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NEW ROBUST DESIGN GUIDELINE FOR IMPERFECTION SENSITIVE COMPOSITE LAUNCHER STRUCTURES

Richard Degenhardt [1,2]
[1] *DLR, Institute of Composite Structures and Adaptive Systems,*
Lilienthalplatz 7, 38108 Braunschweig, Germany
e-mail: richard.degenhardt@dlr.de

[2] *PFH, Private University of Applied Sciences Göttingen, Composite Engineering Campus Stade, Germany*

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Abstract

Up to today there are no design guidelines which allow designing imperfection sensitive CFRP structures in an efficient way. The upcoming EU project DESICOS (New Robust DESIgn Guideline for Imperfection Sensitive COmposite Launcher Structures) contributes to this aim by a new design procedure exploiting the worst imperfection approach efficiently by implementation of the Single Perturbation Load Approach. Preliminary studies already demonstrated high potential. This paper deals with the objectives of the DESICOS project, describes the line of actions of the new approach, and specifies the theoretical and experimental work to be carried out in order to meet the objectives.

1 Introduction

The Space industry demand for lighter and cheaper launcher transport systems. The upcoming EU project DESICOS (New Robust DESIgn Guideline for Imperfection Sensitive COmposite Launcher Structures), which will start in 2012, contributes to these aims by a new design procedure for imperfection sensitive composite launcher structures, exploiting the worst imperfection approach efficiently by implementation of the Single Perturbation Load Approach [1]. Currently, imperfection sensitive shell structures prone to buckling are commonly designed according the NASA SP 8007 guideline using the conservative lower bound curve. The guideline dates from 1968, and the structural behaviour of composite material is not considered appropriately, in particular since buckling load and imperfection sensitivity of shells made from such materials substantially depend on the lay-up design. This is not considered in the NASA SP 8007, which allows designing only so called "black metal" structures. Here is a high need for a new precise and efficient design approach for imperfection sensitive composite structures which allows significant reduction of structural weight and design cost. For most relevant architectures of cylindrical and conical launcher structures (monolithic, sandwich - without and with holes) DESICOS will investigate a combined methodology from the Single Perturbation Load Approach and a Specific Stochastic Approach which guarantees an effective and robust design. A recent investigation demonstrated, that an axially loaded unstiffened cylinder, which is disturbed by a large enough single perturbation load, is leading directly to the design buckling load 45% higher compared with the respective NASA SP 8007 design [2]. Within DESICOS the new methods will be further developed, validated by tests and summarized in a handbook for the design of imperfection sensitive composite structures. The potential will be demonstrated within different industrially driven use cases. This paper deals with the objectives of the DESICOS project, describes the line of actions of the new approach, and specifies the theoretical and experimental work to be carried out in order to meet the objectives.

2 State of the art

2.1 Imperfection sensitivity

In Fig. 1 taken from [3], knock-down factors are shown for axially compressed cylindrical shells depending on the slenderness. The results of tests are presented by dots and show the large scatter. The knock-down factors decrease with increasing slenderness. The discrepancy between test and classical buckling theory shown in Fig. 1 has stimulated scientists and engineers on this subject during the past 50 years. These works focused on postbuckling, load-deflection behaviour of perfect shells, various boundary conditions and its effect on bifurcation buckling, empirically derived design formulas and initial geometric imperfections. Koiter was the first to develop a theory which provides the most rational explanation of the large discrepancy between test and theory for the buckling of axially compressed cylindrical shells. In his doctoral thesis published in 1945 Koiter revealed the extreme sensitivity of buckling loads to initial geometric imperfecttions. His work received little attention until the early 1960's, because the thesis was written in Dutch. An English translation by Riks was published 1967 in [4].

Based on large test series in the 1950s and 60s the determination of lower bounds led to design regulations like NASA SP-8007 [1], but the given knock-down factors are very conservative. To improve the ratio of weight and stiffness and to reduce time and cost, numerical simulations could be used during the design process. The consideration of imperfections in the numerical simulation is essential for safe constructions. Usually, these imperfections are unknown in the design phase, thus pattern and amplitude have to be assumed.

In general, one can distinguish between loading imperfections and geometric imperfections. Both kinds of imperfections have a significant influence on the buckling behaviour and their state of the art is described in the following.

