PROBABILISTIC APPROACH FOR BETTER BUCKLING KNOCK-DOWN FACOTRS OF CFRP CYLINDRICAL SHELLS – TESTS AND ANALYSES

R. Degenhardt, A. Bethge, A. Kling, R. Zimmermann, K. Rohwer
DLR, German Aerospace Center, Braunschweig, Germany
richard.degenhardt@dlr.de, *arne.bethge@dlr.de*, *alexander.kling@dlr.de*,
rolf.zimmermann@dlr.de, *klaus.rohwer@dlr.de*

Abstract

The industry in the fields of civil and mechanical engineering, and in particular of aerospace 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 (the ratio of buckling loads of imperfect and perfect structures) for unstiffened CFRP (carbon fiber reinforce plastics) cylindrical shells, and by validation of the linear and non-linear buckling simulations based on 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.

Introduction

This study concentrates on thin-walled circular cylindrical CFRP 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, 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 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, sensitivity analyses using Monte-Carlo simulation, validation with 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 a rich body of experience in design, manufacturing, testing and analysis of shells prone to buckling.

Cylinder Design

CFRP structures offer a wider range of design variables than metal structures. That allows specifying a cylinder with a large buckling load and high imperfection sensitivity, which most probably will provoke a reasonable scatter of buckling loads and therewith enables successful probabilistic 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. 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. In order to have a preferably small knock down factor the slenderness R/t shall be as large as possible.
3. DLR has large experience with cylinders with a diameter of 500 mm. The corresponding database provides to a good basis for comparison.

Considering these objectives the cylinder design listed in Table 1 was selected.

Geometry / Lay-up	**Nominal**	**Z15U500**	**Z17U500**
Total length	l = 540 mm	l = 539.8 mm	l = 540 mm
Free length	l_f = 500 mm	l_f = 500 mm	l_f = 500 mm
Radius	r = 250 mm	r = 250.267	r = 250.349
Thickness (Ø)	t = 0.5 mm	t = 0.463	t = 0.461
Lay-up	+24-24+41-41		
Cylinder mass		641 g	643,7 g

Table 1. DLR Cylinders: nominal and measured data.

DLR Buckling Test Facility and Measurement Equipment

All buckling tests are performed in the buckling test facility (cf. Figure 1) of the Institute of Composite Structures and Adaptive Systems. The facility is predestinated for high precision buckling tests of thin-walled shells like cylinders or panels. Axial compression up to 1 MN, torsion up to 50 kNm as well as internal pressure between -1hPa (simulating external pressure) and 10 hPa can be applied simultaneously. 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.

Figure 1. Photo of DLR´s buckling test facility.

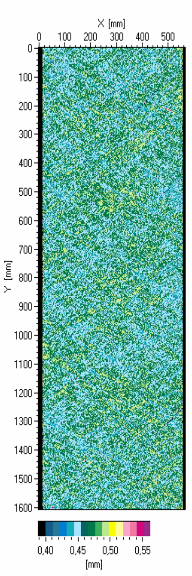

Figure 2. Result of ultrasonic thickness measurement.

In order to get as many results as possible from the experiments advanced measurement systems are applied during the tests. Prior to buckling the test-structures are subjected to ultrasonic inspection searching for defects and measuring the thickness (cf. Figure 2). The photogrammetric system ATOS is used for the full scale measurement of imperfections (cf. Figure 4). 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 3).

Material Properties

The test shells are manufactured from prepreg material IM7/8552 (Hexcel). 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. Table 2 summarizes stiffness and strength results with the corresponding standard deviations.

Stiffness	GPa	(%)	Strength	N/mm2	(%)
$E_{t\,L}$	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

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

Buckling tests on two unstiffened cylinders

Ultrasonic inspections prior to the tests 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 (cf. Figure 4). 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 3 illustrates the measured load-shortening curves 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.

Simulation and comparison with test results

Figure 5 compares a test result with simulations performed with an approximately 12000 element model with shell elements for the CFRP skin. For the non-linear buckling analysis Newton Raphson method with artificial damping is used. Since the cylinder design is chosen imperfection sensitive it is allegeable that the simulation of the perfect cylinder diverges from the buckling test. At this time simulation with either geometric or thickness imperfections can be accomplish. Further analyses with combined imperfections are planned. The classical buckling load, which can be obtained from an analytical formula, is given as small circle. The value is located between the buckling load for the perfect cylinder (simulation 1) and the test result.

Probabilistic Approach for better Buckling Knock-Down Factors

The buckling test of the 10 nominally identical axially compressed CFRP cylinders as well as the simulation will be used for a probabilistic approach for better buckling knock-down factors. The expected result of the probabilistic approach of the buckling test will be a probability density function (P.D.F.) for a given ratio R/t = 500 (cf. Figure 5). 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 behavior. It starts with a nominal model and makes copies of it whereas certain parameters are varied randomly. Via the probability density function of the buckling tests and the deviation of the Monte Carlo Simulation a better knock-down factor will be determined.

