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Reducing Conservatism in Buckling Analyses of Cryogenic Tanks

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Abstract

ArianeGroup and CNES have a long history of joint research efforts in order to mature technologies and know-how to prepare future products. Studied topics cover the full spectrum (design, materials, manufacturing, …) and deal with primary structures, equipments and engines.
This article proposes to illustrate these activities through the example of buckling analyses of cryogenic tanks. Buckling is one of the main sizing driver and is the object of detailed analyses in order to ensure such a catastrophic event will not occur during the life of the launcher (assembly, ground phases and flight). Isotropic cylindrical barrels are used on the Ariane program. These structures are cylindrical shells with a large radius/thickness ratio. They exhibit a strong sensitivity to manufacturing imperfections which drastically reduces the critical buckling load of perfect theoretical structures.
This issue is classically handled through the use of Knock-Down Factors such as the ones proposed by NASA. These KDF have been derived through comparisons of test and theoretical results. Though reputed to be (overly?) conservative, these KDF are widely used since they are very convenient.
Through several successive PhD Thesis carried out at INSA de Lyon and directed by Prof. Ali Limam, a long-term research program has been implemented, involving testing of hundreds of small-scale specimens and numerical buckling analyses. This resulted in the derivation of alternative KDF for buckling of isotropic cylinders for compression, bending and torsion with pressure. Proposed values are significantly larger than SP8007 when pressure is involved. These KDF can be used during preliminary studies (when design has the strongest impact on mass) or for quick assessments of buckling capacities.
Stiffened tanks are also the object of R&T work. Current work involves the use of non linear buckling analyses and testing of 3D printed specimens.

1. CNES/ArianeGroup Joint Research Program

Historically, CNES (Centre National des Etudes Spatiales) has initiated the Ariane story and provide today their support and collaborate with French companies associated to this adventure.
Since the 90's, ArianeGroup and CNES Launcher Directorate joined their effort to work together in the frame of a Research and Technology program setup by CNES.

This program is based on two main ways to proceed:
- Identify and study/maturate new technologies (at low TRL) which could be used and applied to launchers.
- Study, improve the understanding and setup modelling capabilities for complex phenomenon.

This approach is valid for the 3 main domains described on Figure 1 and necessary to design and build a launcher with the objective, at the end, to improve its performances, cost/competitiveness, quality, weight, manufacturing cycles, …

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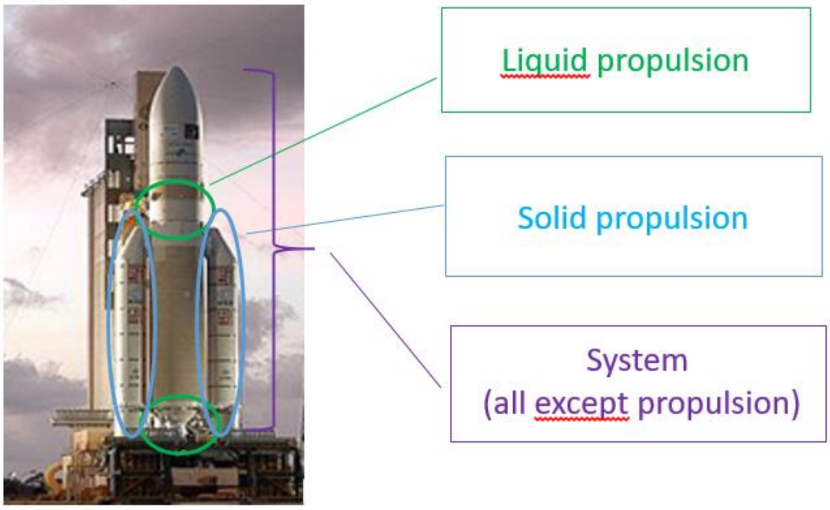

Figure 1: Domains covered by CNES/ArianeGroup R&T

The work presented in this paper took place in the System R&T Domain which is detailed in Figure 2. Buckling topics are part of the "Materials& Structures" subdomain, which amount to almost half of the total effort of the domain (Figure 3).

