6 is that they allow the use of numerical analysis tools for the design of shells.

The classical method for designing a shell structure, called the stress method, is based on buckling curves obtained by calibration of a large number of experimental results concerning the three basic stress conditions: (a) pure axial compression, (b) pure circumferential compression and (c) pure shear. The experimental results were used to produce buckling curves corresponding to a lower bound strength for each one of the three characteristic stress conditions and for a number of construction quality levels, thus providing appropriate reduction factors to be applied on the ideal plastic strength of the shell with respect to an appropriate slenderness definition.

Besides the stress method, EN1993-1.6 proposes the use of two other alternative design methods based either partially (MNA/LBA method) or totally (GMNIA method) on numerical analyses.

In the first method (MNA/LBA) the shell slenderness is estimated via two numerical analyses (e.g. finite element analyses): (a) a linear buckling analysis (LBA) and (b) a plastic geometrically linear analysis (MNA). While MNA is more straightforward, LBA can present more difficulties, as outlined in [6]. After calculating the slenderness on the basis of MNA and LBA results, the same analytical expressions for calculating the reduction factors, as in the stress method, may be used. The selection of the proper reduction factor is normally based on the type of stresses that develop in the shell. As a worst case scenario, the reduction factor for the case of axial stress can be considered.

The second numerical design method, based totally on numerical analyses, is the GMNIA method. According to this method the strength is obtained as the ultimate load from a Geometric and Material Nonlinear Analysis with Imperfections (GMNIA). This type of analysis must be performed taking into account a sufficient number of geometric imperfections and corresponding imperfection amplitudes in order to gain deep insight into the imperfection sensitivity of the shell. A systematic methodology for predicting collapse of steel structures by means of nonlinear numerical analysis has been proposed in [7].

This type of analysis (GMNIA) is particularly useful when it comes to structures that are not explicitly covered by the provisions of EN1993-1.6 [5]. One such example is the cylindrical shell with a cutout, either reinforced or unreinforced. In this case the stress method is not directly applicable as it is based on

* Corresponding author.

http://dx.doi.org/10.1016/j.tws.2015.07.024
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experiments performed on shells without cutouts. For the same reasons, the reliability of MNA/LBA is debatable as at the end reduction factors which are based on experiments on shells without cutout will be used. Thus, the more appropriate method for the design of such structures is GMNIA.

As stated in [5], a hole in a shell of revolution may be neglected in the structural modelling, provided that its largest dimension is smaller than $0.5\sqrt{rt}$, where r is the radius and t is the thickness of the shell. In the case of manholes of wind turbine towers, which provided the incentive for the present investigation, the hole dimensions are significantly larger than this limit. Therefore, its effect in local stress concentrations but mainly in local buckling and the associated reduction of the tower strength can be significant (see [8]). As explained above, the design of such structures must be carried out numerically, since the stress method is based on reduction factors and slenderness definitions that correspond to shells without cutout.

In this paper the accuracy of the MNA/LBA and GMNIA methods for evaluating the strength of a cylindrical steel shell with a cutout, corresponding to manholes of modern wind turbine towers is investigated. Moreover, the effectiveness of a modified slenderness definition initially proposed in [9,10] is studied. For this purpose, an extensive numerical analysis investigation has been performed. After describing the numerical modelling its validation via comparison with experimental results of specimens typical of modern wind turbine towers [8] is briefly discussed. Then, the results of the numerical study are presented. Finally, guidelines regarding the use of alternative numerical analysis methods for the design of cylindrical steel shells with unreinforced or reinforced cutout are given.

2. Description of numerical models

The numerical simulation has been performed with the finite element commercial software ABAQUS [11]. The chosen finite element was the S4 shell element of the ABAQUS element library, which is a 4-node doubly curved general-purpose shell element for finite membrane strains.

In the simulation models an elastic-perfectly plastic material law has been taken into account with Young's modulus, yield stress and Poisson's ratio equal to 210 GPa, 355 MPa and 0.3, respectively.

The cylindrical shells that have been analysed have circular cross-section with middle surface radius r equal to 1.98 m, inspired by a typical wind turbine tower with height in the order of 80 m (Fig. 1a). The thickness of the shells t is varied in order to obtain the desirable radius-to-thickness (r/t) ratios for parametric analyses, varying from 10 to 160. Typical shell thickness at the base of the tower of Fig. 1a would be approximately 40 mm, thus leading to an r/t ratio of about 50.

