Chapter 1

Dealing with Imperfection Sensitivity of Composite Structures Prone to Buckling

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1. Introduction

Currently, imperfection sensitive shell structures prone to buckling are designed according the NASA SP 8007 guideline using the conservative lower bound curve. This guideline dates from 1968, and the structural behaviour of composite material is not appropriately considered, in particular since the imperfection sensitivity and the buckling load of shells made of such materials depend on the lay-up design. This is not considered in the NASA SP 8007, which allows designing only so called "black metal" structures. There is a high need for a new precise and fast design approach for imperfection sensitive composite structures which allows significant reduction of structural weight and design cost. For that purpose a combined methodology from the Single Perturbation Load Approach (SPLA) and a specific stochastic approach is proposed which guarantees an effective and robust design. The SPLA is based on the observation, that a large enough disturbing load leads to the worst imperfection; it deals with the traditional (geometric and loading) imperfections [1]. The stochastic approach considers the non-traditional ones, e.g. variations of wall thickness and stiffness. Thus the combined approach copes with both types of imperfections. A recent investigation demonstrated, that applying this methodology to an axially loaded unstiffened cylinder is leading directly to the design buckling load 45% higher compared with the respective NASA SP 8007 design [2].

This chapter presents in its first part the state-of-the-art in buckling of imperfection sensitive composite shells. The second part describes current investigations as to the SPLA, the stochastic approach and their combination. In a third part an outlook is given on further studies on this topic, which will be performed within the framework of the running 3-year project DESICOS (New Robust DESIgn Guideline for Imperfection Sensitive COmposite Launcher Structures) funded by the European Commission; for most relevant architectures of cylindrical and conical launcher structures (monolithic, sandwich - without and with holes) the new methodology 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.

2. State of the art

2.1. Imperfection sensitivity

In Figure 1 taken from [3], knock-down factors – the relations of experimentally found buckling loads and of those computed by application of the classical buckling theory - are shown for axially compressed cylindrical shells depending on the slenderness. The results 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 has stimulated scientists and engineers on this subject during the past 50 years. The efforts focused on postbuckling, load-deflection behaviour of perfect shells, various boundary conditions and their 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 imperfections. 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].

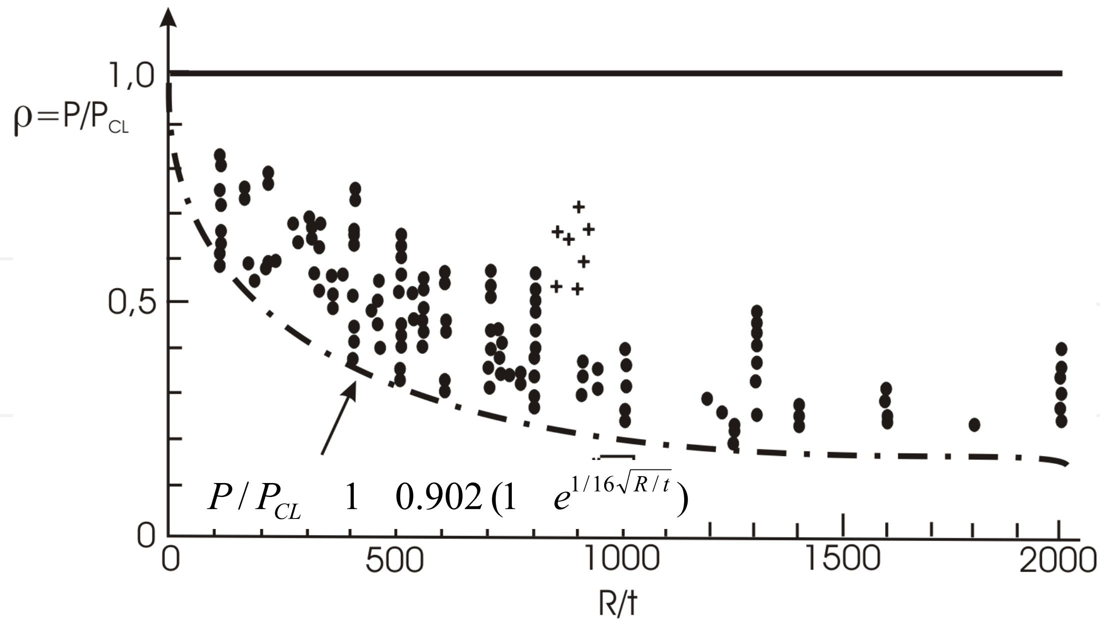


Figure 1. Distribution of test data for cylinders subjected to axial compression [1]

Based on a number of experimental tests 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.

