ACHIEVEMENTS IN THE BUCKLING OF THIN-WALLED COMPOSITE LAUNCHER STRUCTURES

Richard Degenhardt[1], Felipe Franzoni[1], Saullo G. P. Castro[2]

[1]DLR, Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany

[2]Delft University of Technology, Aerospace Structures and Computational Mechanics, Faculty of Aerospace Engineering, Kluyverweg Street No. 1, 2629 HS, Delft, The Netherlands

Abstract

For most structural parts of real launcher structures buckling is the critical design criterion. Due to the high imperfection sensitivity of these structures and to the unknown geometric imperfections during the design phase, it is still today a challenge to predict a reliable design buckling load and to experimentally and non-destructively evaluate the load carrying capacity of real structures. The space industry is looking for new and alternative less-conservative design methods, and non-destructive experimental strategies. This paper presents a summary of different examples to numerically and experimentally predict the buckling load of imperfection sensitive structures. The numerical strategies herein covered are based on the fast Ritz-method, developed for conical and cylindrical structures applicable for linear and non-linear buckling, and static calculations. The experimental examples are all based on the non-destructive buckling estimation enabled by means of the Vibration Correlation Technique (VCT). An overview of experiments on different types of cylindrical shells (unstiffened, stringer-stiffened and grid) with different materials (composite and metallic) and for different load cases and their combination (axial compression, internal pressure and bending) is presented. The examples are on academic laboratory level and on qualification tests of real full-scale space structures.

Keywords: Composite Structures, Buckling, Stability, Imperfection, Experiments, Ritz method, Vibration Correlation Technique

1. Motivation

Space industry strives for significantly reduced development and operating costs. Reduction of structural weight at safe design is one possibility to reach this objective. Figure 1 (left) shows the planned Ariane 6 rocket as one industrial application which will for instance have much higher content on composites. Another one is the use of reliable simulation methods in order to minimize expensive and time-consuming experimental design studies. For most structural parts of real launcher structures buckling is the critical design criterion. Due to the high imperfection sensitivity of unstiffened cylindrical shells (see Figure 2) it is still today a challenge to predict a reliable buckling load. The space industry is looking for new and alternative methods. The paper shows an overview of different examples on new achievements in the prediction of the buckling behaviour of thin-walled space structures. They are based on the fast Ritz-method and on the experimental non-destructive estimation by the Vibration Correlation Technique (VCT). The academic examples are already published, the examples on qualification tests of real space structures are in the publication process but this paper informs already here about the success. The aim of this paper is to demonstrate the wide applicability, especially of the VCT method, for the different type of structures (unstiffened, stringer-stiffened and grid cylindrical shells), materials (composite and metallic) and different load cases and their combination (axial compression, internal pressure and bending). The future research challenges for the VCT method are for instance more combined load cases, realistic boundary conditions, conical and double curved shells or consideration of small holes or damages.

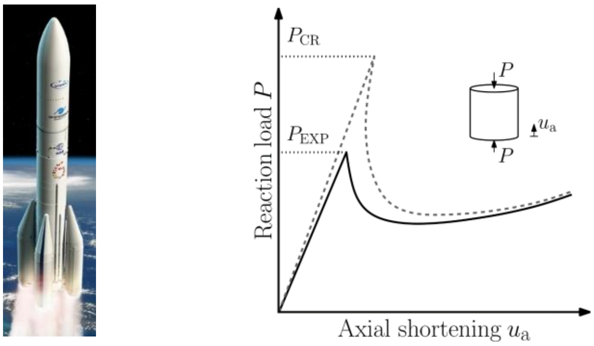

Figure 1 – Left: Ariane 6 launcher (ESA)

Right: Typical load-shortening curve of an unstiffened cylindrical shell

2. Fast simulation of unstiffened cylindrical and conical composite structures [1], [2]

A semi-analytical method based on the Ritz-approach capable to predict the static and the instability response of the non-linear buckling of unstiffened laminated composite cones and cylinders under various loads and boundary conditions is presented. The tool considers geometric and load imperfections. The Ritz method is selected to solve the non-linear set of equations and a new set of appropriate approximation functions for the displacement field is proposed, in order to simulate axial compression, torsion, pressure, load asymmetry, any arbitrary surface or concentrated loads, and any load case combining these loads. Elastic constraints are used to produce a wide range of boundary conditions, covering the four types of boundary conditions commonly used in the literature. For conical shells a novel approximation is proposed in order to efficiently perform the analytical integration of the linear stiffness matrices. Figure 2 shows a comparison of the deformations obtained by the semi-analytical Ritz-approach and FEM (Abaqus) studied on an imperfect composite conical structure loaded by axial compression. More details can be found in [1] and [2].