In case a cutout is introduced, a rectangular shape of height 2900 mm and width 850 mm, chamfered elliptically at the four ends, has been considered (Fig. 1b). Such a cutout is common in wind turbine towers, serving as a manhole for maintenance personnel. The lower edge of the cutout is positioned 550 mm above the bottom of the shells. The vertical axis of the cutout (the longest axis) is positioned in the numerical models so that it coincides with the most compressed meridian of the shell.

The cross-section of the peripheral frame stiffener, used to reinforce the cutout (Fig. 1c), is constant and has a rectangular shape with width b_{fr} and thickness t_{fr}. The area of the removed cross-section due to the cutout is designated as A_0, while the area of the frame stiffener A is equal to $2b_{fr}t_{fr}$. The stiffener's width b_{fr} was taken equal to 350 mm and the chosen A/A_0 ratio in this study was assumed equal to 1.

In order to reduce the computational effort only a lower part of the tower has been modelled and analysed, containing the cutout, where failure is initiated. The height of the modelled part was taken equal to 6350 mm, following successive analyses for different heights, aiming at estimating a minimum height for which the ultimate strength and failure mode are not affected [12]. The bottom edge of the shells was considered as fixed while at the top of the shells a Multi Point Constraint (MPC) was applied in order to simplify the loading application of either a concentrated moment or a concentrated rotation at the centre of the cross-section.

According to [5], a worst case equivalent geometric imperfection should be considered in a GMNIA analysis in order to capture the deleterious effect of initial imperfections in terms of geometry, boundary conditions and material properties. Choice of this worst case imperfection is not straightforward, especially for shells with reinforced or unreinforced cutouts, although in the case of shells without cutouts, the weld imperfection proposed by Rotter and Teng in [13] is commonly considered as either the worst or close to the worst imperfection [14]. For a more complete numerical investigation a number of equivalent geometric imperfections has been considered (Fig. 2): inward weld imperfection (Type A [13]), outward weld imperfection, inward axisymmetric arc imperfection, outward axisymmetric arc imperfection and first linear buckling mode. The first linear buckling mode has been considered only for shells without cutout, since its effect on the strength of shells with reinforced or unreinforced cutouts is negligible [9]. The imperfection is applied at the middle height of the cutout while in the case of shells without cutout it is applied at the mid-height of the shell.

Results from geometric and material nonlinear analyses with imperfections (GMNIA) were used as basis for comparison,

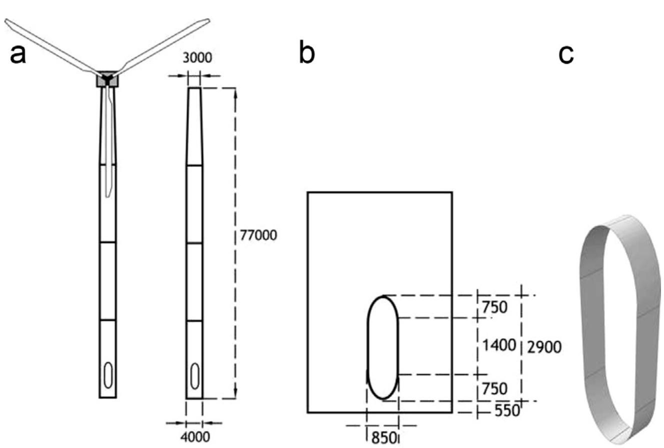

Fig. 1. (a) Wind turbine tower, (b) manhole and (c) frame stiffener (dimensions in mm).

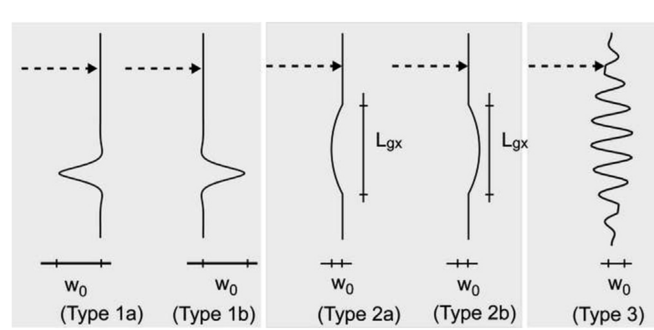

Fig. 2. Equivalent geometric imperfections: weld axisymmetric imperfections of Type A inwards (Type 1a) and outwards (Type 1b), arc axisymmetric imperfections inwards (Type 2a) and outwards (Type 2b) with $L_{gx} = 4\sqrt{rt}$ [5], first linear buckling mode for shell without cutout (Type 3).

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