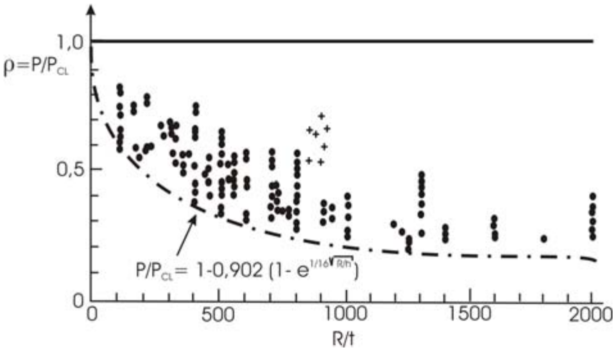

Fig. 1 Distribution of test data for cylinders subjected to axial compression [1]

Loading imperfections mean any deviations from perfect uniformly distributed loading, independent of the reason of the perturbation. Geier et al. tested composite cylindrical shells with different laminate designs [5], and they applied thin metal plates locally between test shell and supporting structure to perturb the applied loads and performed the so-called shim tests [6]. Later, numerical investigations were performed and compared to the test results; the importance was verified [7]. The need to investigate loading imperfections for practical use was shown for instance by Albus et al. [8] by the example of Ariane 5.

Geometric imperfections mean any deviations from the ideal shape of the shell structure. They are often regarded the main source for the differences between computed and tested buckling loads. Winterstetter et al. [9] suggest three approaches for the numerical simulation of geometrically imperfect shell structures: "realistic", "worst" and "stimulating" geometric imperfections. Stimulating geometric imperfections like welded seams are local perturbations which “stimulate” the characteristic physical shell buckling behaviour [10]. “Worst” geometric imperfections have a mathematically determined worst possible imperfection pattern like the single buckle [11]. “Realistic” geometric imperfections are determined by measurement after fabrication and installation. This concept of measured imperfections is initiated and intensively promoted by Arbocz [12]; a large number of test data is needed, which has to be classified and analysed in an imperfection data bank. Within the study presented in this paper, real geometric imperfections measured at test shells are taken into account.

Hühne et al. [1] showed that for both, loading imperfections and geometric imperfections the loss of stability is initiated by a local single buckle. Therefore unification of imperfection sensitivity is allowed; systems sensitive to geometric imperfections are also sensitive to loading imperfections. Single buckles are realistic, stimulating and worst geometric imperfections.

Using laminated composites, the structural behaviour can be tailored by variation of fibre orientations, layer thicknesses and stacking sequence. Fixing the layer thicknesses and the number of layers, Zimmermann [13] demonstrated numerically and experimentally that variation of fibre orientations affects the buckling load remarkably. The tests showed that fibre orientations can also significantly influence the sensitivity of cylindrical shells to imperfections. Meyer-Piening et al. [14] reported about testing of composite cylinders, including combined axial and torsion loading, and compared the results with computations.

Designing a cylinder appropriately is very important because changing only the lay-up or stacking sequence for the same cylinder geometry and thickness can lead to significantly different buckling loads. Zimmermann [15] designed different cylinders with extreme structural behaviour. Hühne [1] selected some of them and performed additional studies. Within a DLR-ESA study one of these cylinder designs, which is most imperfection sensitive, was manufactured 10 times and tested. It allowed a comparison with already available results and enlarged the data base [2].

The buckling process, even under static loading, is highly dynamic. In order to measure the full scale cylinder deformations of that process during testing, the Institute of Composite Structures and Adaptive Systems of DLR has developed a 360° measurement method based on the ARAMIS concept, a high speed optical grating system developed by GOM GmbH (`Gesellschaft für Optische Messtechnik´) [16]. The development includes four self-sustaining fast systems which can measure the 3-dimensional deformation field of an object by applying fast digital cameras with a speed of max. 1,000 images/sec.

2.2 Single-Pertubation-Load Approach

Hühne [1] proposed an approach based on a single buckle as the worst imperfection mode leading directly to the load carrying capacity of a cylinder (cf. Fig. 2). Fig. 3 shows that the buckling load under a pertubation load larger than a minimum value P_1 is almost constant. A further increase of the pertubation load has no significant change on the buckling any more. The buckling load F_1 (cf. Fig. 3) corresponds to the design buckling load. This concept promises therefore to improve the knock-down factors and allows designing any CFRP cylinder by means of one calculation under axial compression and a single-perturbation load. Within a DLR-ESA study, this approach was confirmed analytically and experimentally [2]. However, there is still a need for further studies.