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.

Hühne [1] selected some of the tests described in [13] to [15] 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].

2.2. Single-perturbation-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. Figure 2 explains its mechanism; the lateral perturbation load P is disturbing the otherwise unloaded shell, and the axial compression load F is applied until buckling. This is repeated with a series of different perturbation loads, starting with the undisturbed shell and the respective buckling load F_0. In Figure 3 buckling loads F depending on the perturbation loads P are depicted. The figure shows that the buckling load belonging to a perturbation 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 is considered to be the design buckling load. This concept promises 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, cf. [2]. However, there is still the need for a multitude of further studies.

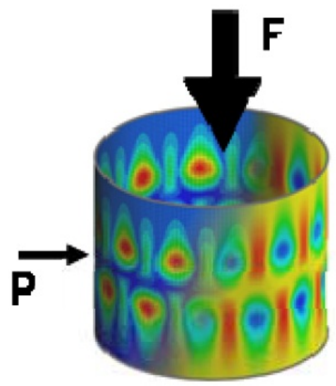


Figure 2. Perturbation load mechanism

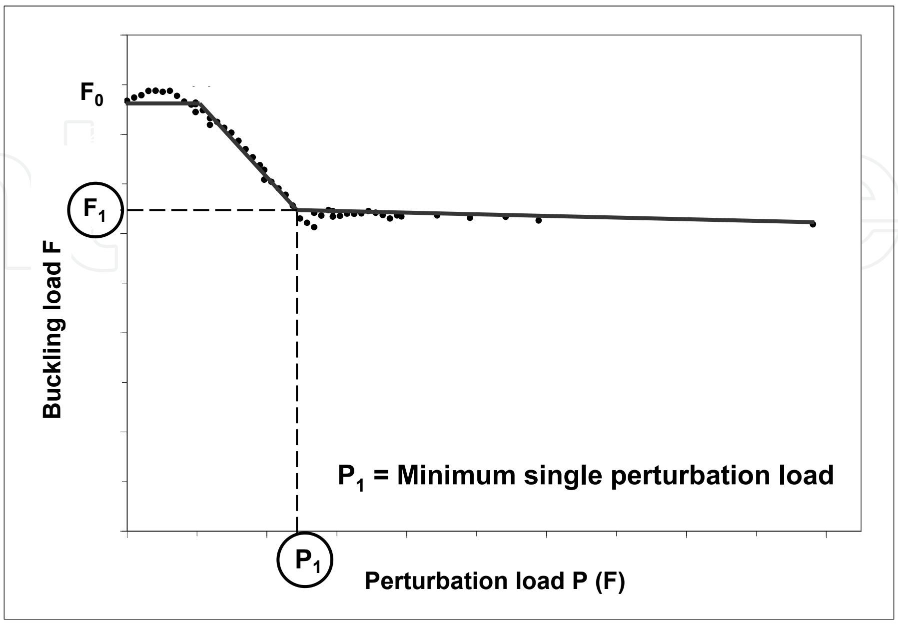


Figure 3. Single perturbation load approach (SPLA)

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.

Recently, probabilistic simulations found the way into all industrial fields. In automotive engineering they are 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. However, setting-up of a probabilistic design approach still suffers by 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

Figure 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.

The work 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.

