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Buckling Tests of Sandwich Cylindrical Shells with and without Cut-outs

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ABSTRACT

The results of buckling tests performed during the project DESICOS funded by the European Commission in the FP7 Programme are here presented. The tested structures are sandwich cylindrical shells that consist of reduced models of a component of the Ariane 5 launcher: the Dual Launch System. In particular, the scaled component is studied with and without the presence of cut-outs. Before performing the tests, the geometric imperfections as well as the thickness variations were measured. The tests were performed using the buckling testing equipment of Politecnico di Milano. The results of the tests contributed to understand the complex phenomenon of buckling of sandwich cylindrical shells, and to study the effect of initial geometric imperfections. They were also used to validate finite element models useful for the design of future launcher structures, and to set-up a probabilistic approach for the buckling analysis of cylindrical shells.

INTRODUCTION

European Space industry demands for lighter and cheaper launcher transport systems. Unstiffened cylindrical shells are representative of several space components, and have been largely investigated in the past years, also because they are high-sensitive to imperfections and consequently a large difference can be obtained from the experimental tests respect to the predicted buckling loads. Currently, in most of the cases, they are designed according to NASA SP 8007 guideline [1] using the conservative lower bound curve.

In the last 10-15 years, several experimental tests were performed to study the buckling behavior of composite cylindrical shells under axial compression [2-10]. It is due from one side to the growing interest of aerospace industry for composite structures, and from the other side to the need of high-fidelity tests for the validation

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of new, accurate and fast design approaches for imperfection sensitive composite structures.

This paper presents part of the buckling tests conducted at the Politecnico di Milano during the DESICOS project [11] funded by the European Commission in the FP7 Programme. The project ended in September 2015, and investigated different methodologies for the shell design, such as the Single Perturbation Load approach [12-13] and stochastic methods for an effective and robust design [14-15]. The methods were applied to components of space launch vehicles, where the buckling is one of the dimensioning criteria, and were validated by tests.

The tested structures here presented are sandwich cylindrical shells that consist of reduced models of a component of the Ariane 5 launcher: the Dual Launch System. The full scale Ariane 5 component is a cylindrical shell, with diameter of 4.54 m, and height that can reach 5.3 m. It consists of sandwich structure with facesheets in laminates made of M40J, and with honeycomb as core material.

Scaled shells were studied within the DESICOS project, trying to keep the same structural behavior of the full-scale component, especially for what concerns the buckling phenomena.

SHELL DESCRIPTION

The present study discusses the buckling tests conducted on the scaled model of the Dual Launch System (SYLDA) of Ariane 5 launcher. The scaled component of SYLDA was designed by Airbus Defence and Space [16], and consists of a cylindrical shell made of sandwich material, whose exterior facesheets are composite laminates.

The shell presents a nominal radius equal to 350 mm and a length equal to 740 mm. The facesheets are laminates made of Hexcel IM7/8552 unidirectional prepreg [17-18], with nominal ply thickness of 0.131 mm. The core material is EVONIK Rohacell WF20024 [19] with nominal thickness of 1.5 mm. The properties of IM7/8552 and of Rohacell are reported in Table I and II, respectively. The stacking sequence of the shell is [19°/-19°/90°/CORE/90°/-19°/19°] for a total thickness equal to 2.286 mm.

TABLE I. HEXCEL IM7/8552 UD CARBON PREPREG

Property	**Value**
Longitudinal modulus, E_{11} [MPa]	150000
Transverse modulus, E_{22} [MPa]	9080
Shear modulus, G_{12} [MPa]	5290
Poisson's ratio, ν_{12}	0.32
Density, ρ [kg/m^3]	1570

TABLE II. EVONIK ROHACELL WF200

Property	**Value**
Young modulus of core, E [MPa]	350
Shear modulus, G [MPa]	150
Poisson’s ratio, ν	0.33
Density, ρ [kg/m^3]	205

The results of the tests conducted on two shells manufactured by GRIPHUS within the DESICOS project are here presented. The first shell does not have cut-outs, whereas the second one includes the presence of three circular cut-outs. A cut-out of diameter equal to 92 mm is located on one side of the shell and two smaller cut-outs of diameter equal to 46 mm on the other side.

In order to be able to apply axial compression to the shells during the tests, tabs were manufactured and attached to the top and bottom of the shells. So the free length of the shell is limited to the central part and measures 620 mm.

