Thin-Walled Structures 108 (2016) 369–380

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Design of cylindrical shells using the Single Perturbation Load Approach – Potentials and application limits

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ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form
29 August 2016
Accepted 4 September 2016

Keywords:
Buckling
Design
Shell structures
Single Perturbation Load Approach

ABSTRACT

The Single Perturbation Load Approach (SPLA) is a promising deterministic procedure on the basis of mechanical considerations to determine reasonable design loads for cylindrical shells in axial compression. In this paper, two main issues are identified that should be understood better in order to appreciate the potential and the limits of application of the SPLA. Firstly, the question whether a single perturbation load in general represents a "worst case" imperfection is addressed. Secondly, the influence of the stiffness properties of the shell on the quality of the SPLA predictions is studied. Finally, an indicator is suggested which identifies, based on the cylinder stiffness properties, whether the SPLA is conservative for a considered shell or not.

1. Introduction

Cylindrical shells under axial compression are prone to buckling, where the experimental buckling load is usually significantly smaller than the theoretical buckling load. Koiter [1] found geometric imperfections to be a main reason for this gap, while also boundary imperfections can have a significant influence on the buckling load [2]. Weingarten et al. [3] proposed a lower bound of the buckling load, based on experimental results available at that time. This lower bound has been adapted in the knockdown factors given by NASA SP-8007 [4]. This design rule turned out to be overly conservative for modern shells [5–8] and has been developed for metallic shells only. Composite cylindrical shells can show very different sensitivities depending on the laminate setup [7,8], which is not captured by NASA SP-8007. The guideline is reworked in the framework of the currently running Shell Buckling Knockdown Factor project [9].

In order to overcome the limitations of the lower bound design philosophy, different approaches have been followed over the years. One group of approaches are probabilistic design procedures (see, e.g., [6,8,10–12]). Since the imperfections are of random nature, the idea of these approaches is to capture this randomness and to determine the stochastic distribution of the buckling load. Based on the stochastic distribution and a chosen level of reliability, a lower bound is obtained. The problem of this type of approach is that it requires imperfection measurements, which are often not available, especially in an early design phase.

It is noted that nondestructive experimental approaches – applicable in structural development stages in which specimens are already available – have recently been presented [13,14], in the line of the vibration correlation technique originally proposed by Singer [15,16].

A deterministic design concept to account for imperfection sensitivity in an early design phase is the Single Perturbation Load Approach (SPLA), which has been proposed by Hühne et al. [7]. The idea is to apply a lateral perturbation load P when determining the buckling load of a cylindrical shell. For increasing perturbation loads, the bucking load decreases, until the perturbation load reaches a certain level P_1. The associated buckling load N_1 has been defined as design load by Hühne. This approach is currently further developed in the context of the European research project DESICOS (New Robust **DES**ign Guideline for **I**mperfection Sensitive **CO**mposite Launcher **S**tructures) [17].

One major restriction regarding the applicability of the SPLA has been raised by Friedrich and Schröder [18]. They showed that the SPLA can be applied for displacement controlled simulations and experiments, but that for load driven scenarios the applicability of the approach has restrictions. This paper focuses on displacement controlled simulations and tests, covering the majority of published experiments. However, in the present contribution, two further issues are identified that should be understood better in order to appreciate the potential and the limits of application of the SPLA. Firstly, the question whether a single perturbation load in general represents a "worst case" imperfection will be addressed. Secondly, the influence

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http://dx.doi.org/10.1016/j.tws.2016.09.005
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of the stiffness properties of the shell on the SPLA predictions will be studied in detail.

With regard to the second issue, a key observation is that one of the composite cylindrical shells Hühne tested showed a lower buckling load in experimental test than the design load N_1 according to the SPLA. Furthermore, probabilistic analyses of the same type of shells showed that also for a second cylinder the design load N_1 has an unacceptably small reliability [8]. Probabilistic analyses in which only geometric imperfections are taken into account indicated that the SPLA covers the effect of geometric imperfection, but not the effect of other types of imperfection such as boundary imperfections [19]. For shells which are sensitive to geometric imperfections, the SPLA nevertheless provides a conservative lower bound. Arbelo et al. [20] applied the SPLA to a large number of cylinders showing further cases in which the buckling load in test was lower than N_1. What is lacking today is a criterion that indicates the range of applicability of the SPLA. This is what the current paper aims to contribute.

In order to reveal the limitations of the SPLA, different laminate configurations should be further investigated. In particular, the strikingly different behavior of two particular shells (Z07 and Z09) that have been investigated both experimentally and numerically in earlier studies, is addressed in the current paper. These composite shells have the same layers, but a reversed stacking sequence. Having the same in-plane stiffness, the only difference is the sign of specific coefficients of the bending stiffness matrix and in particular of the bending-stretching coupling stiffness matrix, which results in significantly different buckling behavior and imperfection sensitivity. The current paper focuses on the behavior of these two particular shells and aims at shedding light on their different type of behavior.

