Composite Structures 134 (2015) 750–761

Contents lists available at ScienceDirect

Composite Structures

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

Stacking sequence influence on imperfection sensitivity of cylindrical composite shells under axial compression

Linus Friedrich [a,*], Simon Loosen [a], Ke Liang [b], Martin Ruess [b], Chiara Bisagni [b], Kai-Uwe Schröder [a]

[a] Institute of Structural Mechanics and Lightweight Design, RWTH Aachen University, Wüllnerstraße 7, 52062 Aachen, Germany
[b] Aerospace Structures and Computational Mechanics, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, Netherlands

ARTICLE INFO

Article history:
Available online 5 September 2015

Keywords:
Composite shells
Shell buckling
Imperfection sensitivity
Axial compression

ABSTRACT

Space launcher vehicle structures are designed as thin walled cylindrical and conical structures which are prone to buckling and are sensitive towards geometrical imperfections. Small deviations in dimensions, which still are within manufacturing tolerances, may lead to a tremendous decrease in load carrying capacity. Thus, imperfections have to be considered during the design phase and this is commonly done using empirical knock down factors. Besides this approach, imperfections can be considered by applying numerical or analytical structural models. Composite materials are used to exploit the light weight potential of unstiffened thin walled structures. For this type of shell structure, the buckling load of the geometrically perfect shell and the imperfection sensitivity are significantly influenced by the laminate stacking sequence. In this paper, the influence of the laminate stacking sequence of composite shells with rotational symmetric imperfections on the buckling behavior is studied and laminate stacking sequences leading to the highest buckling loads of an imperfect shell structure are identified. These stacking sequences are evaluated further by applying non-rotational symmetric imperfections and localized imperfections and the stacking sequences leading to optimum designs of the geometrical perfect shell structure are considered as reference structures.

1. Introduction

The shell buckling phenomena has been subject of research for many years and is currently addressed within the EU project New Robust DESIgn Guideline for Imperfection Sensitive COmposite Launcher Structures (DESICOS) [1] and within the NASA Shell Buckling Knock Down Factor (SKBF) project [2]. Due to the imperfection sensitivity of these structures, deriving an appropriate mathematical description of the shell buckling problem, which allows a reliable and robust buckling load prediction, is a demanding task. To overcome this issue, empirical knock down factors, which are the ratios of experimental buckling loads to theoretical buckling loads of the perfect shell structure, are applied to reduce the buckling load determined theoretically. Early empirical knock down factors established during the 1960s, such as the knock down factor suggested by Seide [3], which is recommended in the NASA SP-8007 Space vehicle design guideline [4] and Almroth [5] are meant to be applied to isotropic shell structures. When these knock-down factors are applied to composite shells, an equivalent shell wall thickness t_{eq} is used to consider different imperfection sensitivities due to various laminate stacking sequences. The equivalent wall-thickness t_{eq} depends on the laminate properties which are described by the ABD stiffness matrix [6] according to the classical laminate theory.

Takano [7] has recently developed an empirical knock down factor for composite shell structures, which is derived from statistical evaluation of a series of buckling loads determined within shell buckling experiments mainly since the year 2000. The results of shell buckling experiments conducted by Bisagni [8], Meyer Piening [9] and Degenhardt [10], to mention a few, are considered in Takano's study. Two empirical knock down factors are suggested by Takano, which both are independent of the R/t-ratio, where t is the actual thickness of the laminate and R the cylinder radius. Two confidence levels are suggested, an A-basis and a B-basis. The knock down factor corresponding to the A-basis is 0.626 and the knock down factor corresponding to the B-basis is 0.479.

The A-basis and B-basis values are valid for $81 \leqslant R/t \leqslant 544$ and $1.54 \leqslant L/R \leqslant 6.67$. Due to only a few experimental data being available for shell structures with $R/t > 350$, provided by Degenhardt [11], the knock down factor suggested by Takano should be used carefully within this range [7].

---

* Corresponding author.
E-mail address: linus.friedrich@sla.rwth-aachen.de (L. Friedrich).
URL: http://www.sla.rwth-aachen.de (L. Friedrich).

http://dx.doi.org/10.1016/j.compstruct.2015.08.132
0263-8223/© 2015 Elsevier Ltd. All rights reserved.

The empirical knock down factors according to [5], according to NASA SP-8007 [4], which is derived by Seide [3], and according to [7] are illustrated in Fig. 1. It can be seen that the A-basis knock down factor according to Takano is higher compared to the knock down factor according to NASA SP-8007 space vehicle design guideline. Furthermore, within the region of validity of Takano's knock down factor, the empirical knock down factor according to the NASA SP-8007 divides into half and thus shows a strong dependency with regard to the R/t-ratio.

Besides the buckling load of the perfect shell structure, the imperfection sensitivity of a laminated composite shell is influenced by the stacking sequence of a laminate [12–15]. To allow the design of a shell structure with low sensitivity towards geometrical imperfections Koiter's b-factor [16] and Zimmermann's "imperfection susceptibility" (IS) index [17] can be applied. With these approaches it is aimed to identify configurations, which lead to the highest buckling load of a real shell structure, that is a shell structure with geometrical imperfections.

