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The single perturbation load approach applied to imperfection sensitive conical composite structures

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ABSTRACT

The importance of taking into account geometric imperfections for cylindrical and conical thin-walled structures prone to buckling had been already recognized by the first authors dealing with new formulations. Nowadays, the analysts still use empirically based lower-bound methods such as the NASA SP-8007 guideline to calculate the required knock-down factors (KDFs), which does include important mechanical properties of laminated composite materials, such as the stacking sequence. New design approaches that allow taking full advantage of composite materials are required.

The single perturbation load approach (SPLA), a new deterministic approach first proposed by Hühne, will be investigated with unstiffened composite conical structures varying the geometry, lamina and layup. The SPLA's capability for predicting KDF is compared with the NASA approach. The SPLA was applied to the geometrically perfect structures and to the structure with geometric imperfections of two types, mid-surface imperfections and thickness imperfections. The study contributes to the European Union (EU) project DESICOS, whose aim is to develop less conservative design guidelines for imperfection sensitive thin-walled structures.

1. Introduction

The stability of shell structures has been an object of studies for more than a century. Thin walled cylindrical and conical structures are widely used in aerospace, offshore, marine, civil and other industries. Nowadays, with the growing application of composite materials a deep understanding of the influence of their properties and the laminate stacking sequence on the mechanical behaviour of shell structures is increasingly more important. As it is already known, one of the most significant sources of discrepancy between theoretical predictions and experimental results for the buckling load is the presence of geometric imperfections. In spite of a multitude of publications on buckling of imperfect shells, such structures are still today generally designed at the preliminary design phase according to the NASA SP-8007 [1] for cylinders and the NASA SP-8019 [2] for truncated cones. Both guidelines date from 1960s and they are based on a lower bound curve which does not consider important mechanical characteristics of laminated composite shells, such as the stacking sequence. An alternative approach to calculate the knock-down factor at the preliminary design phase was proposed by Hühne et al. in 2008 [3]: The Single Perturbation Load Approach (SPLA) is a design method where a lateral load is applied prior to the axial compression, stimulating a single dimple. At this dimple the buckling process will start and a single buckle is produced, which will then propagate until the structure collapses. Esslinger [4], using high speed cameras observed that the buckling mechanism of imperfection sensitive shells always started with a single-buckle, and therefore an imperfection of this shape could be thought as a “worst-case” imperfection. Deml and Wunderlich [5] also came to this conclusion using a modified finite element procedure in which the nodal coordinates were included in the set of degrees of freedom, allowing the solver to find not only the nodal displacements but also the worst nodal positions that, within a given mobility tolerance (i.e. the maximum imperfection amplitude), would produce the minimum non-linear buckling load. However, recent studies have shown that a single dimple may not be the worst case imperfection, and that axisymmetric imperfections [6,7] or the imperfections coming from linear buckling modes [8,7] and multiple perturbation loads [9] may result in a much smaller

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knock-down factors using the same imperfection amplitude as the dimple produced by a single perturbation load. Some of these methods may be unrealistic in the sense that the imperfection pattern produces results that are not observed in real test conditions [7,8,10], e.g. a significant reduction of the axial stiffness prior to buckling.

There have been carried out considerably more numerical, analytical and experimental studies on cylindrical shells than on conical shells. Currently, typical composite launcher structures are investigated by 12 partners in the European project “New Robust Design Guideline for Imperfection Sensitive Composite Launcher Structures” (DESICOS) [11]. The goal of the DESICOS project is to obtain a new design guideline combining probabilistic and deterministic approaches. The aim of this paper is to study the SPLA on conical shell structures and compare it with the NASA design approach.

2. Current design approach

As already mentioned, at the early design phase many launcher vehicle parts are designed using the empirically based guidelines of NASA issued some decades ago. The SP-8019 is a guideline which is specific for truncated cones. However, there was lack of experimental data to cover all the wide range of conical geometric parameters. Nowadays, according to the industrial practice, the buckling problem of truncated cones can be transferred to an equivalent cylinder as sketched in Fig. 1 and then designed using the SP-8007 guideline.