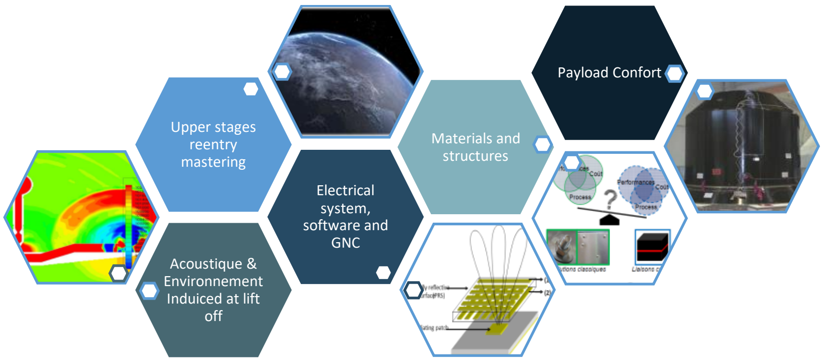

Figure 2: Content of the System R&T Domain

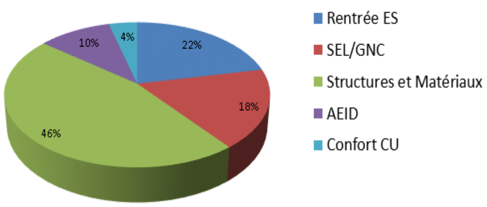

Figure 3: Workshare within System R&T Domain

2. Buckling of Cryogenic Tanks: an example of research project

2.1 Context

Launchers primary structures are submitted to compression and bending loading, on the ground during pre-flight operations (wind) and in flight (thrust, aerodynamic loads, maneuvers). Many of these structures are slender and lightweight shells, which have to be sized against buckling. Ariane 6 lower-stage cryogenic tanks (Figure 4) are good examples of such structures since they are very large isotropic thin-shells for which even assembly operation are possibly critical from a buckling point of view.

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Figure 4: Ariane 6 lower-stage cryogenic tanks

2.2 Rationale for a research project on buckling

Buckling of thin-walled shells have been the focus of many researches, especially since a strong discrepancy between theoretical and experimental buckling loads has been noticed when such structures have been introduced in the aircraft design in the late 20s. This discrepancy is illustrated on Figure 5 as a function of the ratio between the shell radius "R" and thickness "t".

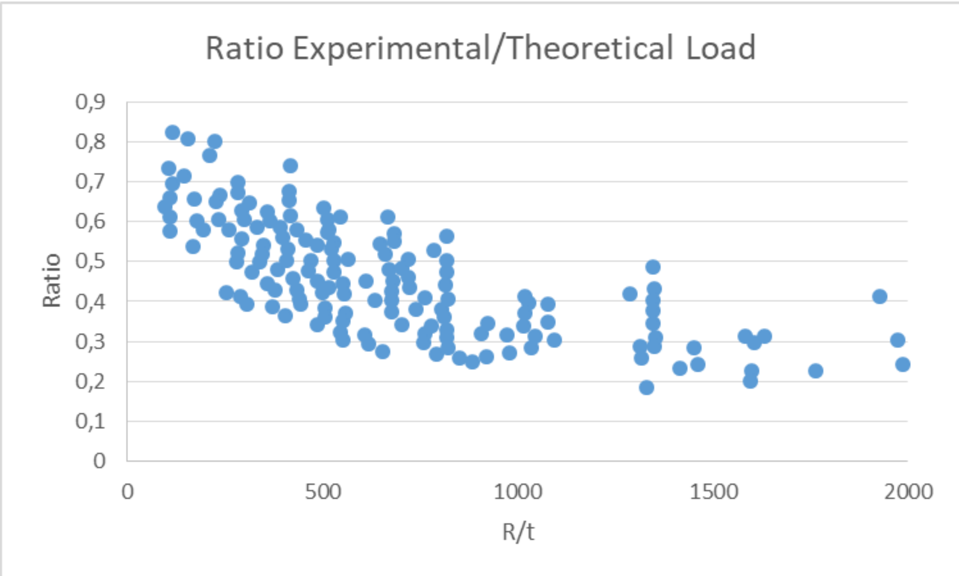

Figure 5: Discrepancy between theoretical and experimental buckling loads (from [1])

The source of the discrepancy has been soon identified as the geometrical imperfections. No manufactured thin-walled barrel is an exact cylinder, which is obviously not taken into account in the main-stream theoretical analyses. NASA has compiled results obtained from the 30s to the 60s and has promoted a sizing rule based on a master curve lower than the experimental results (report NASA SP-8007 [2], first published in 1965). This report is still today a standard in the aerospace industry to size against buckling.

NASA SP-8007 offers several formulas to compute the *Knock-Down-Factors* (KDF) associated to the imperfections.

