PROBABILISTIC APPROACH FOR IMPROVED BUCKLING KNOCK-DOWN FACTORS OF CFRP CYLINDRICAL SHELLS

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OVERVIEW

Aerospace industry demands for significantly reduced development and operating costs. Reduction of structural weight at safe design is one avenue to achieve this objective. The running ESA (European Space Agency) study *Probabilistic Aspects of Buckling Knock Down Factors – Tests and Analyses* contributes to this goal by striving for an improved buckling knock-down factor for unstiffened CFRP cylindrical shells. This needs a large number of linear and non-linear buckling simulations, which are to be validated against test results. DLR is acting as study contractor. The paper presents an overview about the DLR buckling tests, the measurement setup and the buckling simulations which are done so far, and gives an outlook to the results which are expected until the end of the running project.

1. INTRODUCTION

This study concentrates on thin-walled circular cylindrical CFRP (carbon fiber reinforce plastics) shells subjected to axial compression. It is well known that such structures exhibit not only a high load carrying capacity but also are prone to buckling which is highly imperfection sensitive. Imperfections are defined as deviations from perfect parameters like shape, thickness, material properties and loading distributions. They can reduce the buckling load drastically compared to a perfect shell. In order to account for these imperfections the theoretical buckling load of a perfect cylinder must be reduced by a knock-down factor, the ratio of buckling loads of imperfect and perfect cylindrical shell. Thus, the closer the knock-down factor reflects the effect of imperfections the better is the prediction of the real buckling load.

In the still used NASA SP-8007 design guideline from 1968 [1] a lower bound curve for the knock-down factor is provided. The factor decreases with increasing slenderness (the ratio of radius and wall thickness). The values are rather conservative and the structural behaviour of composite material is not considered adequately. Advanced thin-walled cylindrical shell structures under compression are therefore penalized if the knock-down factor based on this design guideline must be applied.

The current ESA study started in May 2006 and will run for 18 months. Its main objective is to achieve a better buckling knock-down factor for unstiffened CFRP cylindrical shells and to validate the linear and non-linear buckling simulations by test results. The main results will comprise an experimental data base (material properties, measured thicknesses, full scale shape imperfections, load-shortening curves, strains, and deformations) obtained by testing 10 nominally identical axially compressed CFRP cylindrical shells as well as sensitivity analyses using Monte-Carlo simulation, validation against tests and a design guideline for that type of structure with a less conservative knock-down factor than taken from NASA SP-8007. All tasks of the ESA study are performed at the Institute of Composite Structures and Adaptive Systems of DLR Braunschweig, which has comprehensive and profound experience in design, manufacturing, testing and analysis of shells prone to buckling.

Independent of the ESA study, which is the main focus of this paper, DLR guided a PhD thesis to develop a promising alternative design concept for unstiffened composite structures. In that work Hühne developed an approach [2], [3], [4] which also promises to improve the knock-down factors. This approach assumes that a larger single buckle initiated by a perturbation load is the worst imperfection mode and leads directly to the load carrying capacity of a cylinder. No further information about the imperfections of the unstiffened structure is needed. This paper shows also test results of one cylinder loaded by a single perturbation load in addition to the axial compression.

2. STATE OF THE ART

2.1. Imperfection sensitivity

In FIGURE 1, taken from [1], 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 FIGURE 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 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 [5].

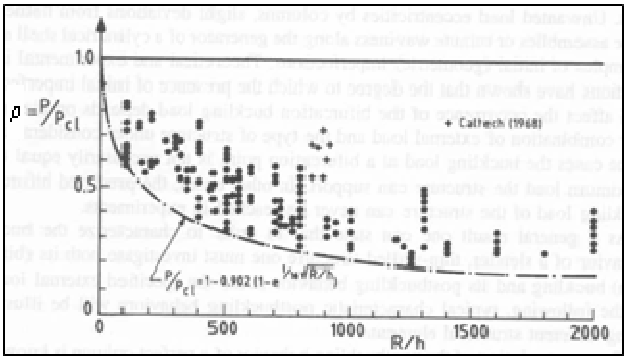

FIGURE 1. Distribution of test data for cylinders subjected to axial compression [1]

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.

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 [6], 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 [7]. Later, numerical investigations were performed and compared to the test results; the importance was verified [8]. The need to investigate loading imperfections for practical use was shown for instance by Albus et al. [9] 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. [10] 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 [11]. “Worst” geometric imperfections have a mathematically determined worst possible imperfection pattern like the single buckle [12]. “Realistic” geometric imperfections are determined by measurement after fabrication and installation. This concept of measured imperfections is initiated and intensively promoted by Arbocz [13]; 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. [2] 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. More information about geometric and loading imperfections is given by Hühne [14].