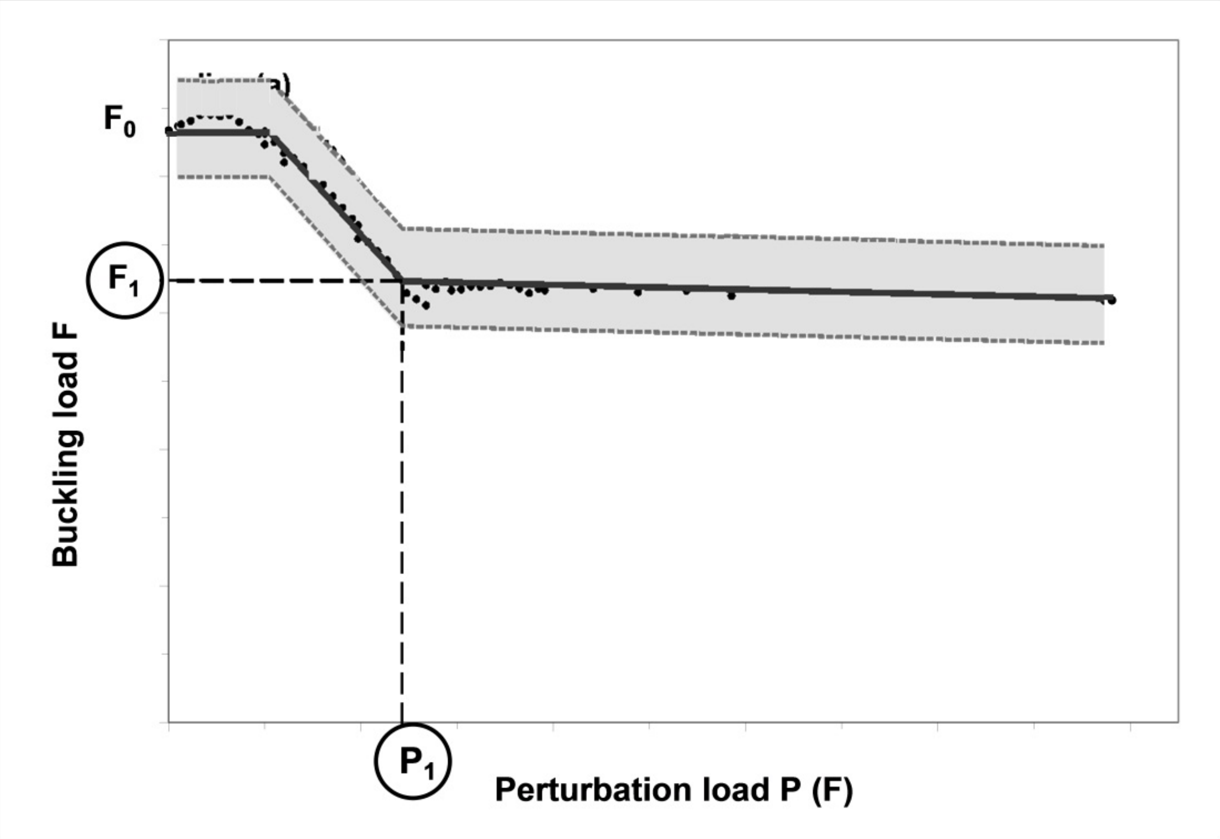


Figure 4. Scatter of buckling load due to the scatter of non-traditional imperfections

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. This can be for instance a probabilistic approach or the Single-Perturbation-Load approach, combined with a specific stochastic approach. In the following the second one is considered in more detail. Independent of the approach dozens of additional tests are necessary, in order to account for statistical scatter as well as for software and guideline validation

3. SPLA combined with specific stochastic approach

3.1. The procedure and first results

Figure 5 summarises the future design scenario for imperfection sensitive composite structures in comparison to the current design scenario. Currently, the buckling load of the perfect structure $F_{Perfect}$ has to be multiplied by the knock-down factor $\rightarrow_{NASA}$ from the NASA SP 8007 guideline. This approach was developed for metallic structures in 1968 and does not at all allow exploiting the capacities of composite structures. Accordingly, with the new design scenario $F_{Perfect}$ is multiplied by ρ_1 which results from SPLA and ρ_2 which comes from the specific stochastic approach.