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For isotropic barrels without internal pressure, there are one formula for compression, and another one for bending. In both cases, the KDF depends on the elastic properties and on the ratio R/t. For typical Ariane tanks, the KDF goes down to 0.25 (buckling load 4 times lower than the theoretical one). A constant KDF is proposed for shearing.
In case of internal pressure (such as for tanks), a correction is proposed for both compression and bending so that the KDF is significantly increased.
Such formulas are very easy to use. The typical application consists in carrying out a Linear Buckling Analysis in order to compute the critical load and then applying the KDF to derive a sizing load. However these KDF are reputed as being conservative and the resulting structures are not fully optimized. Moreover, there is no information on the imperfections observed on the testing specimens, so no way to know the limits of applicability of the NASA SP-8007 KDF.
This is the reason why, more than 30 years, CNES and Aerospatiale (which will later become ArianeGroup) decided to launch a research program on the buckling of cryogenic tank. This research study has first been carried out by Prof. J.F. Jullien and then by Prof. A. Limam.

2.3 Content of the research project

Nine PhD works have been carried out between 1991 and 2018 ([3] to [11]). They have been mostly focused on isotropic barrels but some stiffened specimens have been analyzed as well. The following topics have been studied:

- Loading types: compression, bending, shear, with and without pressure (loads have been applied independently or in combination),
- Geometry: influence of thermal insulation.

Most of the work has involved a combination of experimental work and numerical simulations.

2.4 Experimental work

More than 400 buckling tests have been carried out. For comparison, NASA SP-8007 mentions 200 tests of isotropic cylinders in compression and 145 in bending.
The specimen types and geometries have evolved over the time:

- Initially electro-plated specimens have been used (Figure 6), costly but with good quality,
- Rolled-bonded specimens (Figure 7) have then been used, much cheaper but with low quality (significant imperfections),
- Recently, 3D-printed specimens (Figure 8) have been used for the strong potential to manufacture good-quality stiffened shells at very limited cost,
- Some specimens have coated with soft materials (Figure 9), in order to assess the influence of thermal insulation.

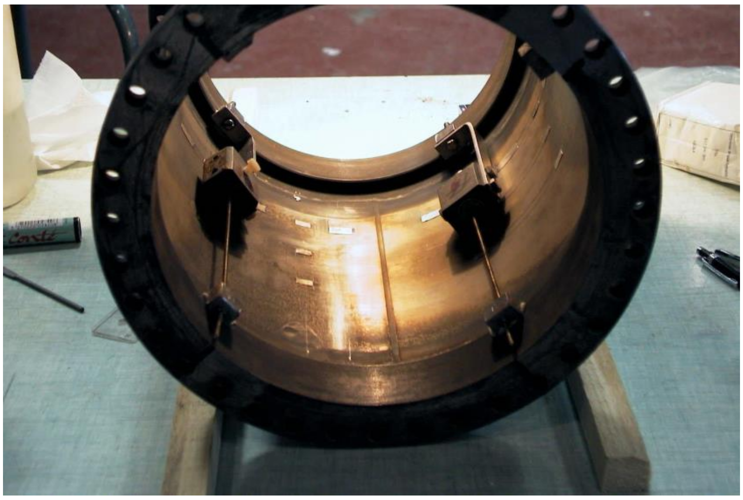

Figure 6: Copper electro-plated specimen

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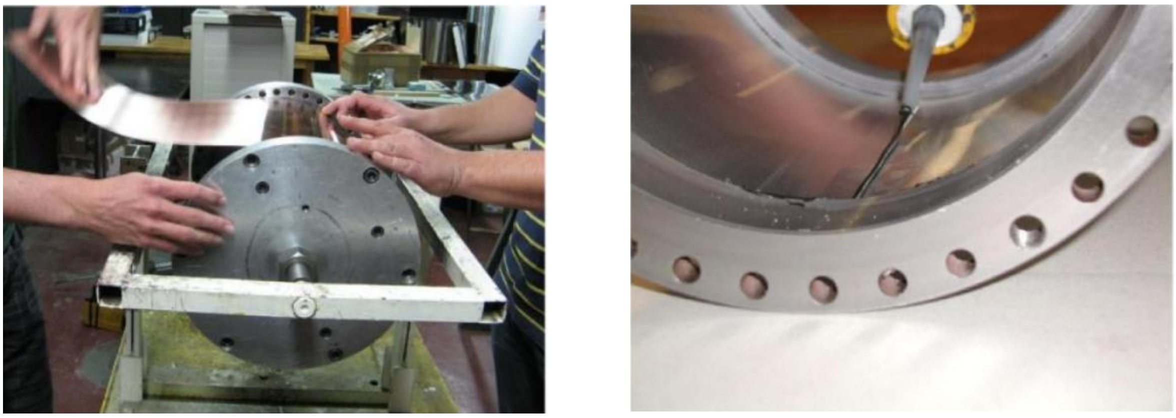

Figure 7: Manufacturing of rolled-bonded specimens

Figure 8: 3D-printed polymer specimen

Figure 9: Specimen with a foam coating

Specific testing devices have been developed and modified over the years, especially to carry out tests with internal pressure (Figure 10 and 11).