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 [15] 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. [16] 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 [17] designed different cylinders with extreme structural behaviour. Hühne [2] selected some of them and performed additional studies. In the ESA study presented in this paper one of these cylinder designs, which is most imperfection sensitive, was selected. It allows also a comparison with already available results and enlarges the data base.

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´) [18]. The new 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. Section 4.4 gives more details.

2.2. 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. [19], [20]) 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. [21] or [22]). Klein et al. [23] applied the probabilistic approach to structural factors of safety in aerospace. Sickinger and Herbeck [24] investigated the deployable CFRP booms for a solar propelled sail of a spacecraft using the Monte Carlo method.

Velds [25] 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 [26] 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.

2.3. Single-Pertubation-Load Approach

Hühne [2], [3], [4] recently proposed an approach based on a single buckle as the worst imperfection mode leading directly to the load carrying capacity of a cylinder. It promises also 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. This concept is rather new and needs to be verified by more tests and analyses. Within the ESA study, additional tests on one of the ten cylinders were performed in order to check the approach and compare it with the probabilistic procedure.

2.4. 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. [26]) or the Single-Pertubation-Load approach as presented in [2]. Independent of the approach dozens of additional tests are necessary, in order to account for statistical scatter. Within the ESA study presented in this paper 10 tests on one cylinder design were performed. Insofar, this study provides one small step towards the large objective of a new design guideline.

3. CYLINDER DESIGN

Within the ESA study 10 cylinders of one nominally identical design had to be tested. So as first step an appropriate design had to be chosen. CFRP structures offer a wider range of design variables than metal structures.

For industrial applications a cylinder shall behave robustly and not very sensitive to certain parameters as imperfections. For research activities, however, (e.g. probabilistic investigation of the buckling behaviour) a cylinder with the opposite behaviour is needed. Its buckling load should be sensitive to imperfections in order to improve statistical investigations.

To analyse the buckling knock-down factor it is important to have a cylinder design which is highly prone to buckling. In the past DLR designed and tested a multitude of different cylinders with respect to buckling load and imperfection sensitivity (e.g. [3]). For the ESA study a cylinder was designed guided by the following objectives and conditions:

1) The cylinder shall be very imperfection sensitive in order to demonstrate as much as possible the sensitivity of certain parameters.
2) For a preferably small knock down factor the slenderness R/t shall be as large as possible.
3) DLR has considerable experience with cylinders with a diameter of 500 mm. The corresponding database provides a good basis for comparison.

Considering these objectives the cylinder design shown in FIGURE 2 was selected. This cylinder was designed by Zimmermann [17]. The nominal data and the lay-up can be taken from TAB 1. The thickness of 0.5 mm is from a practical point of view the minimum required value for testing.

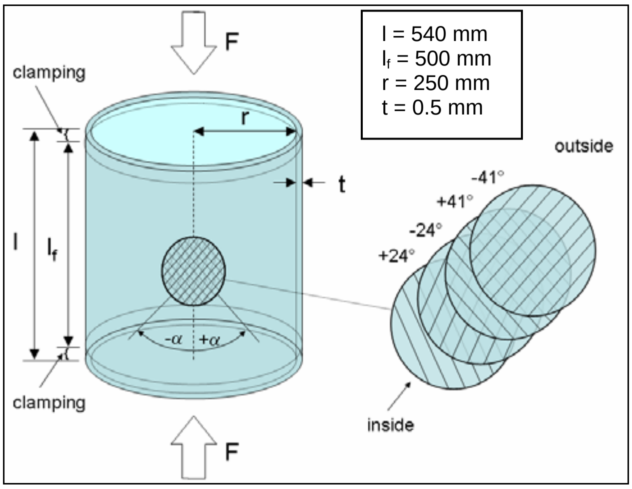

FIGURE 2. Selected cylinder design

4. DLR BUCKLING TEST FACILITY AND MEASUREMENT SYSTEMS

4.1. Buckling Test Facility

All buckling tests were performed in the buckling test facility (cf. FIGURE 3) of the DLR Institute of Composite Structures and Adaptive Systems. The facility is predestined for high precision buckling tests of thin-walled shells like cylinders or panels. Axial compression up to 1 MN, torsion up to 20 kNm as well as internal pressure between -1hPa (simulating external pressure) and 10 hPa can be applied simultaneously.