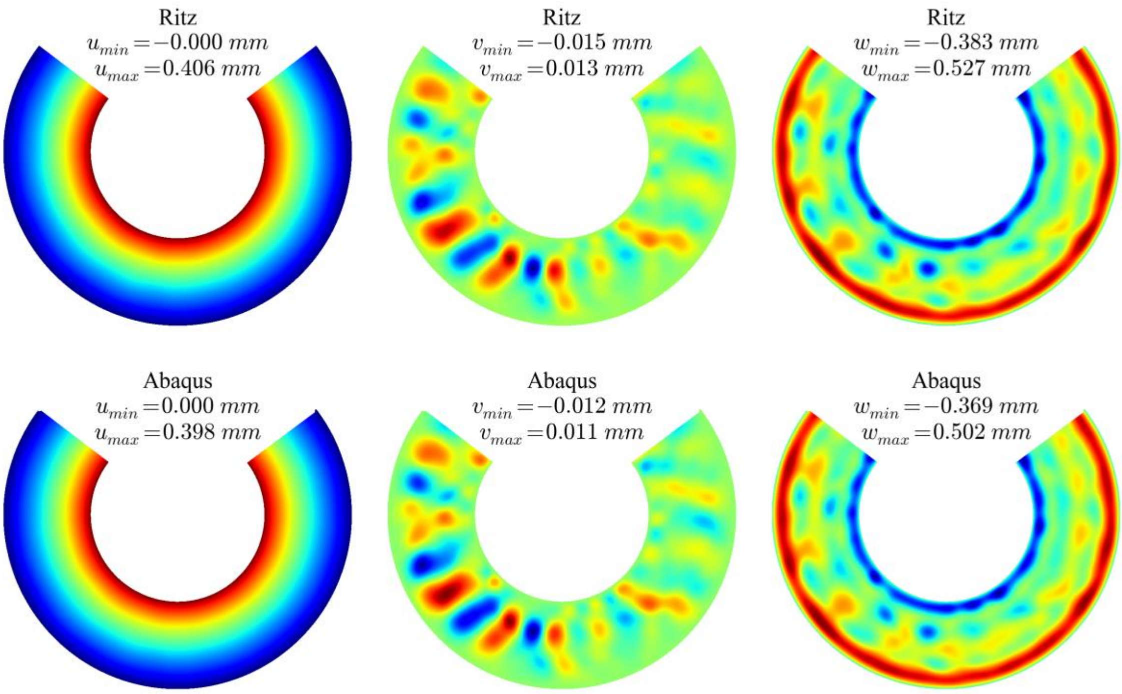

Figure 2 - Imperfect composite conical structure loaded by axial compression; Comparison of the deformations obtained by the semi-analytical Ritz-approach and FEM (Abaqus).

3. Fast simulation of stiffened shells with multi-domain semi-analytical models [3], [4]

Figure 3 shows an assembly of cylindrical shell domains and plate domains. This is an efficient and robust strategy to expand the efficiency of Ritz-based approaches towards more complex geometries. In the present example extracted from Degenhardt et al. [3], the cylindrical shell domains $P01$ and $P02$ are assembled to form the skin of a blade-stiffened cylinder, whereas one plate domain P_S is used for each stiffener. Note that in this example the plate domain is connected with two adjacent cylindrical shell domains, but connecting within another domain instead of at its boundaries would also have been possible, enabling the evaluation of meshless stiffened panels, in which the positioning of the stiffeners can float within the skin domain during a design optimization scheme, for instance. Note in Figure 4 that the approach enables an accurate calculation of the membrane stresses, and in Figure 5 the good correlation of linear buckling modes. The multiple domains are connected based on penalty constants that are calculated based on the actual properties of the structures being connected, as proposed by Castro and Donadon [4].

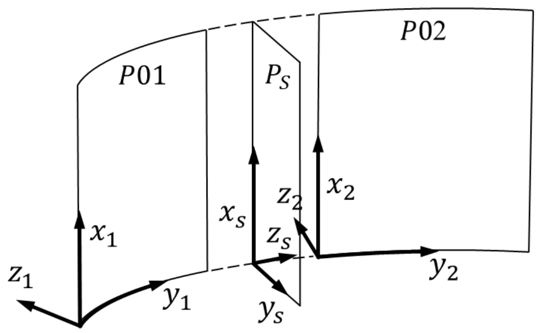

Figure 3 – Assembly of panels to form a blade-stiffened cylinder [8].