Eighteen strain gauges were attached to each shell in the positions decided in agreement within the DESICOS consortium. The strain gauges are placed in back to back configuration at 120° at three different heights. A photo of the shell without cut-outs, and a sketch of the strain gauges position are reported in Figure 1.

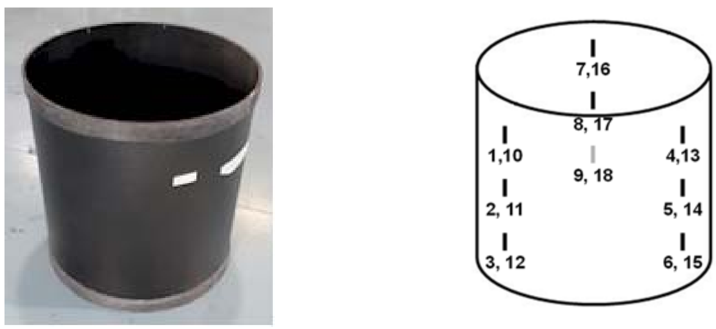

Figure 1. SYLDA shell: photo of the shell and sketch with strain gauges positions.

MEASUREMENT OF GEOMETRIC IMPERFECTIONS

The equipment available at Politecnico di Milano is used to measure the inner and outer shell surfaces [20-21]. Figures 2 and 3 show the top view and the side view of the equipment, respectively. The shell is placed on a rotating platform, and two LVDT transducers, that are located inside and outside the shell and that can translate axially, measure the inner and outer shell-wall surfaces. The circumferential position of the measurements is obtained using two measuring tapes around the shell.

The measurement is limited to the central part of the shells and covers the blue area depicted in Figure 3. Such an area has a length equal to 540 mm. The inner and outer surfaces are measured over a grid consisting of 220 circumferential stations, with a circumferential interval equal to 10 mm. The axial measurements are taken continuously with a sampling frequency equal to 100 Hz. They consist of approximately 2000 axial stations.

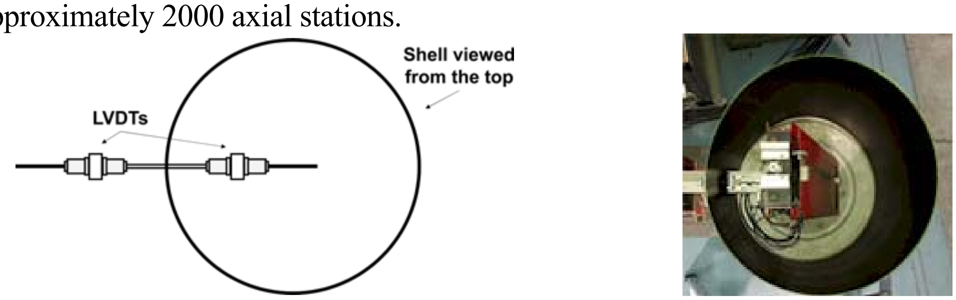

Figure 2. Equipment for measurement of geometric imperfections (top view).

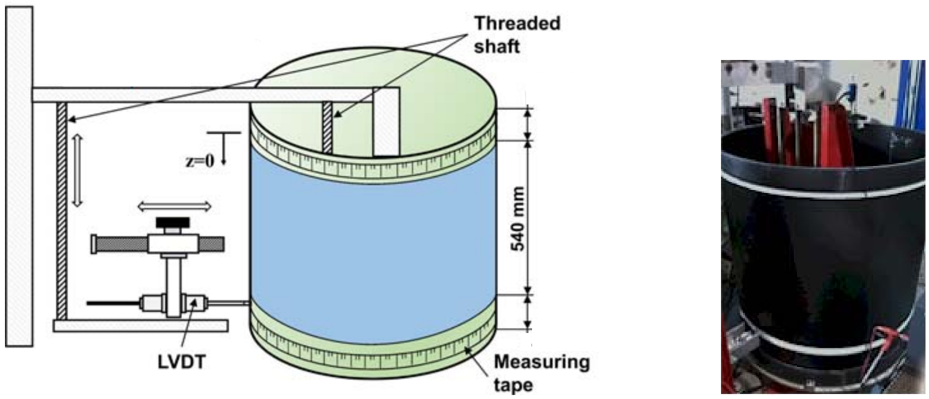

Figure 3. Equipment for measurement of geometric imperfections (side view).

The inner and outer surface measurement w_i and w_o of the shell without cut-outs are shown in Figure 4. They are normalized using the nominal shell thickness t equal to 2.286 mm. Negative and positive value of radial displacement stands for inward and outward displacement, respectively.