Geometry / Lay-up	Unit	Nominal data	Cylinder Z15U500	Cylinder Z17U500	Cylinder Z18U500	Cylinder Z20U500	Cylinder Z21U500
Total length l	[mm]	540	539.8	540.0	540.5	540.0	540.2
Free length l_f	[mm]	500	500.0	500.0	500.0	500.0	500.0
Radius r	[mm]	250	250.27	250.35	250.30	250.23	250.24
Thickness t (Ø)	[mm]	0.5	0.463	0.461	0.478	0.489	0.485
Lay-up		24-24+41-41					
Cylinder mass	[g]		641	643.7	642.3	641.2	637.6

			Cylinder Z22U500	Cylinder Z23U500	Cylinder Z24U500	Cylinder Z25U500	Cylinder Z26U500
Total length l	[mm]		540.1	540.1	540.0	540.0	540.1
Free length l_f	[mm]		500.0	500.0	500.0	500.0	500.0
Radius r	[mm]		250.30	250.23	250.22	250.24	250.27
Thickness t (Ø)	[mm]		0.486	0.478	0.495	0.468	0.478
Cylinder mass	[g]		640.5	642.8	643.0	640	638.7

TAB 1. Overview of the nominal and the measured cylinder data

Tests of panels and shells with up to 1600 mm in length and 1200 mm in width (diameter) can be performed. The extreme stiffness of the facility, combined with the careful load introduction and shortening control enables high precision buckling tests under well defined boundary conditions. The hydraulic cylinder is equipped with a small servo-valve for static tests, and additionally with a second valve for dynamic loading.

In order to get as many results as possible from the experiments advanced systems for the full scale measurement of thicknesses, imperfections and deformations are applied before or during the tests. They are explained in the next sections shortly. More details are given in [27].

FIGURE 3. Photo of DLR´s buckling test facility.

4.2. Thickness Measurement

Prior to buckling the test-structures are subjected to the automatic ultrasonic testing using water split coupling to detect any defects in the structure (e.g. delaminations). The same test method is utilized for full field thickness measurement (imperfections).

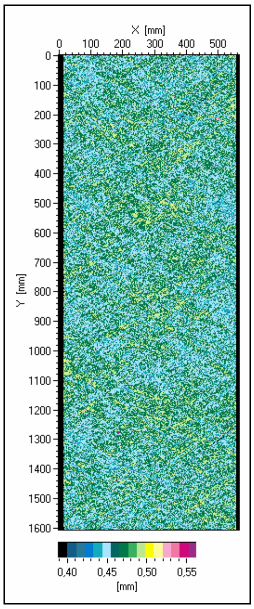

FIGURE 4. Result of ultrasonic thickness measurement

The test is carried out with a broadband transducer in echo-technique and the results are displayed in different scans. Carbon fibers, resin and defects (e.g. air pockets) have different sound conduction, which can be recognised in the response of the ultrasonic signal. These results provide a basis for quality assurance. Because of no identifiable defects in the scans the attention in this paper lies on the thickness measurement. The specimen thickness is calculated by the difference of the time between the echo of the surface at the front and the surface of the back. FIGURE 4 illustrates a scan of one cylinder measurement. The different colours describe different thicknesses. Through transferring this measurement into the FE-Model it is possible to inspect the potential influence of the imperfection through thickness.

4.3. Geometric Imperfections

The photogrammetric system ATOS is used for the full scale measurement of geometric imperfections. Photogrammetry is a measurement technology in which the three-dimensional coordinates of points on an object are determined by measurements made in two or more photographic images taken from different positions. In the case of ATOS two cameras, the relative position of which is known, take pictures of the cylinder. The absolute precision of the measurements is about 0.02 mm. The deviation of the best-fit cylinder is shown in FIGURE 5, on the left hand scaled by 100 and on the right hand as a false colour picture.