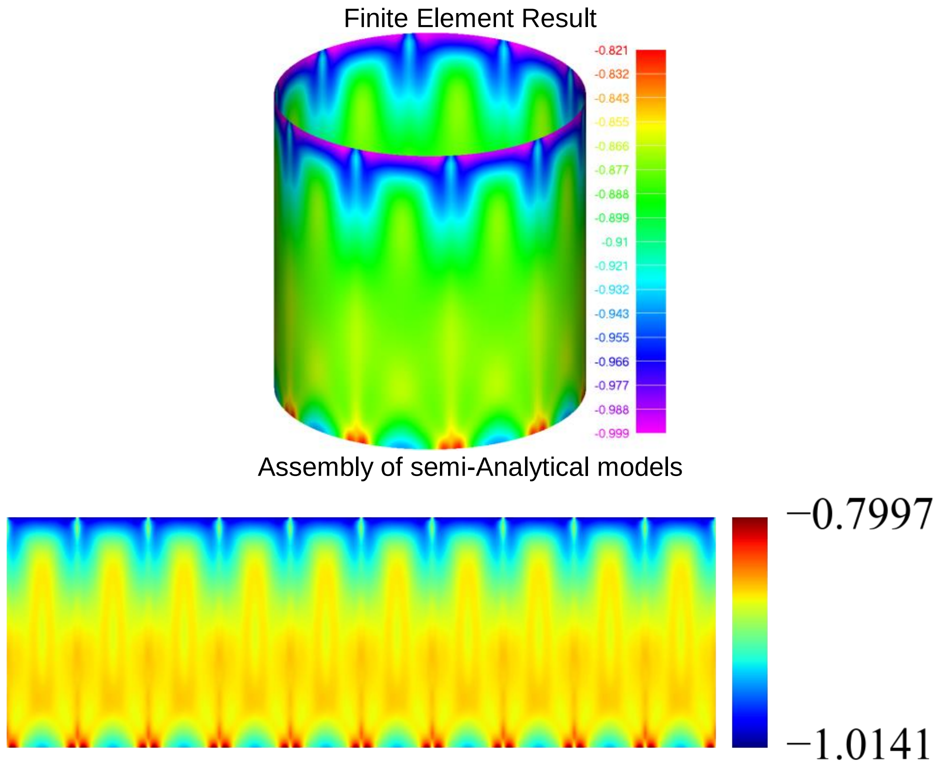

Figure 4 – Membrane stress N_{xx} field for the stiffened cylinder [3]