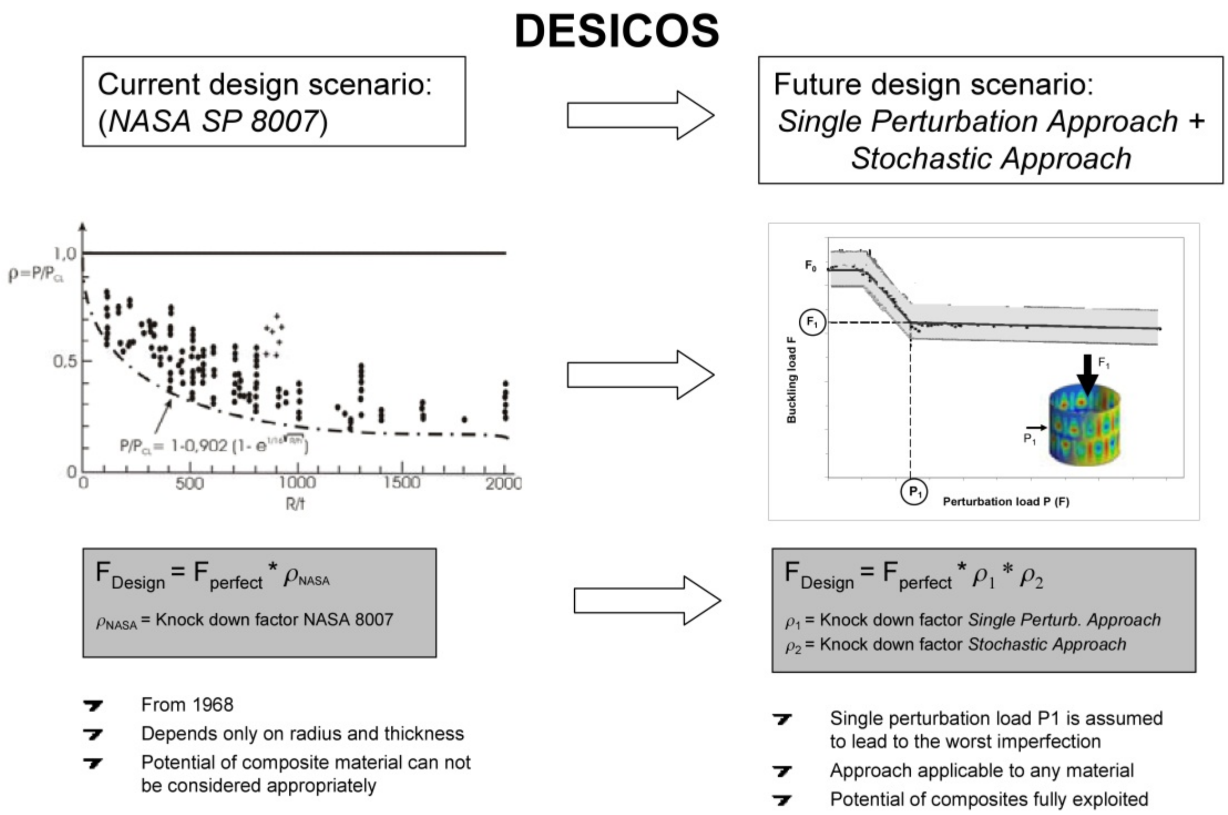
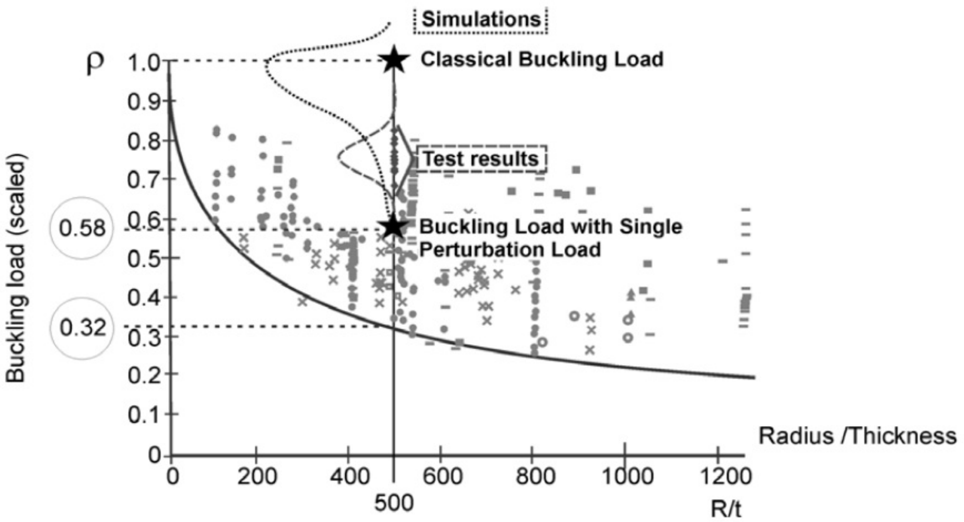


Figure 5. Future design scenario for composite structures

First studies (cf. [2]) demonstrated the high potential of this combined approach which is summarized in Figure 6. In this example a composite cylinder (R/t=500) with 4 layers was designed according the current and the future design scenarios. The classical buckling load was calculated and utilized as reference (scaled buckling load ϱ=1.0, marked by a star). The buckling load calculated by the SPLA was at ϱ=0.58 (marked by a star). All experimentally extracted results revealed first buckling beyond the one calculated by the SPLA (safe design). The knock down factor from the SPLA was found to be 0.58 (times 0.8 from stochastic), whereas the one form NASA SP was 0.32. The result was that the load carrying capacity could be increased by 45%. It corresponds to approximately 20% weight reduction for the same load. In [2] the results were validated by tests on 10 nominally identical structures.

The improvement of load carrying capacity by 45% for the investigated 4-ply laminate can be considered to be representative for the following reasons: That laminate set-up was chosen because of its remarkable imperfection sensitivity known from foregoing investigations. With high imperfection sensitivity NASA SP 8007 is not as conservative as with a lower one, nevertheless the improvement of load carrying capacity came to 45%. With lay-ups leading to low imperfection sensitivity the NASA SP 8007 is extremely conservative because it is overestimating the negative influence of imperfections. In that case the improvement of load carrying capacity may be even higher than 45%. Thus the margin of 45% is at the lower limit of improvement of load carrying capacity, and it is not relevant for the expected improvement due to the novel approach whether the 4-ply laminate is optimal or representative for the real construction.