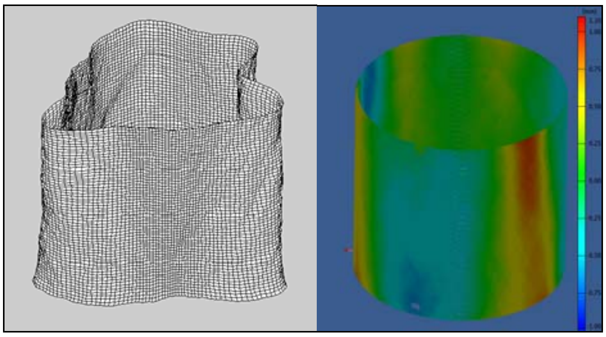

FIGURE 5. Geometric imperfections

4.4. High Speed Deformation Measurement

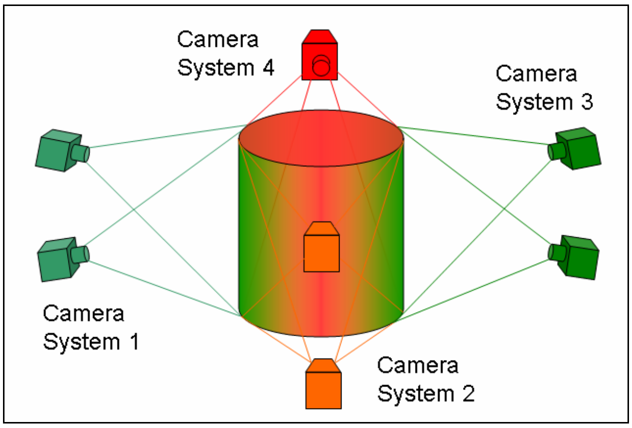

FIGURE 6. 360° measurement on a cylinder

In addition to standard measurement systems (e.g. strain gauges), the ARAMIS-system, which is also based on photogrammetry, is applied during the tests for a continuous 360° measurement of full-scale deformations in all 3 directions (cf. FIGURE 6). The coupling of four single ARAMIS systems allows circumferential measuring of a cylinder during dynamic deformation processes like buckling tests. At this point, all measured full field displacements are transferred to a global coordinate system of the cylinder by means of at least three reference points, with the result that a complete 3-D visualisation of the cylinder deformation is displayed.

5. MATERIAL PROPERTIES

The material selected was prepreg IM7/8552 (Hexcel) which was already successfully used within several international projects DLR participated in. Test series on small specimens were performed in order to obtain accurate properties of the material used in the project including information about their sensitivity and reliability. The testing methodology followed the procedure given in the German standards DIN EN 2561, DIN EN 2597, DIN EN 2850 and DIN EN 6031. TAB 2 summarizes stiffness and strength results with the corresponding standard deviations.

Stiffness	GPa	(%)	Strength	N/mm^2	(%)
$E_{t\,L}$	175.3	(1.38)	$R_{t\,L}$	2440	(3.64)
$E_{c\,L}$	157.4	(2.39)	$R_{c\,L}$	1332	(7.24)
$E_{t\,T}$	8.6	(2.9)	$R_{t\,T}$	42	(26.45)
$E_{c\,T}$	10.1	(4.11)	$R_{c\,T}$	269	(5.98)
$G_{L\,T}$	5.3	(1.12)	$R_{L\,T}$	129	(0.84)

t = tension, c = compression, L = longitudinal direction, T = transverse direction

TAB 2. Material properties of CFRP prepreg IM7/8552 UD, mean value and (standard deviation)

6. MANUFACTURING OF THE CYLINDERS

The cylinder design selected in Chapter 3 was manufactured 10 times. For the manufacturing process the following laying technique was applied:

a) The cylinders are manufactured on an appropriate cylindrical mandrel (male tool).
b) Cut prepreg plies of the required angle are laid-up on the tool to build up the required stacking sequence.
c) The set-up is sealed with a vacuum bag which is then evacuated. To cure the prepreg the mandrel is placed in an autoclave which provides the required pressure and temperature (bleed set-up and manufacturing parameters according to correspon-ding manufacturing specification).
d) All production parameters are monitored and logged.
e) The cured CFRP cylinder is trimmed to the required length and removed from the mandrel.
f) To ensure the laminate quality appropriate QA action is carried out.

TAB 1 summarises the nominal data of the cylinders and the realised data for each cylinder. The measurement techniques used are explained in Chapter 4.