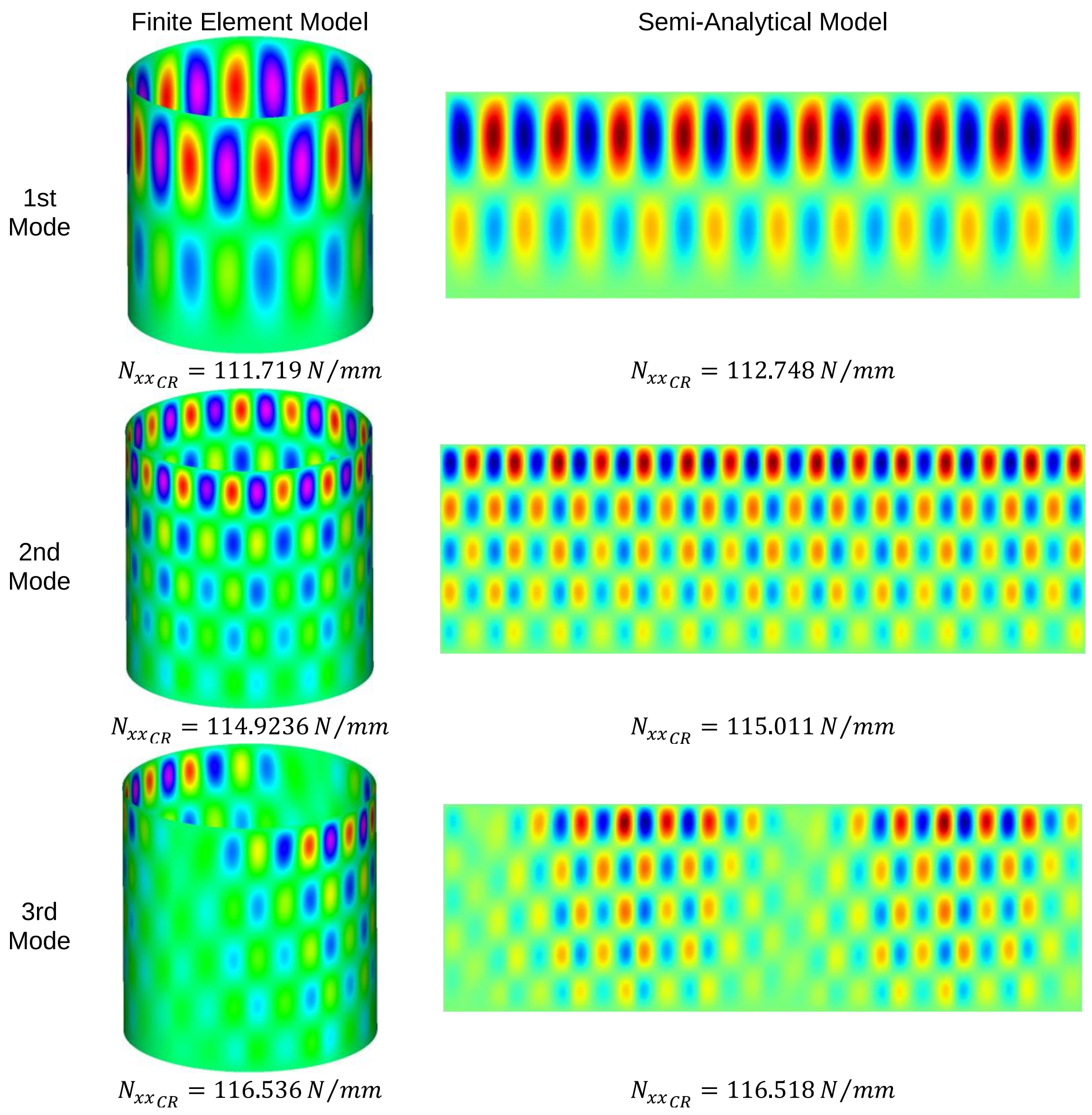

Figure 5 – Linear Buckling Modes for the Stiffened Cylinder [3]

4. Non-destructive prediction of the buckling load of space structures by the Vibration Correlation Technique

4.1 Arbelo's VCT approach [5], analytically verified by Franzoni [6]

The Vibration Correlation Technique (VCT) allows a non-destructive prediction of the buckling load in the experiment. It is based on the relation that the eigenfrequency becomes smaller under the increase of the axial compression and in the case of the bucking the eigenfrequency is zero. For beams the relationship is linear. For shells the relation is due to the imperfection sensitivity nonlinear. In 2014, Arbelo developed an improved empirical VCT formulation for the buckling prediction of cylindrical shells [3]. He suggested evaluating the second-order best-fit relationship of the results in the form ($1-p^2$) versus ($1-f^2$) and, to minimize the adjusted relationship for estimating ξ^2 (see Figure 4). f is the ratio between the natural frequency of the loaded structure and the natural frequency of the unloaded structure, both associated with the same vibration mode. p is the ratio between the axial load and the critical buckling load P_{CR}. The buckling load is calculated using Eq. 1.

$$P_{VCT} = P_{CR}(1-\xi) \quad (1)$$

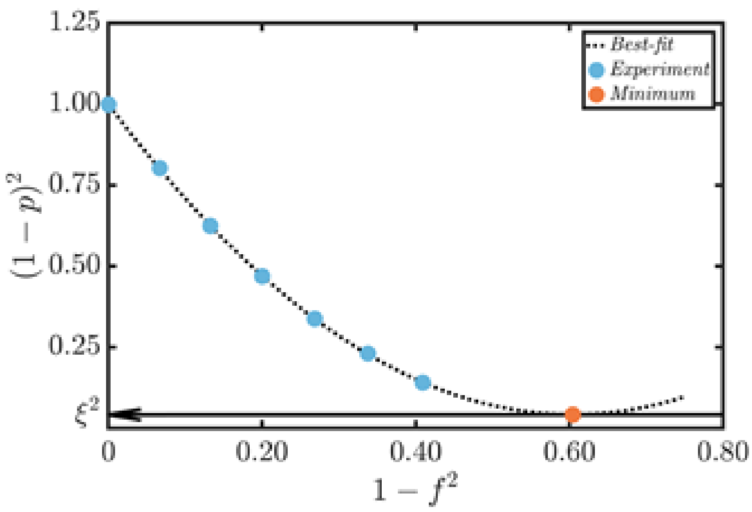

Figure 4 – Arbelo’s VCT approach [5].