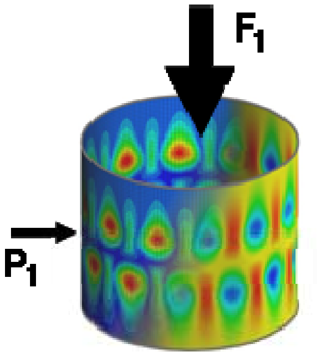

Fig. 2 Pertubation load mechanism

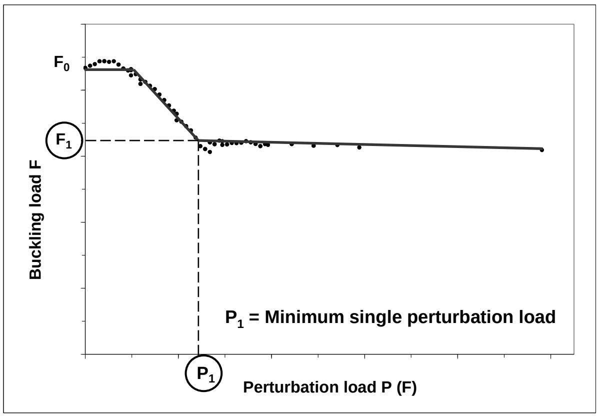

Fig. 3 Single perturbation load approach (SPLA)

2.3 Probabilistic research

In general, tests or analysis results are sensitive to certain parameters as boundary conditions or imperfections. Probabilistic methods are a possibility to assess the quality of results. The stochastic simulation with Monte Carlo (e.g. [17]) allows the statistical description of the sensitivity of the structural behaviour. It starts with a nominal model and makes copies of it whereas certain parameters are varied randomly. The random numbers, however, follow a given statistical distribution. Each generated model is slightly different, as in reality.

Nowadays, probabilistic simulations found the way into all industrial fields. In automotive engineering it is successfully applied in crash or safety (e.g. [18]). Klein et al. [20] applied the probabilistic approach to structural factors of safety in aerospace. Sickinger and Herbeck [21] investigated the deployable CFRP booms for a solar propelled sail of a spacecraft using the Monte Carlo method.

Velds [22] performed deterministic and probabilistic investigations on isotropic cylindrical shells applying finite element buckling analyses and showed the possibility to improve the knock-down factors. In addition, a set-up of a probabilistic design approach has still a lack of knowledge due to the incomplete base of material properties, geometric deviations, etc..

Arbocz and Hilburger [23] published a probability-based analysis method for predicting buckling loads of axially compressed composite cylinders. This method, which is based on the Monte Carlo method and first-order second-moment method, can be used to form the basis for a design approach and shell analysis that includes the effects of initial geometric imperfections on the buckling load of the shell. This promising approach yields less conservative knock-down factors than those used presently by industry.

2.4 Specific Stochastic Approach

Fig. 4 shows the variation (gray shaded band) of the buckling load resulting from its sensitivity to the scatter of the non-traditional imperfections (e.g. thickness variations). It demonstrates the need to cover this by the development of an additional knock-down factor ρ_2 in combination to the knock-down factor ρ_1 from SPLA.

An efficient design is feasible, if knowledge about possibly occurring imperfections exists and if this knowledge is used within the design process. Whereas the traditional imperfections are dealt with the SPLA, the non-traditional ones are taken into account by probabilistic methods, which enable the prediction of a stochastic distribution of buckling loads. Once the distribution of buckling loads is known, a lower bound can be defined by choosing a level of reliability. Degenhardt et al. [2] found less conservative knockdown factors than through the NASA-SP 8007 lower bound, by executing probabilistic analyses with non-traditional imperfections. This concept builds a decent foundation for extension in DESICOS.

The project work of DESICOS for the stochastic approach consists in checking which structural parameters substantially influence the buckling load and defining realistic limits for their deviations from the nominal values, in varying them within the limits and performing buckling load computations for these variations. The results are evaluated stochastically in order to define a guideline for the lower limits of the buckling loads within a certain given reliability. From these limits a knock-down factor is derived.

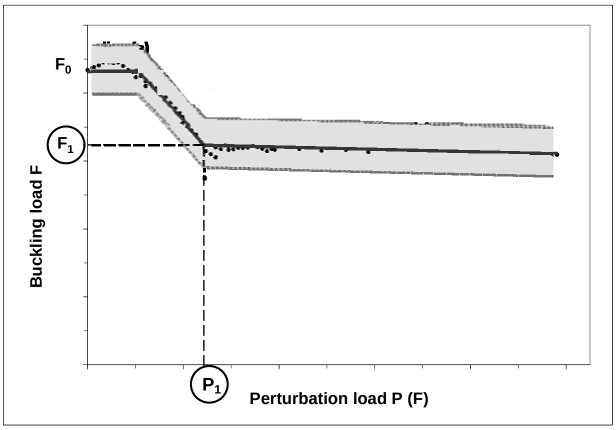

Fig. 4 Scatter of buckling load due to the scatter of non-traditional imperfections

2.5 Conclusions

From all this it becomes obvious that a great deal of knowledge is accumulated concerning the buckling of cylindrical shells under axial compression. However, the NASA guideline for the knock-down factors from 1968 is still in use, and there are no appropriate guidelines for unstiffened cylindrical CFRP shells. To define a lower bound of the buckling load of CFRP structures a new guideline is needed which takes the lay-up and the imperfections into account. Because there is a huge number of lay-up possibilities for each geometry, the new guideline must be different than the NASA SP-8007. This can be for instance a probabilistic approach [e.g. [23]) or the Single-Pertubation-Load approach as presented in [1]. Independent of the approach dozens of additional tests are necessary, in order to account for statistical scatter. In the following the idea of the DESICOS project is described which will try to combine both approaches.