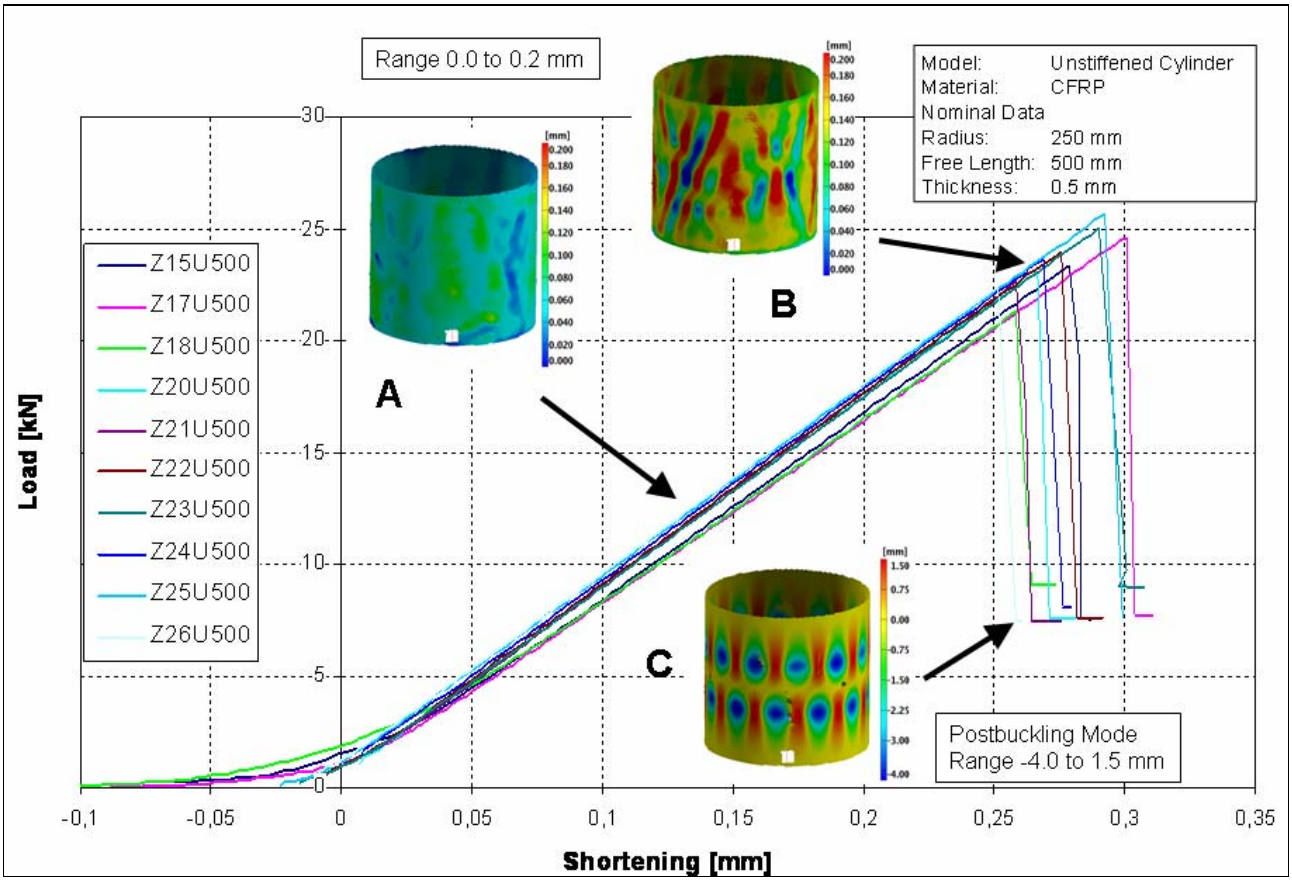

FIGURE 7. Load shortening curves of all tested cylinders and ARAMIS measurement of Z15U500

Cylinder	Buckling load [kN]	Shortening at buckling [mm]	Axial stiffness [kN/mm]
Z15U500	23.36	0.279	83.61
Z17U500	24.63	0.301	81.82
Z18U500	21.32	0.258	81.89
Z20U500	23.08	0.266	84.67
Z21U500	22.63	0.259	86.23
Z22U500	23.99	0.276	84.82
Z23U500	25.02	0.290	84.51
Z24U500	23.62	0.269	85.05
Z25U500	25.69	0.293	84.34
Z26U500	22.43	0.252	84.99

TAB 3. Overview of all buckling test results

7. BUCKLING TESTS

The tests of the 10 nominally equal cylinders were performed at the buckling test facility described in Section 4.1. Before testing ultrasonic inspections assured the absence of major inhomogeneities in the laminate and provided information on the thickness distribution. Next, the cylinders were inspected by the ATOS system to measure the shape imperfections. During the test the cylinders were loaded by axial compression just beyond the buckling load. In that loading area the structure behaves elastically and will not be damaged. The full scale deformations and buckling shapes were measured using the ARAMIS-system. FIGURE 7 illustrates the measured load-shortening curves of all tests with 3 selected ARAMIS measurement pictures obtained from the 360° measurement of cylinder Z15U500. Picture A and B are from the pre-buckling and Picture C from the early postbuckling region. Picture B is just before and Picture C just after the first buckling load. TAB 3 summarizes main results from the buckling tests. The buckling loads range between 21.32 kN and 25.69 kN. It shows also the shortening at buckling and the axial stiffness.

8. NUMERICAL STABILITY ANALYSIS

For the early design phase fast calculation methods are needed. For this purpose Geier and Singh [28] developed a method to calculate the buckling load semi-analytically based on the shallow shell theory. In combination with the knock-down factor one has a fast method for designing an axially compressed cylindrical CFRP shell. Unfortunately, the knock-down factor has still to be taken from the conservative NASA SP-8007 design guideline, which does not take any information about the lay-up into account.