In the next years this VCT approach was validated many times by different experiments, however, it was still of empirical nature. In 2019, Franzoni verified analytically Arbelo’s empirical VCT prediction of the buckling load imperfection sensitive shells [6]. This was a significant step in research and gave the VCT approach of shells a stronger physical foundation.

The space industry is highly interested in that approach and the method is currently applied in different future qualification tests of real launcher structures (see Section 3.5 and 3.6). Some structures have to survive the first load cases of the qualification tests as they shall be tested in other load cases under different loading as well. Thus, it is very important that the structure is not damaged in the first load case. VCT is one possibility to check in-situ during the buckling test the buckling prediction. The closer the applied load comes to the buckling load the better is the VCT prediction. The space industry is therefore highly interested in such an alternative non-destructive prediction of the buckling load by the new VCT method to be surer that buckling is not reached in the first load case.

In the following an overview of very different already published examples is given but also the information about first successful industrial VCT tests.

4.2 Metallic cylinder axially loaded with internal pressure [7]

Throughout this example, the VCT method is verified as a non-destructive experimental procedure for the estimation of the axial buckling load considering a pressurized orthotropic skin-dominated cylindrical shell. The specimen, a simplified downscaled model of a launcher propellant tank, was manufactured considering standard procedures for aerospace applications. An experimental campaign was proposed for the corroboration of the methodology, in which buckling and noncontact vibration tests were performed. Figure 5 (left) shows the cylindrical shell in the DLR buckling test facility. A numerical investigation based on FE models is proposed for evaluating the variation of the natural frequency up to the vicinity of buckling allowing a study of the convergence of the VCT method as the number of load steps and the considered maximum load level are increased simultaneously. Figure 5 (right) shows for the load-shortening curve and buckling mode a good agreement of the numerical simulation and experiment until buckling.

During the experimental campaign, the first vibration mode was measured for 8 axial load steps considering three internal pressure levels and the unpressurized condition. The VCT estimations presented a good correlation when compared to their respective experimental result for the buckling load, once the deviations are within 4.0% and 10.0%. Moreover, the method provided better estimations of the buckling load for the tests associated with greater values of the KDF. The VCT herein applied is a non-destructive experimental procedure once the maximum axial load level considered during the vibration tests is 72.3% of the linear buckling load for the test considering 0.03 bar of internal pressure.

Considering the numerical assessment, techniques for including measured initial geometric imperfections and detailed boundary conditions in the FE model previously validated for unstiffened cylindrical shells were extended for the case of stiffened cylindrical shells. The nonlinear buckling load is within 3.0% and 5.4% deviation of the experimental results of the buckling load. Moreover, the numerical vibration modes and natural frequencies results were analyzed through an algorithm based on the MAC index. This procedure allows a high density of load steps to be considered resulting in a good understanding of the variation of the natural frequencies and vibration modes as related to the axial loading. The VCT method is employed for a numerical assessment achieving a good correlation and a conservative convergence when compared to the nonlinear buckling load.

The numerical study concludes that the VCT method applied to the test specimen herein evaluated provides conservative results and show a decreasing deviation from the nonlinear buckling load when the number of load steps and the maximum load level are both simultaneously increased. These results could be reproduced prior to the planning of a VCT test helping to define the maximum applied axial load level and the number of load steps needed for a good estimation of the buckling load. More details can be found in [7].

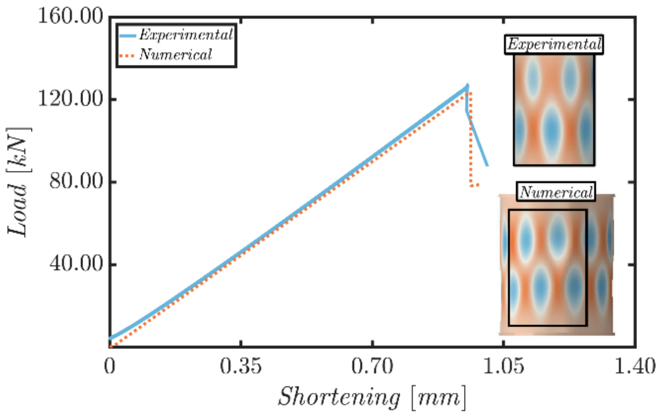

Figure 5 - Left: Metallic structure in the DLR buckling facility load by axial compression and internal pressure