- $\rho_{NASA} = 0.32$
- $\rho_1 = 0.58$
- $\rho_2 = 0.80$ (Conservative estimation)

$F_{Design} = F_{perfect} * \rho_{NASA}$	$F_{Design} = F_{perfect} * \rho_1 * \rho_2$
$F_{Design} =$ 32 * 0.32 = **10.2 kN**	$F_{Design} =$ 32 * 0.58 * 0.8 = **14.8 kN**

Improvement: 45 %

Figure 6. Potential of the future design scenario [2]
Example: CFRP cylindrical shell (R/t = 500, 4 layers), $F_{perfect}$ = 32 kN

3.2. The key role of experiments

New design methods or new software tools in the engineering have to be validated by test results. In addition, stochastic approaches require comprehensive data bases. In order to achieve suitable results appropriate test facilities and measurement systems, but also experience is needed. In the following, facilities and procedures are listed as currently used at DLR, cf. [16].

The buckling test facility is the main instrument to investigate buckling phenomena and to validate software simulations. Figure 7 shows on the left the axial compression configuration and on the right the compression-shear-configuration of the buckling test facility of the DLR Institute of Composite Structures and Adaptive Systems. The test facility can be changed from one configuration to another according to the test requirements.

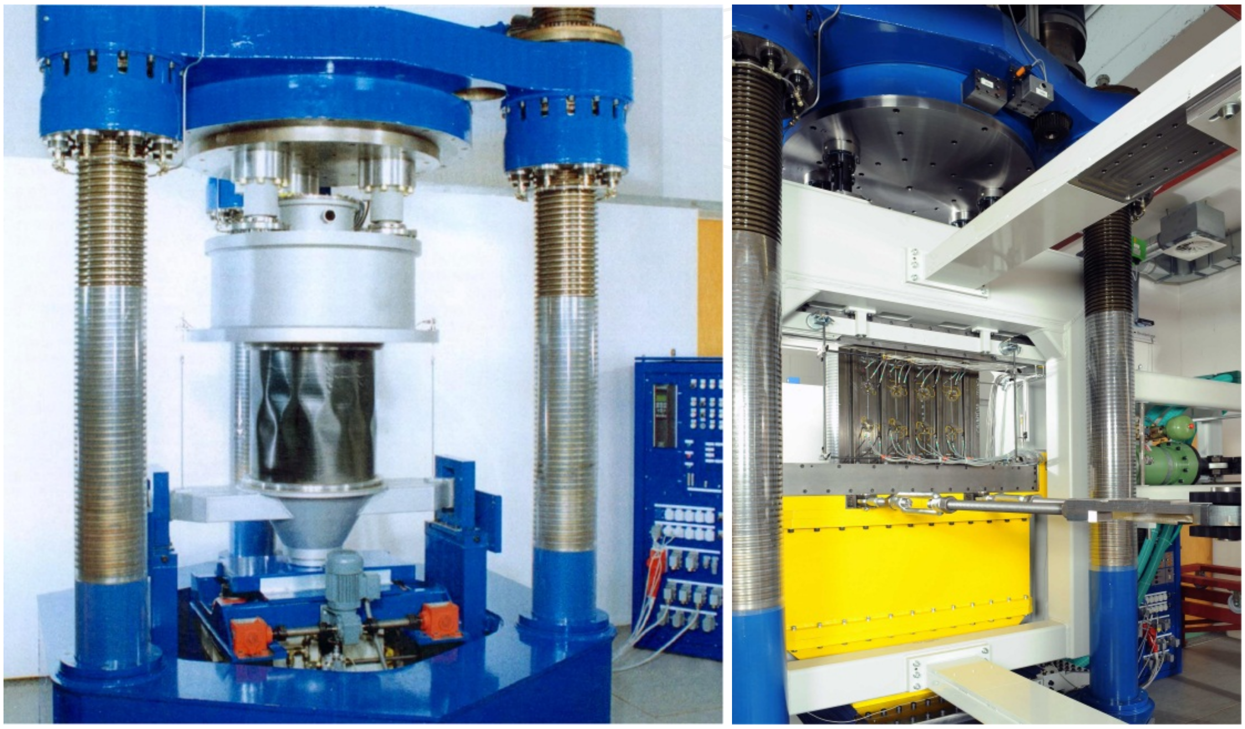


Figure 7. DLR's buckling test facility, axial compression configuration (left), compression-shear-configuration (right)