In this study the Monte Carlo method is used in combination with the FEM for evaluating an improved knock-down factor. The assignment of the Monte Carlo simulation is executed by ST-ORM (commercial meta-computing system for stochastic optimization and robustness management). To choose the most effective numerical analysis all solvers available in ABAQUS/standard calculation methods were used. These are linear buckling analysis, Newton Raphson Method, Newton Raphson Method with artificial damping (Stabilize method), Riks (Arc-length), Newton Raphson Method with continuously parallel running linear buckling analyses, Newton Raphson Method with a dynamic analysis restart and dynamic analysis with ABAQUS/explicit. To keep the calculation as efficient as possible an investigation of the mesh size was accomplished. The amount of elements reaches between 675 and 97,200. The result of these investigations led to a FE-Model with about 12,000 elements and an analysis with ABAQUS/standard (Newton Raphson with artificial damping) as solver. 2000 of these elements are used to model the test boundary condition as closely as possible (clamped in a ring of resin) with 3D-elements (cf. FIGURE 9). The black curve in FIGURE 8 corresponds to the simulation of this FE-model without considering measured imperfections and thicknesses.

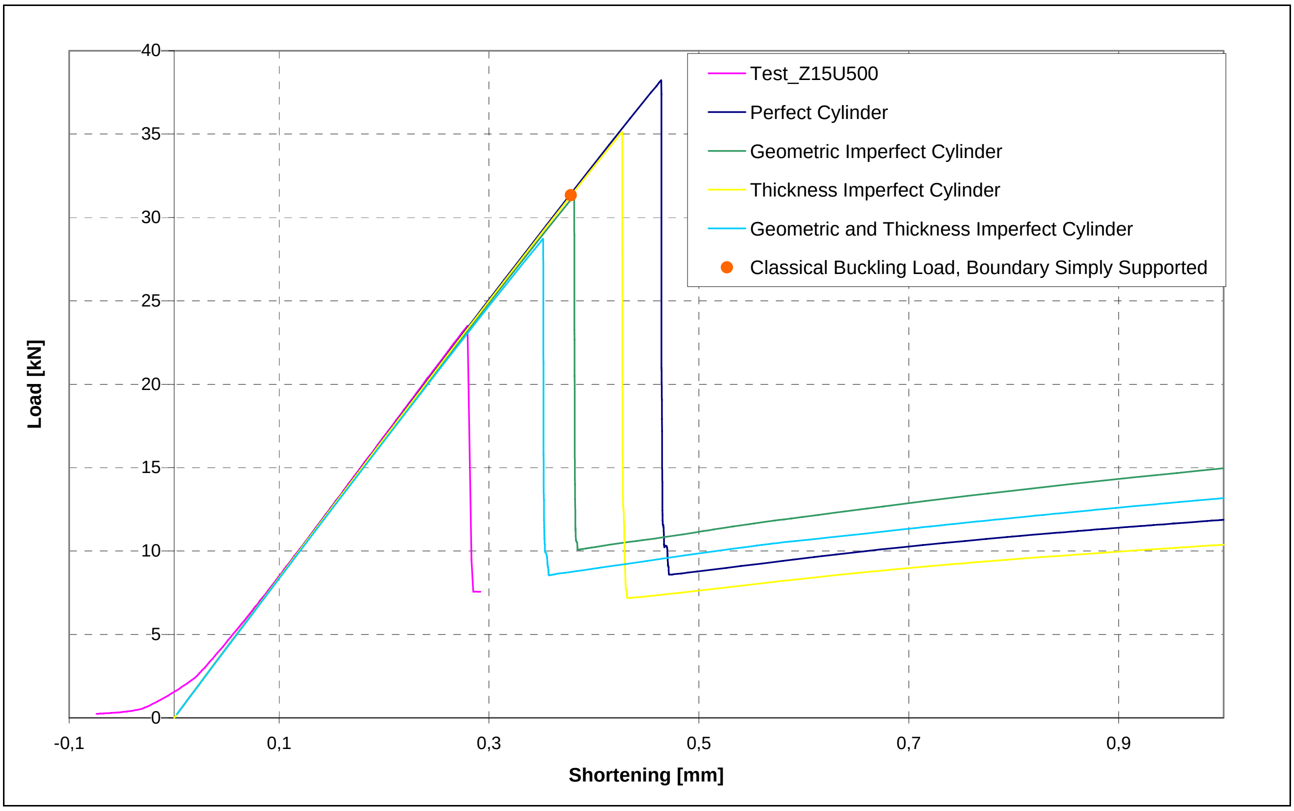

FIGURE 8. Comparison of test and simulation

By choosing an imperfection sensitive cylinder design every kind of imperfection or boundary conditions has a strong influence on its behaviour. That is why the buckling load of the simulation with the perfect cylinder diverges significantly from the buckling test. But with each infliction of imperfection in the FE-analysis the buckling load gets closer to the test result. The curves show the influences of the geometric imperfection and the variation in the thickness. With an in-house tool the thickness scan (cf. FIGURE 4) can be considered in the FE-model. This lowers the buckling load by about 3.1 kN. Another DLR tool includes the geometric imperfection into the model. This imperfection lowers the buckling load by about 6.9 kN. Both imperfections together push the buckling load of the perfect cylinder (38.2 kN) down to 28.7 kN. The classical buckling load is given as a small circle. The value (31.3 kN) is located between the buckling load for the perfect cylinder (simulation 1) and the test result.