Acknowledgements

The running study *Probabilistic Aspects of Buckling Knock Down Factors – Tests and Analysis* is funded by the European Space Agency (ESA). All support is gratefully acknowledged. The information in this paper is provided as is and no warranty is given that the information is fit for any particular purpose. The reader thereof uses the information at its sole risk and liability.

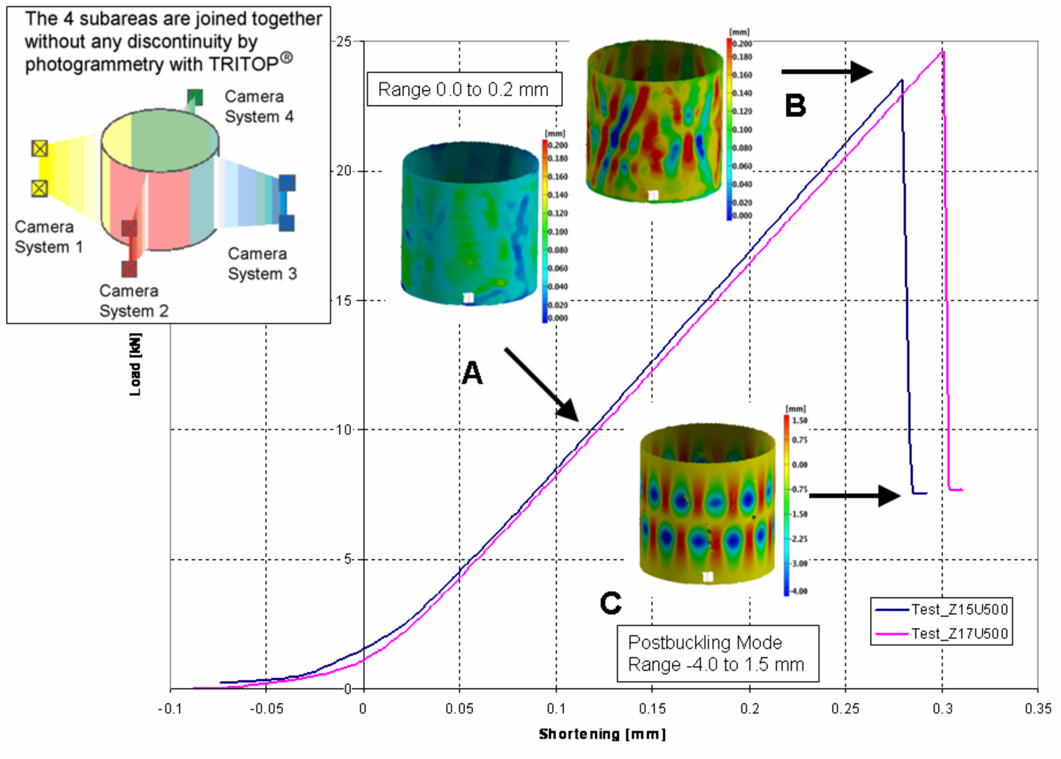

Figure 3. Load shortening curves of cylinders Z15U500, Z17U500 and ARAMIS measurement of Z15U500.

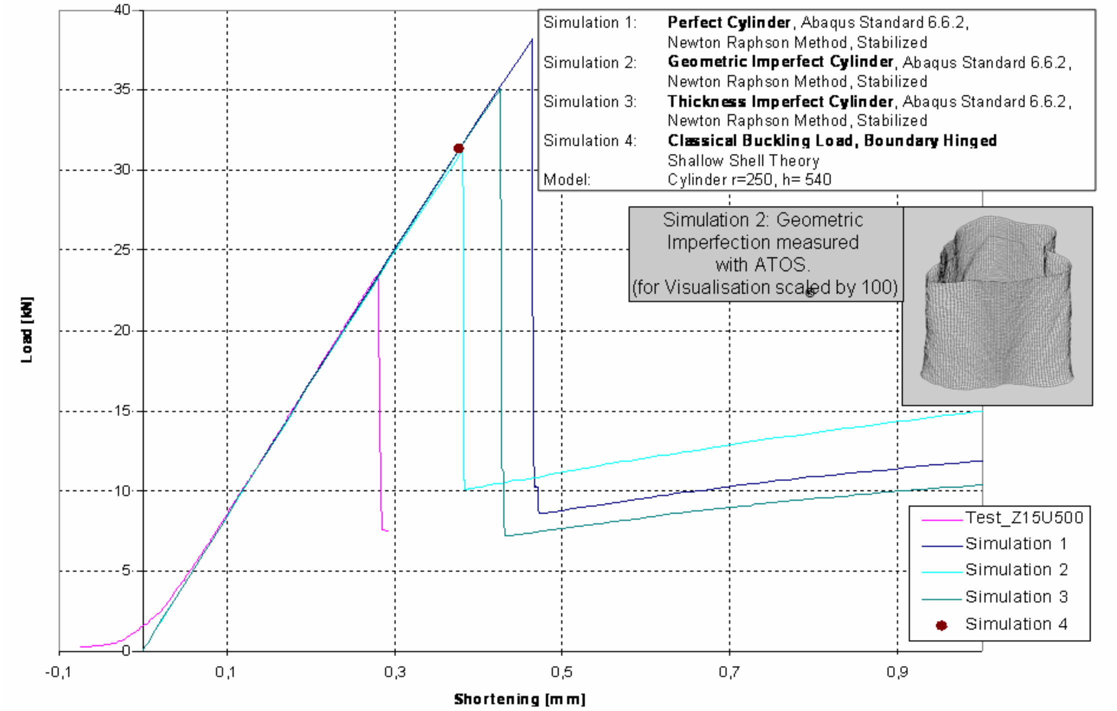

Figure 4. Comparison of test and simulation.

