Thin-Walled Structures 127 (2018) 629–645

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Robust knockdown factors for the design of cylindrical shells under axial compression: Analysis and modeling of stiffened and unstiffened cylinders

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ARTICLE INFO

Keywords:
Buckling
Robust design
Knockdown factor
Imperfection
Stiffened cylinder
Orthogrid
Reduced energy method
Linear buckling eigenmode
Weld land buckling

ABSTRACT

For the design of thin-walled cylindrical shells under axial compression empirical knockdown factors are applied. These knockdown factors are based on experimental results from the beginning of the 20th century and have been shown to be very conservative for modern shell structures.

In order to determine less conservative and physically based knockdown factors for the design of axially loaded shells, different analytical and numerical design approaches have been developed. In this paper common as well as new shell design approaches are presented in detail and evaluated regarding the lower-bound buckling load. Among these design approaches are the EN 1993 1–6, the reduced energy method, linear buckling eigenmode imperfections, perturbation approaches and the new threshold knockdown factors.

Important analysis and modeling details of each design approach are described and test examples are given and validated. Advantages and disadvantages of each approach are listed and design recommendations are given.

A comparison of deterministic design approaches with modern probabilistic design methods is shown and the range of application of both design philosophies is discussed.

Orthogrid stiffened cylinders with weld lands from NASAs Shell Buckling Knockdown Factor Project (SBKF) are modeled, analyzed and lower-bound buckling load calculations for improved knockdown factors are shown.

1. Introduction

Thin-walled shell structures are important structural elements for launch-vehicle systems like the Changzheng-5 [1]. Most of the primary structures of the Changzheng-5 are either cylindrical or conical shells (see Fig. 1 - left). The cylindrical shells are subjected to axial compression due to the weight of the upper structural elements and propulsive loads during launch (Fig. 1 - right).

The maximum load carrying capability of thin-walled cylindrical shells under axial compression is defined as the buckling load N_{per} (see Fig. 2).

A large amount of cylinders was tested at the beginning of the 20th century in order to understand shell buckling under axial compression. The buckling results are shown in Fig. 3 by means of knockdown factors (KDFs) which are defined as ratio of the experimentally determined buckling load to the theoretical perfect buckling load.

In Fig. 3 different knockdown factors are shown over the radius-to-thickness ratio (R/t – slenderness). The data collection in Fig. 3 shows that there is a significant deviation between buckling theory and corresponding experimental data. The KDFs range mainly from about 0.4…1 and are in some cases even below 0.2. Modern manufacturing and testing results in much higher experimental KDF [3] (see red dot in Fig. 3 – KDF ~ 0.88).

A main cause for the large discrepancy between buckling theory and experiment are shape deviations from the ideal cylinder geometry (geometric imperfections [5,6] and manufacturing specified imperfection signatures [7]). Depending on the shape and amplitude of the geometric imperfections; a single dimple appears within the shell during loading. This single dimple initiates the buckling process and occurs in thin-walled shells like cylinders [8] cones [9,10] and spheres [11].

Dinkler and Kröplin [12] used dimples in numerical simulations of cylindrical shells in order to quantify the imperfection sensitivity. The formation of dimple imperfections caused by imperfect geometry and load introduction was studied by Hühne et al. [13] and corresponding experimental data are described in [14,15]. Other detailed experimental reports regarding the cylinder buckling mechanism [16,17] and the importance of single dimples are given in [18–20]. Interesting

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https://doi.org/10.1016/j.tws.2018.01.041
Received 14 August 2017; Received in revised form 6 December 2017; Accepted 31 January 2018
0263-8231/

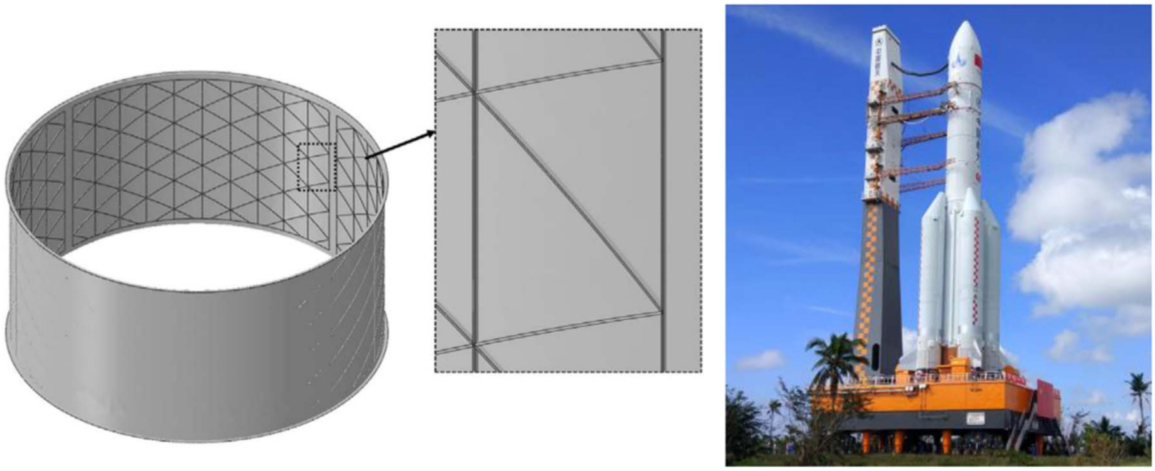

Fig. 1. Stiffened isogrid shell [2] (left) – Changzheng 5 [1] (right).