The axial compression configuration is best suited for investigation of imperfection sensitivity on cylindrical structures. All parts of the test device are extremely stiff. The test specimen is located between an axially supporting top plate and a lower drive plate. The top plate can be moved in vertical direction on three spindle columns in order to adapt the test device to various lengths of test specimens. Due to the great sensitivity of stability tests against non-uniform load introduction even the small necessary clearance inside the spindle drives is fixed during the tests by automatically operating hydraulic clamps. The top plate functions as a counter bearing to the axial force that is applied to the movable lower drive plate by a servo-controlled hydraulic cylinder. The drive plate acts against the specimen, which itself acts against a stout cylindrical structure that is meant to distribute the three concentrated forces coming from three load cells at its upper surface, into a smooth force distribution. The test specimen is placed between the load distributor and the drive plate. Although the test device and test specimen are manufactured with particular care one can not expect, that the fixed upper plate and the load distributor are perfectly plane and parallel to each other, nor can one expect the end plates or clamping boxes of the test specimen to be perfectly plane and parallel. To make sure, that the test specimen will be uniformly loaded, thin layers of a kind of epoxy concrete, i.e. epoxy reinforced with a mixture of sand and quartz powder, are applied between the end plates or clamping boxes of the test specimens and the adjacent parts of the test device. This has the side effect of securing the test specimens against lateral displacement. In order to determine the offset of the load measurement it is required, that at least one side of the specimen may be separated temporarily from the test facility. This is achieved by using a separating foil between the top plate and the upper epoxy layer. Two displacement transducers (LVDT) are used to measure axial shortening of the specimen during the tests. Their signals are recorded and, moreover, used for control purposes as actual values. Hence, the test device is displacement controlled. According to the particular arrangement of the transducers the elastic deformation of the test device does not influence the control by shortening at quasi-static loading. Table 1 summarizes the characteristics of the test facility.

Load case	
Axial compression	Max. 1000 kN
Torsion	Max. 20 kNm
Internal pressure	Max. 800 kPa
External pressure	Max. 80 kPa
Shear	Max. 500 kN
Geometry limits of the test structure	
Length	Max. 2100 mm
Width (diameter)	Max. 1000 mm
Load frequency (axial compression only)	Max. 50 Hz

Table 1. Characteristics of the DLR buckling test facility

Before testing geometric and material imperfections are measured by the following systems (or equivalent)

1. ATOS: The ATOS system is based on photogrammetry (precision: 0.02 mm), Figure 8 illustrates an example of measured imperfections which are scaled by a factor of 100 to improve the visibility
2. Ultrasonic inspection

During testing the deformations are measured by the ARAMIS system:

It is based on photogrammetry (precision: 0.02 mm). The system used allows also a 360° measurement of shell surface displacements on a CFRP cylinder (cf. Figure 9 and Figure 11).

All measured full field displacements are transferred to a global coordinate system of the cylinder by means of at least three reference points in each area. The reference points are allocated to the global coordinate system by TRITOP, another photogrammetric system. The result of this procedure is a complete 3-D visualisation of the cylinder deformation (cf. Figure 9). The four camera pairs can also be placed on one part of the structure which allows a quadruplicating of the number of taken pictures per time (Figure 10). A 360° survey of a CFRP cylinder (selected deformation patterns of one loading and unloading sequence) is presented in Figure 11.

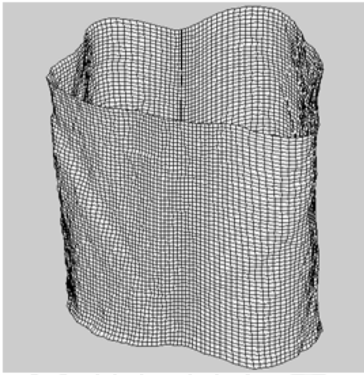


Figure 8. Measured geometric imperfections (ATOS)