Koiter's b-factor describes the initial post-buckling behavior of a shell structure and thus allows us to gain information about the imperfection sensitivity of that structure. Positive b-factors indicate a shell structure, which is not imperfection sensitive, while negative b-factors indicate shell structures that are imperfection sensitive [13]. The absolute value of the b-factor indicates the degree of imperfection sensitivity and allows to compare different laminate stacking sequences with regard to the imperfection sensitivity. In [18], it is highlighted that the b-factor is highly sensitive to the buckling mode and thus the application of sensitive methods to determine a robust design is of doubtful value. For this reason, the b-factor is not evaluated further in this paper.

The imperfection susceptibility index, IS-index, was introduced by Zimmermann [17]. This terminology is chosen to allow for a clear distinction from the term imperfection sensitivity, which is often understood as a direct reduction of the buckling load of the perfect shell structure. The IS value is the number of buckling states between $1 \cdot F_{crit}$ and $1.05 \cdot F_{crit}$, which are in the neighborhood of the critical buckling load. The IS-index is based on the assumption that a high IS-value indicates high imperfection susceptibility and a low IS-value indicates low imperfection susceptibility.

In the 1990s, Zimmermann performed a series of structural mechanical optimizations of the geometrically perfect shell structure [19], and carried out multiobjective optimizations [17] to obtain shell structures with maximum buckling load and maximum imperfection tolerance. Zimmermann's eventual criterion space is described as illustrated in Fig. 2. It can be seen that the shell structure with a high buckling load has a high IS value, indicated as B in Fig. 2, whereby a shell with low IS-value also shows a low buckling load, indicated as A in Fig. 2. Thus, shell structures that conform with the upper path between point A and point B in Fig. 2 are the configurations desired within the optimization performed using Zimmermann's multiobjective optimization framework. This kind of optimum is considered to be a Pareto optimum. In [17], two shell structures forming a Pareto optimum leading to low IS values in conjunction with high buckling loads were studied experimentally and the results indicated that the shell structures can not be considered to be imperfection tolerant. These results were based on single experiments only. In this paper, the meaning of the IS-value is studied further.

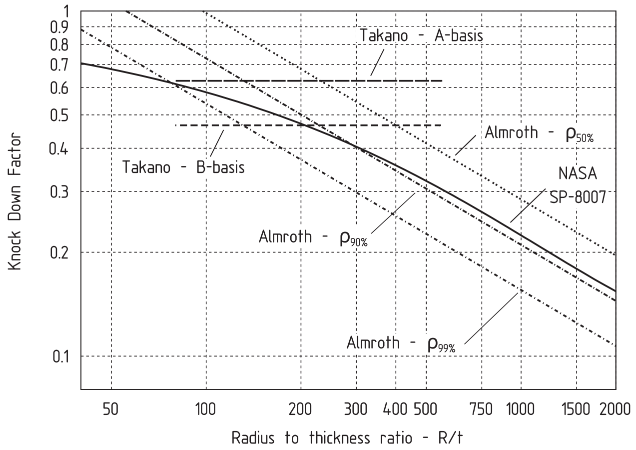

Fig. 1. Comparison of different empirical knock down factors.

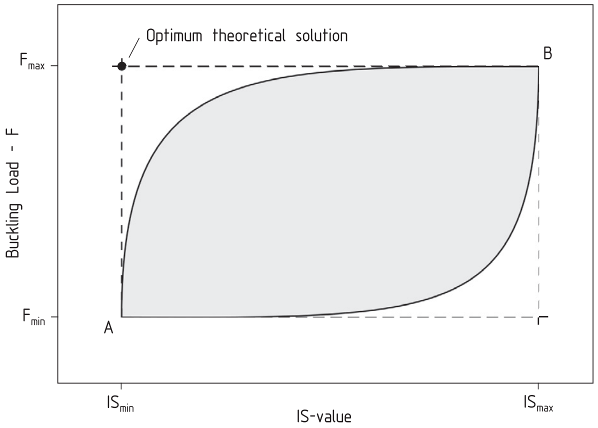

Fig. 2. Criterion space according to [14].

In 1970, Khot [12] conducted several studies on the imperfection behavior of laminated composite shells having rotational symmetric imperfections, as shown schematically in Fig. 3. For this purpose laminate stacking sequences such as $[0^\circ, \theta^\circ, -\theta^\circ]$ (in–out) are considered, whereby θ is the design variable. Basically, it can be stated that according to these studies, the laminate stacking sequence, which leads to the highest buckling load for the geometrical perfect shell structure also leads to the highest buckling load of the imperfect shell structure. In these studies, the number of possible designs is driven by a single parameter, θ, which is varied in 1°-steps considering 90 possible configurations.

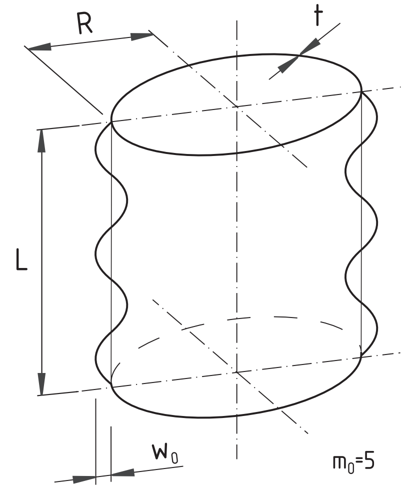

Fig. 3. Shell Structure with rotational symmetric imperfections (RSI), which denoted the number of halfwaves in longitudinal direction $m_0 = 5$.