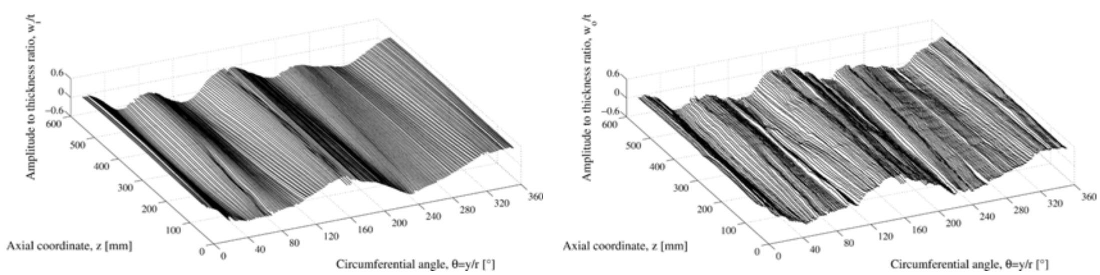

Figure 4. Inner and outer surface measurement of shell without cut-outs.

The measurements show that the imperfections are periodic in the circumferential direction with four circumferential half-waves, whereas they exhibit slight variations in the axial direction. The imperfection amplitude of the inner surface varies from -0.51 t to +0.48 t, whereas the outer surface has an imperfection amplitude which varies from -0.52 t to +0.58 t.

Figure 5 presents the polar diagram of the shell considering the inner and outer surface measurements at three different heights of the shell, scaled by a factor of 50.

The thickness variation of the shell is obtained as the difference between the outer and inner surface measurements. It varies from -0.19 t to +0.17 t, and is divided in bands of approximately 100 mm as consequence of the manufacturing technology.

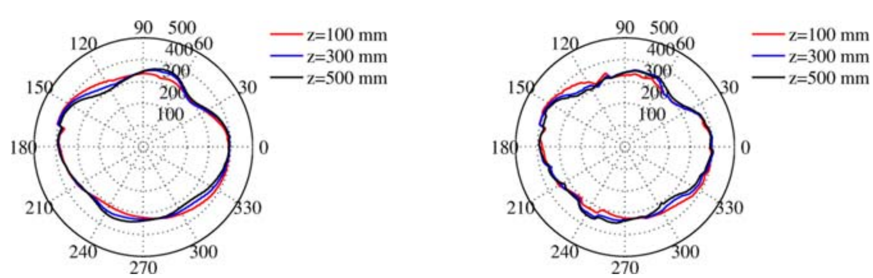

Figure 5. Polar diagrams of inner and outer surface measurements of shell without cut-outs.

The measurements of the inner and outer surfaces w_i and w_o of the shell with cut-outs are shown in Figure 6. The measured data are normalized by the nominal shell thickness *t* equal to 2.286 mm.

It can be noted that the shape of the imperfections is close to the one measured on the shell without cut-outs. Also the maximum and minimum imperfection amplitudes are similar. The imperfection amplitude of the inner surface varies from -0.51 *t* to +0.43 *t*, whereas the outer surface has an imperfection amplitude which varies from -0.59 *t* to +0.46 *t*.

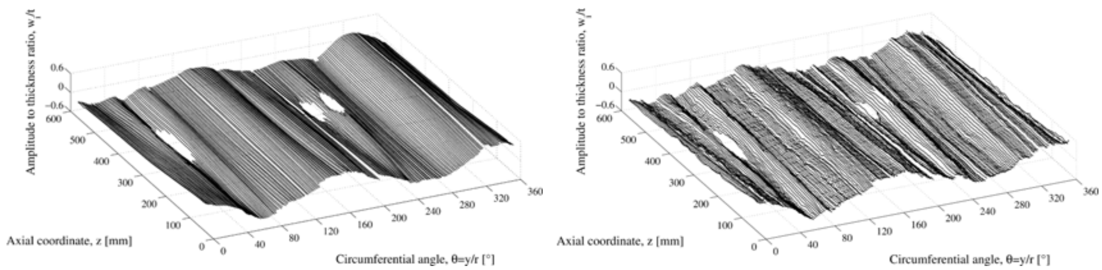

Figure 6. Inner and outer surface measurement of shell with cut-outs.

Figure 7 presents the polar diagram of the shell with cut-outs considering the inner and outer surface measurements at three different heights of the shell, scaled by a factor of 50.