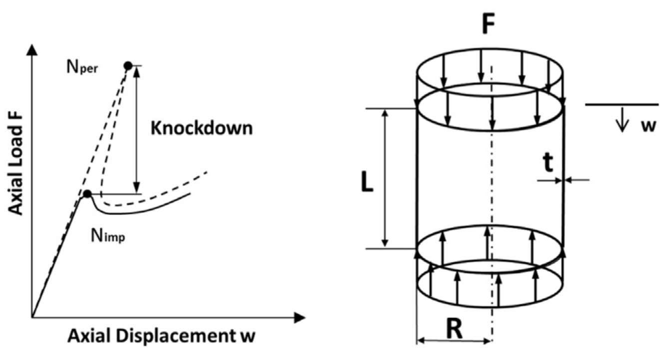

Fig. 2. Load-displacement curve and corresponding buckling loads of an unstiffened cylindrical shell.

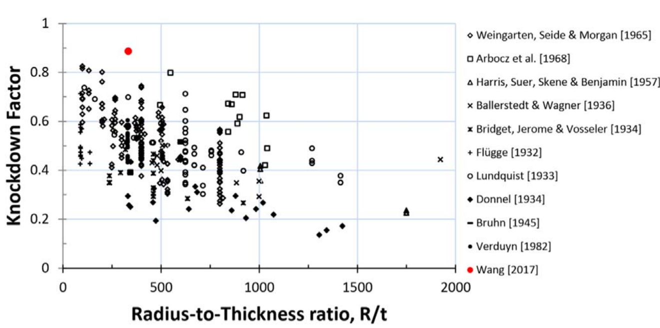

Fig. 3. Distribution of experimental data for axial compressed cylindrical shells vs. different R/t ratios after [4].

cylinder buckling studies regarding dimples caused by different finite element meshing approaches are given by Tahir [21] who also proposed a novel design philosophy based on the artificial neural network [22,23].

A concept for the non-destructive testing of cylindrical shells, the shock-sensitivity, also uses single dimples and was proposed by Thompson and Sieber [24]. Another non-destructive testing procedure for the buckling load estimation, the vibration correlation technique, is very well described in [25–27].

The concept of dimples as realistic, worst and stimulating geometric imperfection in numerical simulations for the design of cylindrical shells was proposed by Winterstetter and Schmidt [28] and studied by Deml and Wunderlich [29]. Horak et al. [30] showed that the worst geometric imperfection of a cylinder has the form of a single dimple as opposed to eigenmode [31] or axisymmetric [32] imperfections.

Hühne [33,34] proposed a single dimple based numerical design concept for unstiffened cylindrical composite shells, the Single-Perturbation Load approach [35,36]. Detailed comparisons of the SPLA with probabilistic design methods for cylindrical shells are given by Kriegesmann et al. in [37,38].

Within the DESICOS project [39–41] (new robust **DES**ign guideline for **I**mperfection sensitive **CO**mposite launcher **S**tructures) the SPLA for the design of cylindrical shells was thoroughly investigated [42,43] and resulting studies [44] showed that the SPLA in its original definition cannot be used in every case to determine lower-bound buckling loads for shell design. Consequently, different iterations of the SPLA were proposed. For example a SPLA with multiple perturbation loads [45,46] or a SPLA supported with probabilistic methods [47].

The authors [4] developed the first physical based analytical lower-bound curves for design of axially loaded cylindrical and conical shells, the threshold knockdown factors. It could be validated [48] for the first time that the knockdown factor for the buckling load indeed depends on the slenderness of the shells. The threshold KDFs were validated with a large number of empirical data for modern shells and it was concluded that these new KDFs deliver conservative and accurate approximation of experimental buckling loads and are therefore suitable for preliminary shell design.

Although new numerical and analytical design approaches deliver very promising results, there are still open questions regarding the definition of the lower-bound buckling load. The purpose of this paper is to compare different lower-bound methods for the design of cylindrical shells under axial compression.

This paper is structures as follows: in the first part different test configuration of unstiffened and stiffened cylindrical shells are presented along with results of linear bifurcation analyzes (LBA) as well as geometrically nonlinear analyzes (GNA).

In the second part common and new design approaches are presented and demonstrated by means of a simple unstiffened isotropic shell. Afterwards results for composite shells from [49,50] are presented and a comparison of deterministic lower-bound and probabilistic design methods is given.

In the last section numerical studies for orthogrid stiffened cylinders [51,52] from NASAs shell buckling knockdown factors project (SBKF) are presented [53,54].

1.1. . Abbreviations and glossary

Exp.	Experiment
F	Axial Force
GNA	Geometrically nonlinear analysis
GNIA	Geometrically nonlinear analysis with imperfections
h	Boundary perturbation height