FIGURE 10 compares the post-buckling pattern between the test and simulation. The left picture is obtained by the 360° ARAMIS measurement and agrees quite well with the simulation in the right figure. This buckling behaviour was observed for 10 tested cylinders.

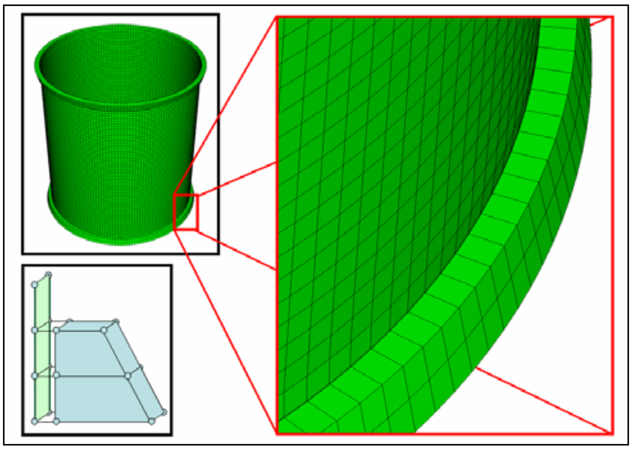

FIGURE 9. FE-Model of the CFRP cylinder with boundary conditions

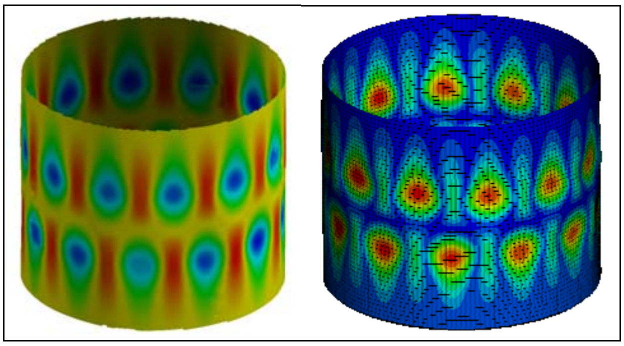

FIGURE 10. Postbuckling pattern Left: Test results obtained by ARAMIS – Right: Simulation

9. PROBABILISTIC APPROACH FOR BETTER BUCKLING KNOCK-DOWN FACTORS

The buckling test results as well as the simulations of the 10 nominally identical axially compressed CFRP cylinders are used for a probabilistic approach which aims for better buckling knock-down factors. The expected result of the probabilistic analysis will be a probability density function (P.D.F.) for a given ratio R/t = 500 (cf. FIGURE 11).

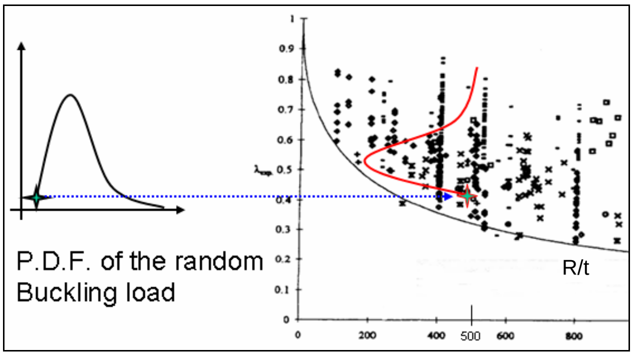

FIGURE 11. Stochastic deviation for a given R/t ratio as expected result

In general, test 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 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. First investigations with significant parameters (e.g. material properties, thicknesses, imperfections, fibre orientation, etc.) in the Monte Carlo simulation were performed. One result was that the young modulus E_{11} in fibre direction and the orientation of the layer have the most significant influence. The Ant-Hill diagram in FIGURE 12 shows the result of every calculation in a Monte Carlo simulation as single dot. The white lines mark the mean value of the point cloud and by selecting a dot (blue circle) the parameters of this calculation are shown in a separate window. In FIGURE 12 the correlation between E_{11} (x-axis) and the buckling load (y-axis) becomes noticeable. All buckling loads displayed as a histogram provide the visualization for the distribution function (cf. FIGURE 13).