The thickness variation of the shell is obtained as the difference between the outer and inner surface measurements. The thickness distribution varies from -0.18 *t* to +0.36 *t*. The high positive value of thickness is due to the presence of a thicker region at around 240°, where one of the smaller cut-outs is located.

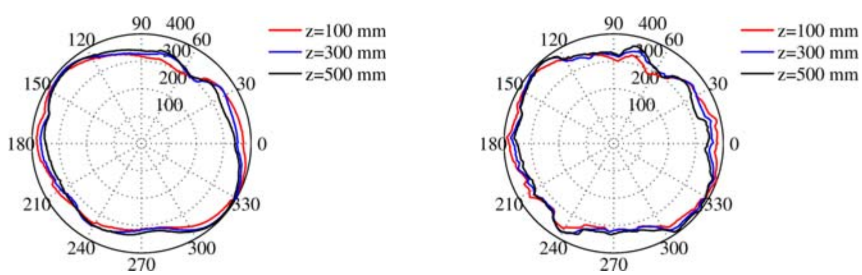

Figure 7. Polar diagrams of inner and outer surface measurements of shell with cut-outs.

TESTING EQUIPMENT

The tests were performed using the buckling testing equipment of Politecnico di Milano [2-4]. It was modified to be able to perform the tests of the DESICOS shells. It allows performing the tests in displacement control, thanks to four stepping motors located at the four corners of the equipment. The effective load applied to the shell is measured through a load cell under the lower platform, while the shortening of the shell is taken through two LVDTs that measure the distance between the upper and lower platform. A photo of the testing equipment is reported in Figure 8.

Figure 8. Buckling testing equipment.

RESULTS OF SHELL WITHOUT CUT-OUTS

The sandwich cylindrical shell without cut-outs was tested under axial compression. The buckling load was measured equal to 242 kN. From the video taken during the test, it is possible to note that the load was hold for about 20 seconds, before the shell collapsed. The failure of the shell started in the position of the buckles and propagated around the shell causing the collapse.

The load-shortening curve is reported in Figure 9, while the measurements acquired by the strain gauges during the test are reported in Figure 10.

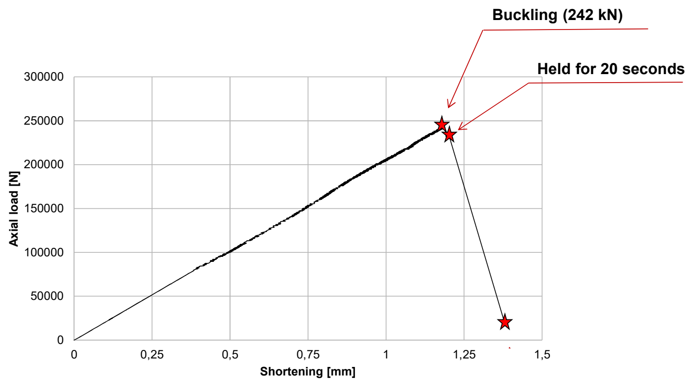

Figure 9. Load-shortening curve of shell without cut-outs.