3 DESICOS project

3.1 Objectives

The main objectives of DESICOS is realised by the implementation of the *Single Perturbation Load Approach* (SPLA) for buckling of imperfection sensitive structures. This approach considers the 'traditional' imperfections like the geometric and implicitly also the loading ones. In order to guarantee a robust design, the approach is combined with a specific stochastic procedure, which considers the 'non-traditional' imperfections like variations of thickness, material properties, etc. The outcome of the single perturbation load approach is the knock down factor ρ_1 and the outcome of the stochastic approach under consideration of specific aspects of composites (stacking, etc.) leads to the knock down factor ρ_2. Both factors are combined together in order to define the design load, cf. Eq. (1). This concept promises to exploit the full potential of composite structures in an efficient way.

$$F_{Design} = F_{perfect} * \rho_1 * \rho_2 \qquad (1)$$

ρ_1 = Knock down factor *Single Perturb. Approach*

ρ_2 = Knock down factor *Stochastic Approach*

3.2 Consortium

The DESICOS consortium merges knowledge from 2 large industrial partners (ADTRIUM-SAS from France and Astrium GmbH from Germany), one enterprise belonging to the category of SME (GRIPHUS from Israel), 2 research establishments (DLR from Germany and CRC-ACS from Australia) and 7 universities (Politecnico di Milano from Italy, RWTH Aachen, Leibniz University and the Private University of Applied Sciences Göttingen from Germany, TECHNION from Israel, TU-Delft from Netherlands and Technical University of Riga from Latvia). The large industrial enterprises and the SME bring in their specific experience with designing and manufacturing of space structures as well as their long grown manufacturing philosophies for high quality stiffened composite structures. The academic partners and the research organisations provide their special knowledge in methods and tool development as well as testing. This consortium composition assures the expected rapid and extensive industrial application of the DESICOS results.

3.3 Workpackages

The partners co-operate in the following technical work packages:

- WP1: Benchmarking on selected structures with existing methods: Benchmarks are defined for method evaluation purposes. The objective is the knowledge of the abilities and deficiencies of existing approaches.
- WP2: Material characterisation and design of structures for buckling tests: The first focus is on the design of structures which will be manufactured and tested in WP4. For that purpose, small specimens will be built and tested in order to characterise the specific composite material properties.
- WP3: Development and application of improved design approaches: In this workpackage new design approaches are developed, modelling and analysis strategies are derived. Finally, all methods are validated by means of the experimental results obtained from the other workpackages.
- WP4: Manufacture, inspection and testing of structures designed in WP 2: This workpackage deals with the manufacturing and testing of structures. The objective is to extend the data base on buckling of imperfection sensitive structures. Based on the designs from WP2 as input, a total of 14 (monolithic, sandwich, stiffened and unstiffened, cylindrical and conical) structures will be considered.
- WP5: Design handbook and industrial validation: WP5 comprises the final technical part; all the results of the project are assembled in order to derive the final design guidelines and to validate them as well as the new methods. The input is summarized in the improved design procedures, the documentation of the designs as well as the documentation of the experiments and their evaluated results.

3.4 Expected results

To reach the main objective, improved design methods, experimental data bases as well as design guidelines for imperfection sensitive structures are needed. The experimental data bases are indispensable for validation of the analytically developed methods. Reliable fast methods will allow for an economic design process. Industry brings in experience with the design and manufacture of real shells; research contributes knowledge on testing and on development of design methods. Design guidelines are defined in common, and the developed methods are validated by industry.

The results of DESICOS comprise:

- Material properties, measured according to the applicable standards
- Method for the design of buckling critical fibre composite launcher structures, based on the combined SPLA and stochastic procedures, validated by experiments
- Experimental results of buckling tests including measured imperfections, buckling and postbuckling deformations, load shortening curves, buckling loads
- Guidelines how to design composite cylindrical shells to resist buckling
- Reliable procedure how to apply the Vibration Correlation Technique (VCT) in order to predict buckling loads non-destructively by experiments
- Handbook including all the results
- Demonstration of the potential with different industrially driven use cases.

4 Summary

The main objective of the upcoming DESICOS project is the future design scenario for imperfection sensitive CFRP structures. The results comprise extended experimental data bases, improved design methods as well as design guidelines. More details can be found at www.desicos.de.

5 Acknowledgements

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