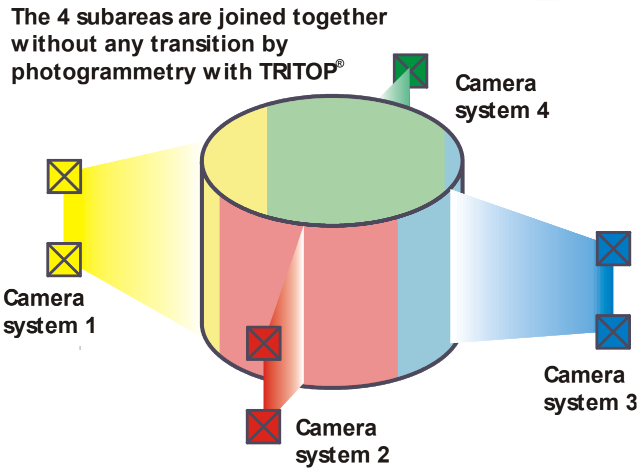


Figure 9. 360° Measurement on a cylinder

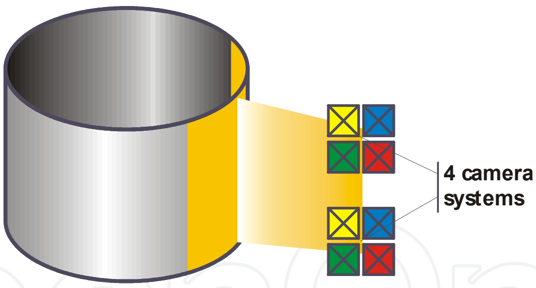


Figure 10. High Speed ARAMIS Set-Up

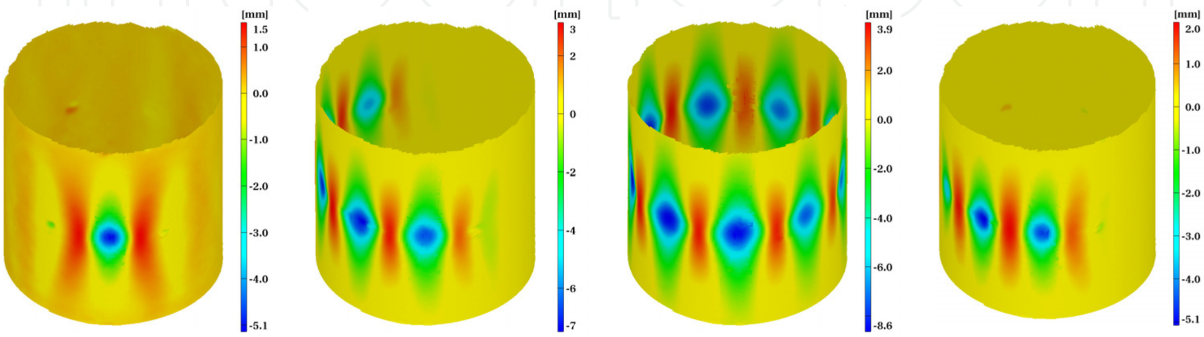


Figure 11. Results of a 360° Measurement on a CFRP cylinder (selected deformation patterns of one loading and unloading sequence)

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Figure 12 illustrates the measured load-shortening curves of 10 tests with three selected pictures extracted from ARAMIS measurement obtained from the 360° measurement. Picture A and B are from the pre-buckling and Picture C from the early post-buckling state. Figure 13 compares the post-buckling pattern between test and Finite-Element simulation. The left picture is obtained by the 360° ARAMIS measurement. It agrees quite well with the simulation in the right figure. This buckling pattern was observed for all 10 cylinders. More details can be found in [2].