Once the theoretical buckling load P_{cr} is calculated, the next step is to calculate the knock-down factor (KDF) “γ”, an empirical correction factor, which takes into account disparities between test and theoretical predictions using the following formula:

$$\gamma = 1 - 0.902(1 - e^{-\phi}) \tag{1}$$

where

$$\phi = \frac{1}{16}\sqrt{\frac{R_{eq}}{t_{eq}}} \tag{2}$$

The equivalent thickness t_{eq} depends on the shell's bending and extensional stiffness terms of ABD-matrix [12]:

$$t_{eq} = 3.4689\sqrt[4]{\frac{D_{11}D_{22}}{A_{11}A_{22}}} \tag{3}$$

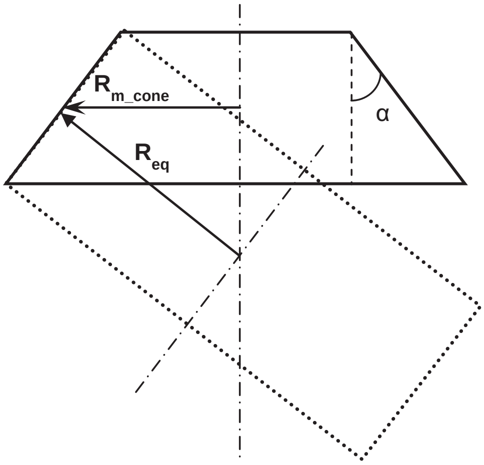

Fig. 1. Cone converted to equivalent cylinder.

The equivalent radius of a cone (Fig. 1) is calculated according to the following formula:

$$R_{eq} = \frac{R_{m\_cone}}{\cos(\alpha)} \tag{4}$$

where R_{m_cone} is the average radius of a cone:

$$R_{m\_cone} = \frac{r_{top} + r_{bot}}{2}, \tag{5}$$

where r_{top} and r_{bot} are the radius of the top edge and the radius of the bottom edge, respectively. Finally, the design load is computed using the following formula:

$$P = \gamma P_{cr} \tag{6}$$

where P_{cr} is the reference buckling load that could be calculated from the linear buckling analysis.

This formula (1) for “γ” was originally proposed by Seide in 1960 and improved by Weingarten in 1965, to the form presented in NASA SP-8007.

The NASA design approach is often believed to be conservative [3,13–15], and besides it does not consider the influence of lay-up on the knock down factor. Arbelo et al. [16] showed that for some cases the NASA SP-8007 can be non-conservative, also by not considering the important influence of the stacking sequence on the buckling behaviour, as explained by Zimmermann [17] and Geier et al. [18]. Thus, a new design approach that allows taking full advantage of using composite materials and adequately considers their mechanical properties is required.

3. Single perturbation load approach

Koiter in 1945 [19] was the first who theoretically demonstrated the already experimentally observed imperfection sensitivity that affects the buckling behaviour of thin-walled structures. Nowadays, with the everyday increasing computational power, it became easier to consider imperfections in numerical simulations. However, in the early design stage of new structures the real geometric imperfection pattern is not available. The SPLA is a deterministic method which assumes that one can simulate an initial geometric imperfection with an applied single perturbation (lateral) load (PL) that will cause a single buckle to occur along with the axial compression (Fig. 2).

Idealization of a typical SPLA KDF curve is shown in Fig. 3. As one increases the value of the perturbation load, the buckling load gets smaller down to a threshold where it remains nearly constant. This threshold of perturbation load is called P_1 (cf. point

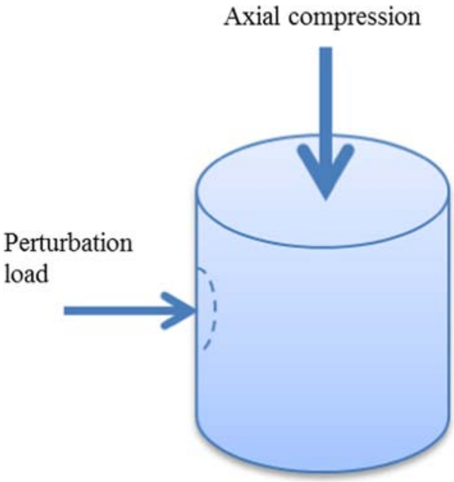

Fig. 2. Schematic mechanism of the SPLA.