Right: Comparison between the numerical and experimental results at 0.03 bar internal pressure [7]

4.3 Buckling tests including VCT measurement with the same samples at different test facilities [8]

In this example the VCT approach is considered for estimating the buckling load of unstiffened composite laminated cylindrical shells tested in two different test facilities (see Figure 6). Three nominal identical specimens named ZD27, ZD28 and ZD30 were manufactured in DLR Institute of Composite Structures and Adaptive Systems. All cylinders were tested 10 times each for buckling at DLR, corroborating the equivalence of the specimens. For assessing the robustness of the VCT, ZD28 and ZD29 were tested at DLR and, ZD27 was tested at TU Delft Faculty of Aerospace Engineering. Additionally, a buckling test of ZD27 was performed at TU Delft, which established a basis for comparison between the two buckling test facilities.

Comparing DLR and TU Delft experimental buckling loads of ZD27, there is 22% of deviation as related to the DLR result. This discrepancy can be associated with the differences between the test set-ups and it evidences the need for verifying the robustness of the methodology. However, the VCT method predicted within an acceptable range the experimental buckling load of ZD27 (tested at TU Delft) and the buckling loads of ZD28 and ZD29 (both tested at DLR); therefore, the robustness of the methodology of representing the in-situ boundary conditions has been proved throughout this experimental campaign. All VCT estimations are conservative (associated with negative deviations) and, in an acceptable range. Moreover, one may notice that the estimations associated with smaller magnitudes of the KDF are in better agreement within the same cylinder regardless of the theoretical buckling load considered for calculating the load ratio p. More details can be found in [8].

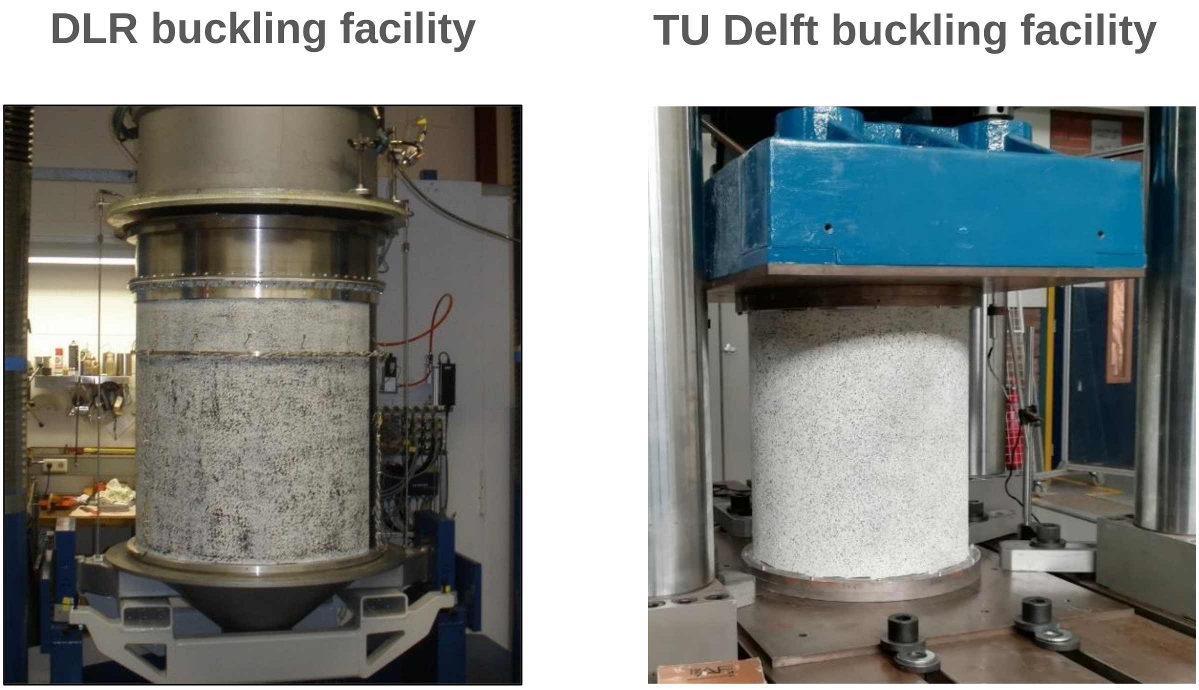

Figure 6 – Buckling tests including VCT measurement with the same samples at 2 different test facilities [8]