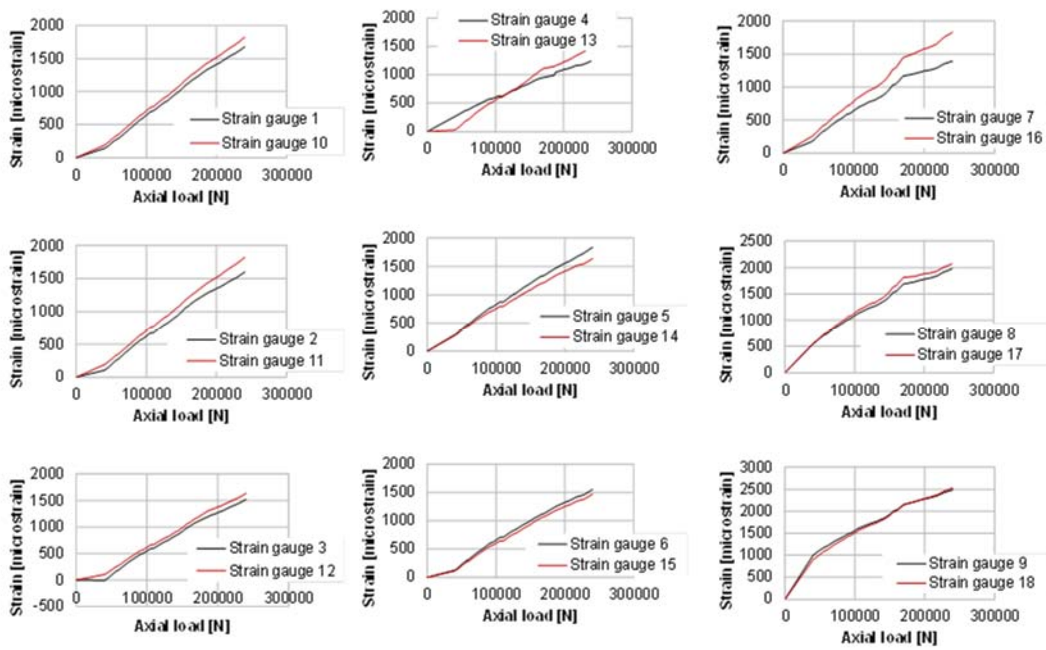

Figure 10. Strain gauges measurements of shell without cut-outs.

A photo taken during the test at 200 kN is shown in Figure 11. It is possible to note that no buckling is visible. Figure 11 reports also a photo taken immediately after the collapse.

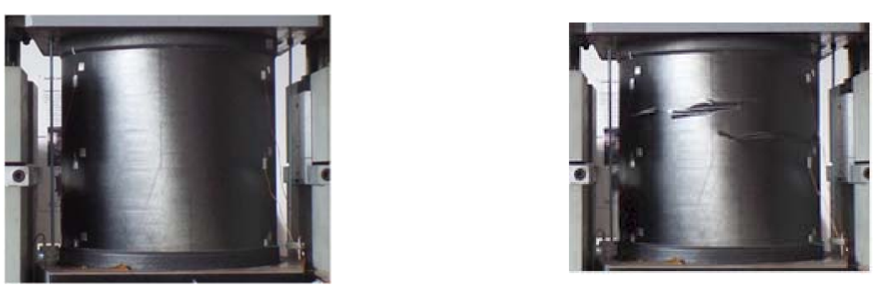

Figure 11. Photos of shell without cut-outs taken immediately before and after the collapse.

RESULTS OF SHELL WITH CUT-OUTS

The sandwich cylindrical shell with cut-outs was also tested under axial compression. The buckling load was equal to 166 kN. In this case, the shell did not collapse immediately after the buckling, and it was possible to keep the buckling shape for a few minutes before unloading the shell. No damages were visible after the test.

The buckling load is equal to about 70% of the buckling load of the shell without cut-outs. The load-shortening curve is reported in Figure 12.

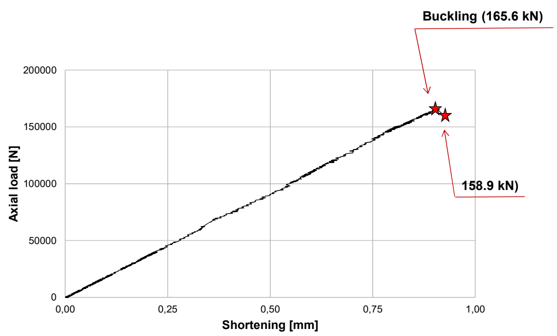

Figure 12. Load-shortening curve of shell with cut-outs.

A photo taken on the front side of the shell at 165 kN just before buckling, and at 159 kN after buckling are shown in Figure 13. Buckling is also visible on the back side of the shell. A photo taken at 165 kN before buckling and a photo taken after buckling are shown in Figure 14.

Figure 13. Photos of shell with cut-outs taken before and after buckling on the front side.

Figure 14. Photos of shell with cut-outs taken before and after buckling on the back side.

CONCLUSIONS

The paper presented the results of buckling tests conducted on sandwich cylindrical shells during the project DESICOS funded by the European Commission in the FP7 Programme.

The shells are scaled models of a component of the Ariane 5 launcher: the Dual Launch System. The component is studied with and without the presence of cut-outs. Before performing the tests, the geometric imperfections as well as the thickness variations were measured. The shell without cut-outs collapsed immediately after buckling, while the shell with the cut-outs buckled without collapsing. The buckling load of the shell with cut-outs resulted equal to about 70% of the buckling load of the shell without cut-outs.

The results of the tests contribute to understand the complex phenomenon of buckling of sandwich cylindrical shells, and to study the effect of initial geometric imperfections and thickness variations. They were used to validate finite element models that can be useful for the design of future launcher structures, and to set-up probabilistic approaches for the buckling analysis of cylindrical shells.

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