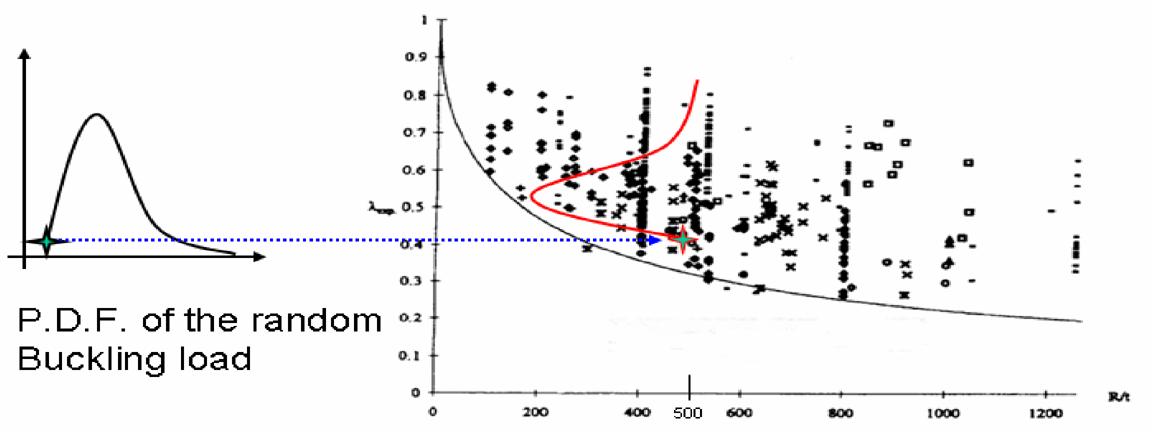

Figure 5. Expected result, a stochastic deviation for a given R/t ratio.

References

Koiter, W. T. (1967), *On the Stability of Elastic Equilibrium. NASA-TT-F-10833*.

Geier, B., H. Klein and R. Zimmermann (1991), "Buckling tests with axially compressed unstiffened cylindrical shells made from CFRP", *Proc., Int. Colloquium on Buckling of shell Structures, on land, in the sea and in the air,* J.F. Julien, ed.: Elsevier Applied Sciences, London and New York, 498-507

Geier, B., H. Klein and R. Zimmermann (1994), "Experiments on buckling of CFRP cylindrical shells under non-uniform axial load", *Proceedings, Int. Conference on Composite Engineering,* ICCE/1 28-31 August 1994

Zimmermann, R. (1996), "Buckling Research for Imperfection tolerant fibre composite structures," *Proc. Conference on Spacecraft Structures, Material & Mechanical Testing,* Noordwijk, The Netherlands, 27-29 March, ESA SP-386

Meyer-Piening, H.-R., M. Farshad, B. Geier, R. Zimmermann (2001), "Buckling loads of CFRP composite cylinders under combined axial and torsion loading - experiment and computations." *Composite Structures 53*, 427-435.

Degenhardt R., J. Tessmer (2007), "New Achievements in Stability of Composite Airframe Structures", *Proceedings of the 12th Australian International Aerospace Congress,* Melbourne, Australia, 19-22 March, **2007**

Degenhardt R., R. Rolfes, R. Zimmermann, K. Rohwer (2006), "COCOMAT - Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of COllapse", *Journal of Composite Structures, Vol. 73 (2006),* pp. 175-178

Zimmermann R., R. Rolfes (2006), "POSICOSS - Improved postbuckling simulation for design of fibre composite stiffened fuselage structures", *Composite Structures, Vol. 73 (2006),* pp. 171-174.

Zimmermann R., H. Klein, A. Kling (2006), "Buckling and postbuckling of stringer stiffened fibre composite curved panels – Tests and computations", *Composite Structures, Vol. 73 (2006),* pp. 150-161.

Degenhardt R., A. Kling, K. Rohwer, "Design and Analysis of Stiffened Composite Panels Including Postbuckling and Collapse", *Journal of Computers and Structures* (paper accepted)

Degenhardt R., A. Kling, H. Klein, W. Hillger, Ch. Goetting., R. Zimmermann, K. Rohwer, A. Gleiter, "Experiments on Buckling and Postbuckling of Thin-Walled CFRP Structures using Advanced Measurement Systems", *International Journal of Structural Stability and Dynamics* (paper accepted, to be printed in June 2007, Vol. 7, nº 2)