4.4 Composite lattice sandwich cylinders (CLSC) under axial compression [9]

This example deals with an analytical formulation for the free vibration of axially loaded composite lattice sandwich cylinders (CLSC) and numerical and experimental validations of the VCT applied to such structures. From an analytical point of view, the equations are obtained through the Rayleigh-Ritz method considering first-order shear deformation theory (FSDT). For the numerical verification of the VCT, three types of linear and nonlinear finite element analyses are performed. At first, numerical results for the critical buckling load and the first natural frequency at different load levels are compared with the corresponding analytical ones, validating the numerical models. Then, the numerical models are extended considering geometric nonlinearities and imperfection to simulate the variation of the first natural frequency of vibration with the applied load. As well, a nonlinear buckling analysis is also performed using the Riks method for a better comparison of the VCT results. Four specimens were fabricated using a new rubber mold and a filament winding machine. The experimental buckling test was carried out, verifying the results of the VCT approach. The results demonstrate that the maximum difference between the estimated buckling load using the VCT approach and the corresponding nonlinear and experimental buckling loads is less than 5%, being the VCT result more accurate than the numerical one. Moreover, the proposed VCT provided a good estimation of the buckling load of the CLSC, considering a maximum load level of at least 62.1% of the experimental buckling load. More details can be found in [9].

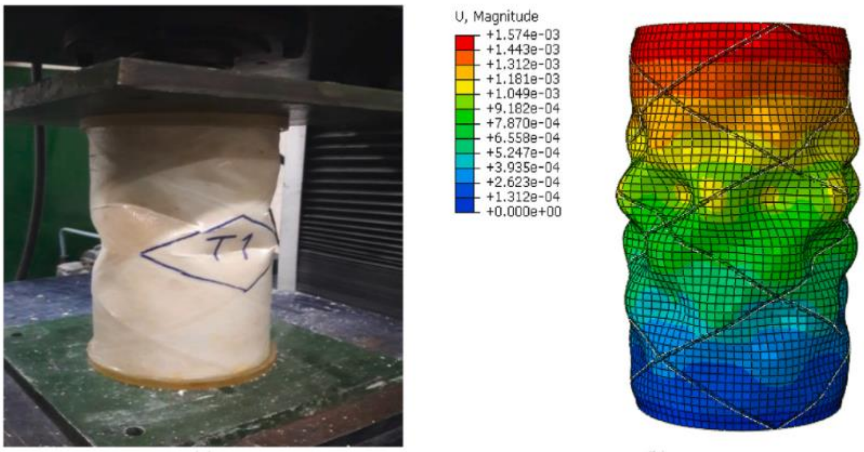

Figure 7 – Experimental (right) and numerical (left) buckling mode shapes of the CLSC [9]

4.5 VCT test for the Ariane 6 LH2 section under combined loading

MT Aerospace preformed at IMA in Dresden just recently a qualification test of an LH2 section (see Figure 8) of the planned Ariane 6. The structure was loaded by axial compression and bending. 2 different load cases were performed. The first load case was just below global buckling and the structure was not destroyed. During the tests a VCT measurement at 10 load steps was performed in parallel. It was one alternative method for non-destructive prediction of buckling. It was the first time ever, that VCT was applied to a real space structure in a qualification test. The results were achieved just recently and are so far confidential. However, it can be said that the tests were successful and the VCT method could predict in both load cases the buckling load quite close at conservative site. A full publication of these tests is in preparation with a larger consortium.

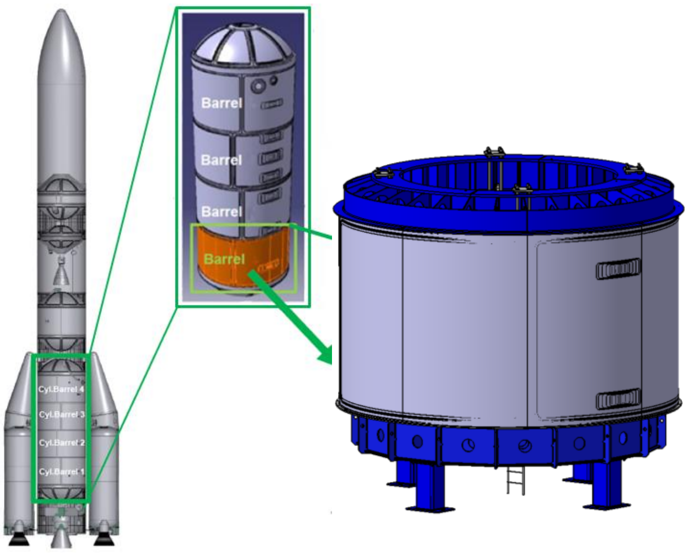

Figure 8 – Ariane 6 LH2 Section

4.6 Double-curved Flexline fairing under combined loading

2022 the VCT method is planned to be applied also during the buckling qualification test of the Flexline payload fairing to be tested by RUAG, shown in Figure 9. The challenge will be here that the structure is double curved with combined loading. This will be also a premier for VCT for these conditions.

