Thin-Walled Structures 54 (2012) 140–155

Contents lists available at SciVerse ScienceDirect

Thin-Walled Structures

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

Experimental investigation of buckling of wind turbine tower cylindrical shells with opening and stiffening under bending

C.A. Dimopoulos *, C.J. Gantes

Metal Structures Laboratory, School of Civil Engineering, National Technical University of Athens, Greece

ARTICLE INFO

Article history:
Received 13 June 2011
Received in revised form
17 February 2012
Accepted 19 February 2012
Available online 22 March 2012

Keywords:
Shells
Opening
Stiffening
Buckling
Experiments
Numerical analysis
Wind turbine tower

ABSTRACT

An experimental and numerical study of the buckling behavior of cantilevered shells with opening and stiffening is presented in this paper. Unlike previous experimental studies, the present work focuses on shell slenderness as well as opening and stiffening reflecting the main geometric characteristics of wind turbine towers. The specimens can be classified as medium slenderness shells affected mainly by inelastic effects and secondarily by geometric imperfections. Both load–displacement curves as well as strain measurements are presented and compared with numerical predictions by finite element analyses, accounting for both inelastic effects and geometrical nonlinearity as well as for contact interaction between the various parts of the specimens. A good agreement between numerical and experimental results was found in terms of load–displacement curves and ultimate load. Due to the influence of the shape and size of geometric imperfections, a complete match of the numerically obtained strains to the corresponding experimental ones was not possible. The provided stiffening was found to be able to compensate the strength loss due to the presence of the cut-out.

1. Introduction

Shells, due to their importance as structural elements in many engineering structures, have been receiving a great attention by scientists. Their response has been investigated both experimentally and numerically, especially when it comes to cylindrical shells under axial compression or bending.

Axial compression tests in the elastic region were conducted by Lundquist [1], Tennyson [2], Weingarten et al. [3], Schneider et al. [4] and Athiannan and Palaninathan [5] just to name a few. In the inelastic region some experimental work on axially compressed shells is that of Lee [6], Batterman [7], Osgood [8], Horton et al. [9], Bardi et al. [10] and Bardi and Kyriakides [11].

It is well known nowadays that the experimental buckling loads of very thin shells in compression, which buckle in the elastic region, exhibit a wide scatter and may be significantly lower than the classical analytical predictions. This phenomenon can be attributed mainly to the inevitable geometrical imperfections and secondarily to loading eccentricities, boundary conditions and variability in thickness and material properties. As the shell slenderness decreases the effect of those factors on the collapse loads becomes less significant.

As far as the bending loading is concerned, some experimental work on thin shells is that of Mossman and Robinson [12], Rhode and Lundquist [13], Imperial [14], Lundquist [15,16], Donnell [17]. In the studies of Suer et al. [18] and Mathon and Limam [19], the effect of the internal pressure was also taken into account. In the inelastic region, experiments for the case of pure bending have been carried out by Moore and Clark [20], Jirsa et al. [21], Sherman [22], Tuggu and Schroeder [23], Reddy [24], Kyriakides and Shaw [25] and Kyriakides and Ju [26]. In the work of Johns et al. [27], Corona and Kyriakides [28] and Ju and Kyriakides [29] the effect of external pressure on the bending strength of the shells was also included.

The aforementioned references concerned shells without any geometrical discontinuity on their surface. However, in some engineering structures, such as wind turbine towers, chimneys and tanks, it is mandatory to provide openings in order to fulfill various practical needs, such as manholes. The effect of openings on the shell strength was investigated in a number of experimental works. In some cases, the effect of stiffening of the opening on the collapse load of shells was also considered due to its practical importance. Typical experimental studies of axially compressed shells with openings are those of Starnes [30–33], Tennyson [34], Toda [35–38], Schulz [39], Almroth and Holmes [40], Bennet et al. [41], Han et al. [42] and Shariati and Rokhi [43].

In the case of shells with openings under bending, experimental work has been carried out by Yeh et al. [44], Poursaedi et al. [45] and Knödel and Schulz [46]. Yeh et al. [44] studied the

* Corresponding author.
E-mail address: dchristoforos@hotmail.com (C.A. Dimopoulos).

0263-8231/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tws.2012.02.011

elasto-plastic buckling of aluminum cylindrical shells with unreiforced cut-outs with orthogonal or circular shape under the state of pure bending, both experimentally and numerically. The ratio of diameter to thickness was equal to 50 while the ratio of length to diameter was equal to 7.9. Poursaedi et al. [45] studied the plastic buckling of stainless steel cylindrical shell with rectangular or circular cut-outs under bending. The diameter to thickness ratio of the specimens was 40.4 and their length to diameter ratio was 7.94. In contrary to previous work, Knödel and Schulz [46] studied experimentally the strength of cylindrical steel shells with rectangular cut-outs, with chamfered angles, under bending. The effect of stringer stiffeners of various cross-section profiles on the strength was also studied. However, the slenderness of their specimens was, in general, significantly larger than values corresponding to wind turbine towers. Moreover, in the few cases with lower slenderness, the angles of their openings was significantly larger (in the order of 120°) than the typical openings of wind turbine towers (approximately 25°).