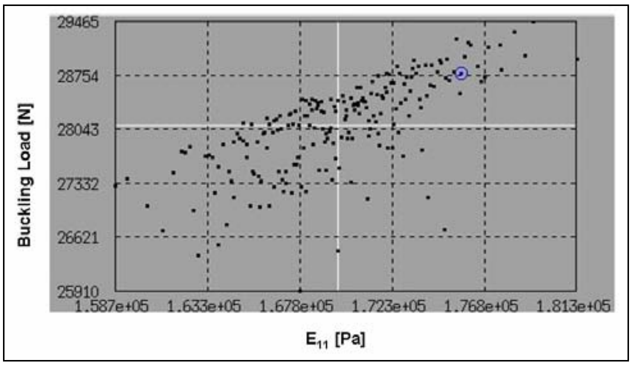

FIGURE 12. 2D Ant-Hill diagram of buckling load and E_{11}

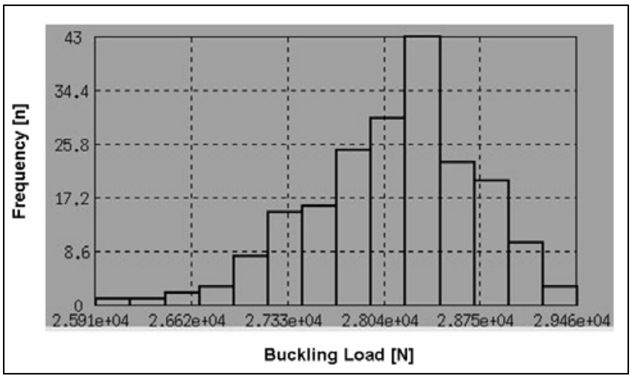

FIGURE 13. Histogram of the buckling load of 200 calculations

Via the probability density function of the buckling tests and the deviation of the Monte Carlo Simulation a better knock-down factor is expected to be determined.

10. ALTERNATIVE: SINGLE-PERTURBATION-LOAD APPROACH

In addition to the buckling test under axial compression one buckling test under axial compression plus a single perturbation is accomplished. This approach assumes that a larger single buckle is the worst imperfection mode and leads directly to the load carrying capacity of a cylinder. This very interesting structural behaviour and first results were already shown in [2]. The aim of the ESA study is focussed on the probabilistic approach. However, a test series were performed on one cylinder on voluntary basis, and the outcome is presented here. The aim was to find out if the structural phenomena presented in [2] can be repeated. The large single buckle is induced by a lateral load (FIGURE 14). In this case the applied perturbation load has values between 0 N and 10 N. The position is located at half the cylinder length (l / 2 = 270mm). FIGURE 15 shows test results of the buckling load N as a function of the perturbation load P. Each dot represents one test result. The curve is simplified by three lines which are marked in red. The characteristic value N_1, where the second line meets the third line, characterises a lower limit of the load carrying capability. FIGURE 15 shows in principal the same structural behaviour as presented in [2]. The Single-Pertubation-Load approach assumes the buckling load N_1 as design load. There is a large advantage especially for CFRP cylinders because only one calculation with an appropriate single perturbation load under axial compression seems to be required. However, the task for the future is to verify this phenomenon on more cylinders by tests and simulations and to develop an analytic or empirical method for determining N_1 or the minimum perturbation load P_1.

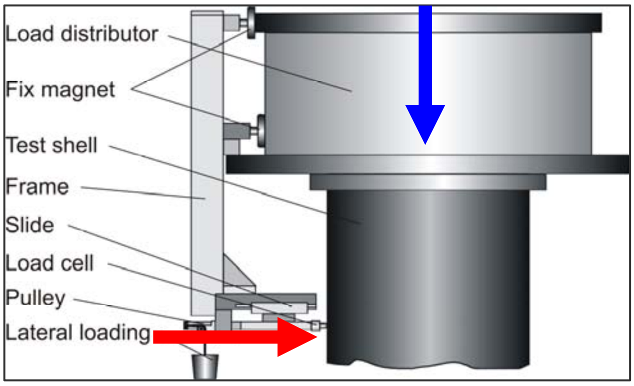

FIGURE 14. Schematic description of the test set-up under axial loading and a single perturbation load

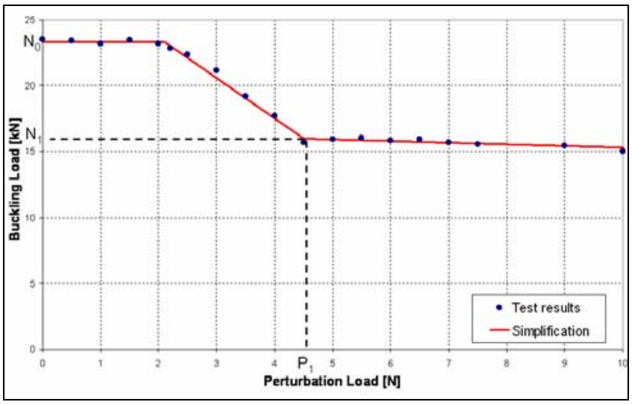

FIGURE 15. Test results of under axial compression and perturbation loads

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