Figure 9 – Payload fairing of the Flexline launcher

5. Acknowledgements

The research leading to these results has received funding from the following sources:

- European Community's Seventh Framework Programme (FP7/2007-2013) under Priority Space, Grant Agreement Number 282522 (DESICOS).
- European Space Agency (ESA), Contract number 4000119184/17/NL/MH/GM.
- European Community's Eighth Framework Programme (FP8/H2020), under Priority ERDF (European Regional Development Fund), Grant Agreement Number ZW 6- 85042584

All support is gratefully acknowledged. The information in this paper reflects only the authors' views and the European Space Agency is not liable for any use that may be made of the information contained therein.

6. Contact Authors E-mail Address

Mailto: richard.degenhardt@dlr.de

7. Copyright Statement

References

[1] Castro S, Mittelstedt C, Monteiro F, A. Arbelo M, Ziegmann G, Degenhardt R. "Linear buckling predictions of unstiffened laminated composite cylinders and cones under various loading and boundary conditions using semi-analytical models", *Int. Journal of Composite Structures*, Vol. 118 (2014), pp. 303-315, https://doi.org/10.1016/j.compstruct.2014.07.037

[2] Castro S, Mittelstedt C, Monteiro F, A. Arbelo M, Degenhardt R. "A semi-analytical approach for the linear and non-linear buckling analysis of imperfect unstiffened laminated composite cylinders and cones under axial, torsion and pressure loads ", *Int. Journal of Thin-Walled Structures*, Vol. 90 (2015) pp. 61–73,

https://doi.org/10.1016/j.tws.2015.01.002

[3] Arbelo M, Degenhardt R, Castro S, Zimmermann R. Numerical characterization of imperfection sensitive composite structures. *Composites Structures*, Vol. 108, (2014), pp. 295-303, https://doi.org/10.1016/j.compstruct.2013.09.041

[4] Degenhardt R, Castro S G P, Błachut J, Arbelo M, Wagner R, Hühne C, Niemman S, and Khakimova R. Stability of Composite Shell–Type Structures. *Stability and Vibrations of Thin Walled Composite Structures*, Elsevier, pp. 253–428 (2017), https://doi.org/10.1016/B978-0-08-100410-4.00007-7

[5] Castro S G P, and Donadon M V. Assembly of Semi-Analytical Models to Address Linear Buckling and Vibration of Stiffened Composite Panels with Debonding Defect. *Composite Structures*, 160, pp. 232–247 (2017), https://doi.org/10.1016/j.compstruct.2016.10.026

[6] Franzoni F, Degenhardt R, Albus J, Arbelo M. Vibration correlation technique for predicting the buckling load of imperfection-sensitive isotropic cylindrical shells: an analytical and numerical verification. *Thin-Walled Structures*, Vol. 140, (2019), pp 236-247, https://doi.org/10.1016/j.tws.2019.03.041

[7] Franzoni F, Wilckens D, Odermann F, Skuķis E, Kalniņš K, Arbelo M, Degenhardt R. Assessing the Buckling Load of a Pressurized Orthotropic Cylindrical Shell Through Vibration Correlation Technique. *Thin-Walled Structures*, Vol. 137, (2019), pp 353-366, https://doi.org/10.1016/j.tws.2019.01.009

[8] Franzoni F, Odermann F, Lanbans E, Bisagni C, Arbelo M, Degenhardt R. Experimental validation of the vibration correlation technique robustness to non-destructive buckling load prediction of the composite cylinders. *Composite Structures*, Vol. 224 (2019), https://doi.org/10.1016/j.compstruct.2019.111107

[9] Davoud Shahgholian-Ghahfarokhi D, Hossein Rahimi G, Liaghat G, Degenhardt R, Franzoni F. Buckling prediction of composite lattice sandwich cylinders (CLSC) through the vibration correlation technique (VCT): Numerical assessment with experimental and analytical verification. *Composites Part B*, Vol. 199 (2020), https://doi.org/10.1016/j.compositesb.2020.108252