More experimental work on steel cylindrical shells with reinforced or unreinforced rectangular cutouts under bending are those of Baehre and Knödel [47] and Öry et al. [48]. As in the case of Knödel and Schulz experiments [46], in these two studies, either the angles of the openings and/or the slenderness of the specimens are generally larger than those encountered in wind turbine towers.

To the authors' knowledge no previous experimental work has been carried out that is especially designed so as to correspond to wind turbine towers, which exhibit specific geometrical and loading characteristics. In order to cover this gap, an experimental study is presented in this paper which focuses on the buckling behavior of cantilever shells with opening and stiffening that reflect the main geometric characteristics of wind turbine towers. The specimens are loaded with a prescribed transverse displacement at the end of the cantilever, thus making bending the predominant action. Both load–displacement curves as well as strain measurements at a number of characteristic positions of the external surface of the shells are presented. These results are compared with numerical analyses performed with the commercial finite element program ABAQUS [49]. Three different refinement levels of numerical modeling are presented, which are characterized by different levels of accuracy. In the less satisfactory model, the presence of bolts tying the flanges is neglected and the support is considered to be fully clamped. In the most accurate model, the interaction of bolts and flanges and the interaction between flanges as well as a partially clamped support are taken into account.

2. Geometric characteristics of specimens and experimental set-up

A total number of six shells with the same overall geometry were tested, among which the first two had no opening, the next two had an unstiffened opening near their base, while in the last two the opening was stiffened. The shape of the opening was rectangular with elliptical ends and the stiffening, when used, was a frame welded around the opening. The geometrical characteristics of these shells (external diameter, thickness, cut-out dimensions and stiffening) were chosen in such a manner as to correspond to the characteristics of wind turbine towers encountered in practice. The other parts of the specimens were dimensioned with sufficient overstrength, so that they would remain in the elastic region during the whole duration of loading.

The various parts of the test specimens are shown in Fig. 1. Each specimen consisted of three parts. The first part (Block 18), used in all tests, was a shell with external diameter of 400 mm

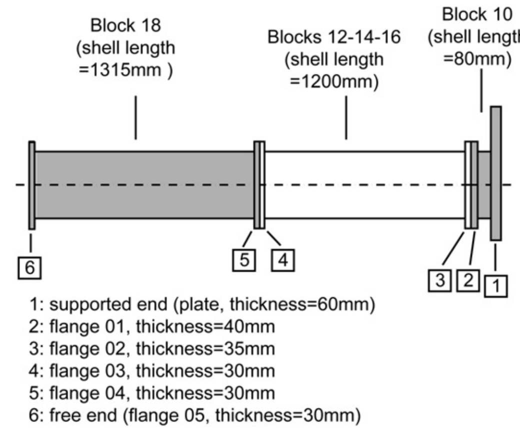

Fig. 1. Basic parts of test specimens.

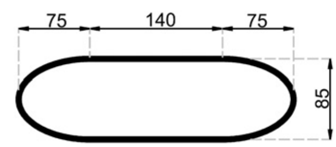

Fig. 2. Geometrical properties of the opening.

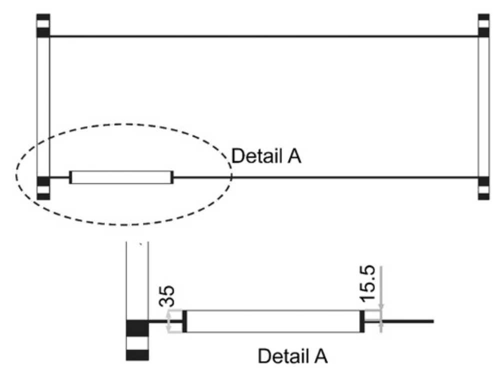

Fig. 3. Arrangement of the stiffener.

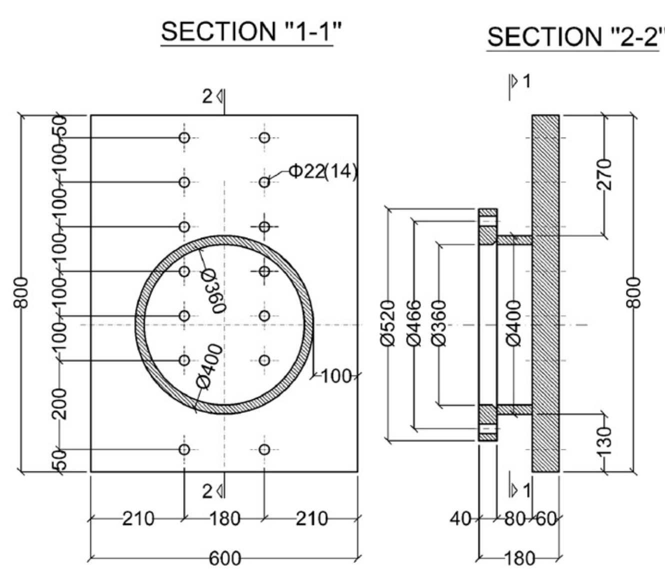

Fig. 4. Dimensions of Block 10 plate.