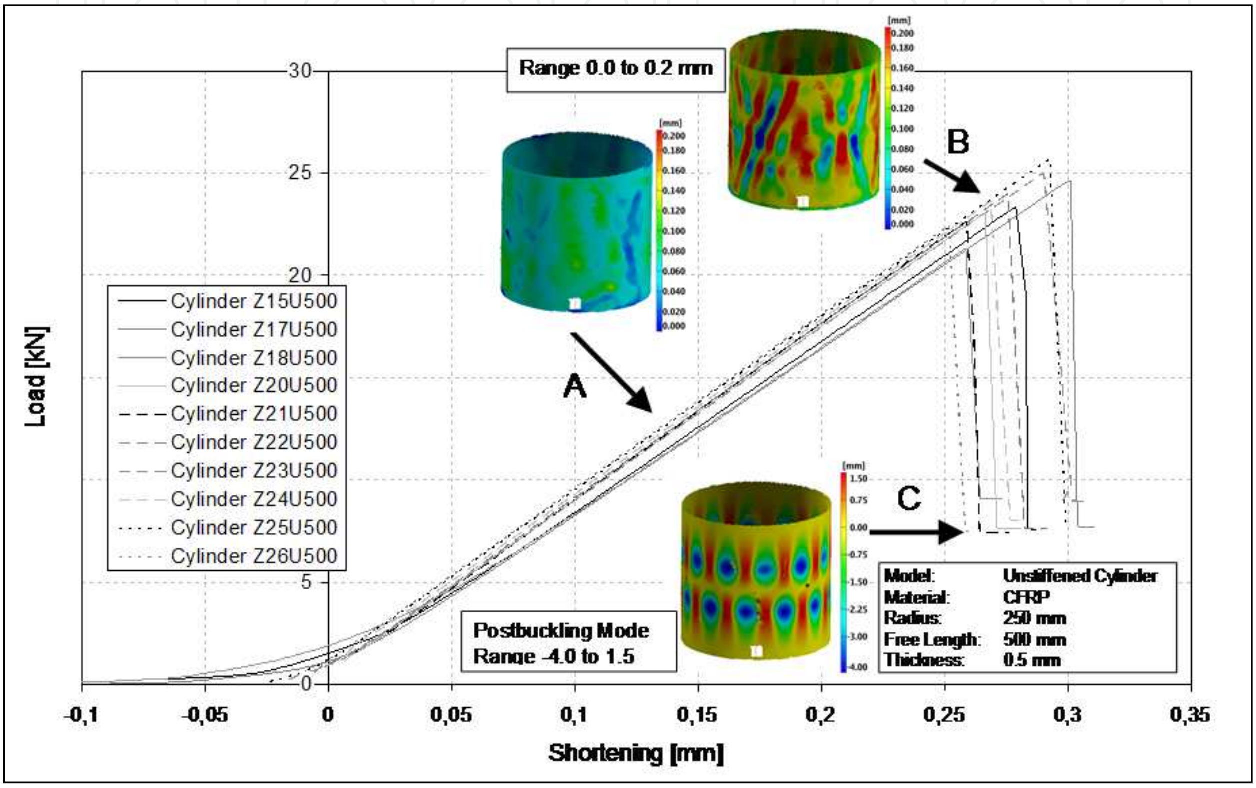

Figure 12. Load shortening curves of 10 tested cylinders and ARAMIS measurement

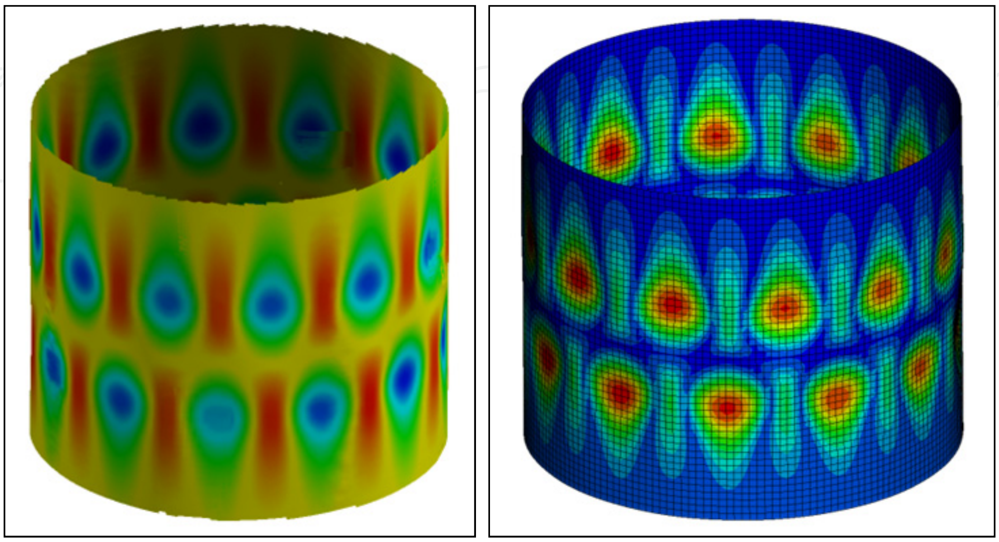

Figure 13. Postbuckling pattern. Left: Test results obtained by ARAMIS – Right: Simulation results

4. DESICOS project

4.1. Main objective

The main objective of DESICOS is to establish an approach on how to handle imperfection sensitivity in space structures endangered by buckling, in particular for those made from fiber composite materials. It shall substitute the NASA SP 8007, which is extremely conservative and not really applicable for composite structures, cf. Figure 5.

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.

4.2. 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 output is summarized

in the improved design procedures, the documentation of the designs as well as the documentation of the experiments and their evaluated results.

4.3. 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.

5. Summary

This chapter summarises the state-of-the-art of imperfection sensitive composite structures prone to buckling. The current design process according the NASA SP 8007 is shown and its limitations to design structures made of composites are explained. A new promising approach which combines the Single Perturbation Load Approach and a Stochastic Approach - as an alternative to the NASA SP 8007 - is presented. It is further developed in the EU project DESICOS the objectives and expected results of which are given. More details can be found at www.desicos.de.

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