A similar pair of cylinders (Z32/Z33) has been investigated by Geier et al. [21], who explained the change of buckling load caused by reversing the stacking sequence. Castro et al. [22] deeply investigated these two cylinders in presence of a perturbation load, showing their significantly differing sensitivity. For the cylinders Z07 and Z33, which both show a high imperfection sensitivity, Castro et al. [23] furthermore investigated the influence of different imperfection shapes on the buckling load and lower bounds of these shells.

In the present paper, the buckling behavior and the characteristics of the imperfection sensitivity are monitored for a range of shell properties varying continuously from the Z09 properties to the Z07 properties. Numerical investigations are carried out with both, the SPLA approach and a semi-analytical implementation of Koiter's b-factor method. The single mode b-factor method gives an estimate of the imperfection sensitivity and can also provide an estimate of the decrease of the load carrying capability of the shell for a given imperfection [12]. Koiter's b-factor method will be used to assess the applicability of the SPLA by comparing the prediction of the imperfection sensitivity obtained using the b-factor method with the prediction obtained using the SPLA. With the help of the b-factor method and the analytical approach given by Geier et al. [21], the possibility is investigated to formulate a simple, practical indicator to identify cases in which the SPLA should be used with caution.

2. The Single Perturbation Load Approach – status

The basic idea of the SPLA proposed by Hühne et al. [7] is given in the following section. Furthermore, the results of applying this approach to various types of shells are given and it is evaluated which other types of imperfections are captured by the SPLA.

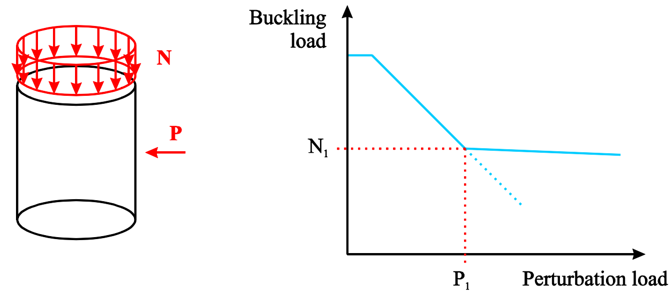

Fig. 1. Basic idea of the SPLA.

2.1. General concept

When applying a lateral perturbation load P to a cylindrical shell as shown in Fig. 1, left, the buckling load N is reduced compared to the buckling load of perfect, unperturbated shell. However, when the perturbation load exceeds a certain value P_1, a further increase does not decrease the collapse load any further (see Fig. 1, right). The associated buckling load N_1 is defined as design load.

For very small perturbation loads, the perturbation load hardly influences the buckling load. When the perturbation load exceeds P_1, a small drop occurs in the load-displacements curve, as shown in Fig. 2 (beginning with P=70 kN) for an aluminum cylinder tested at NASA Langley Research Center [24]. (This cylinder will be referred to as NASA test article, NTA, in the following.) This first point of instability is indicated by a blue dotted line in Fig. 1, right. At this point, the cylinder buckles locally, while the cylinder is still able to carry more load until the global buckling load is reached. The mechanical mechanism is discussed in detail in [7].

It is difficult to predict in advance the order of magnitude of P_1. Therefore, a multitude of buckling analyses is required to determine P_1. If the drop in the load displacement curve occurs, the design load obtained can be regarded as a conservative approximation of N_1. For a faster determination of P_1, Steinmüller et al. [25] gave an empirical equation to approximate P_1 for fiber composite cylinders based on the laminate setup.

2.2. Is the Single Perturbation Load a "worst case" imperfection?

Before tackling the question for which types of shells the SPLA is conservative, it is evaluated in how far the single perturbation can be considered as a "worst case" imperfection. Therefore, subsequently two other types of perturbations or imperfections are

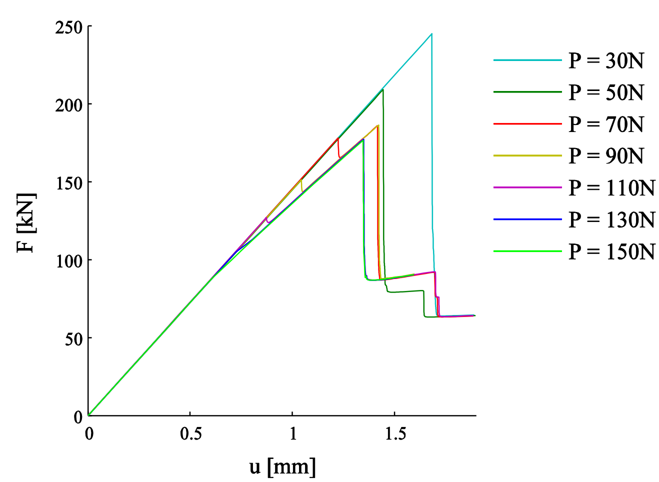

Fig. 2. Load-displacement curves from simulation of the NASA test article (NTA) for different perturbation loads.