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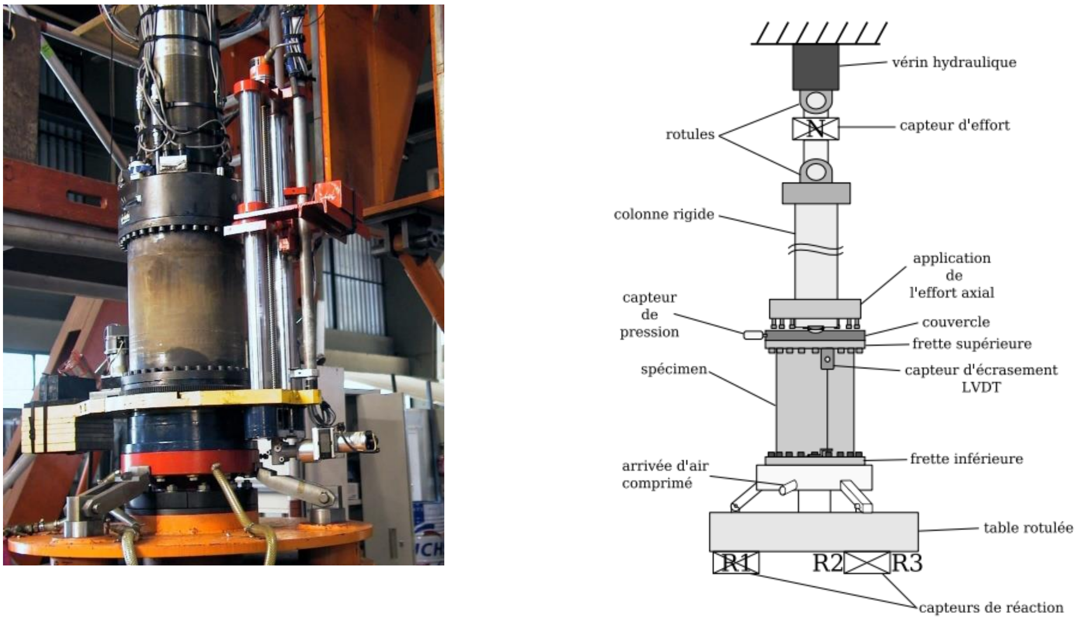

Figure 10: testing machine for compression with pressure

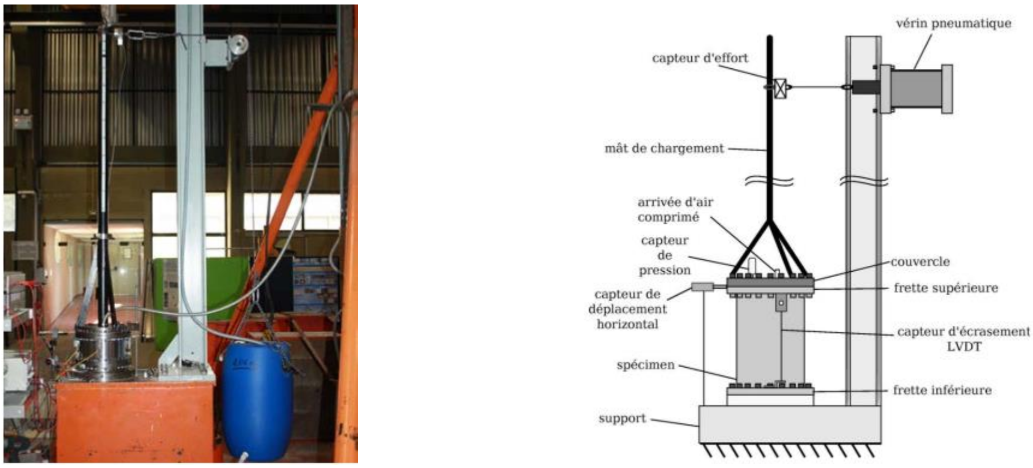

Figure 11: testing machine for shear/bending test with pressure

To characterize the initial imperfections and take them into account in the non linear simulations, shape scanning has been used (Figure 12). Monitoring of the shape of the specimens during testing using Digital Image Correlation has been carried out (Figure 13) to follow the evolution of the imperfections with pressure and better detect the onset of buckling.

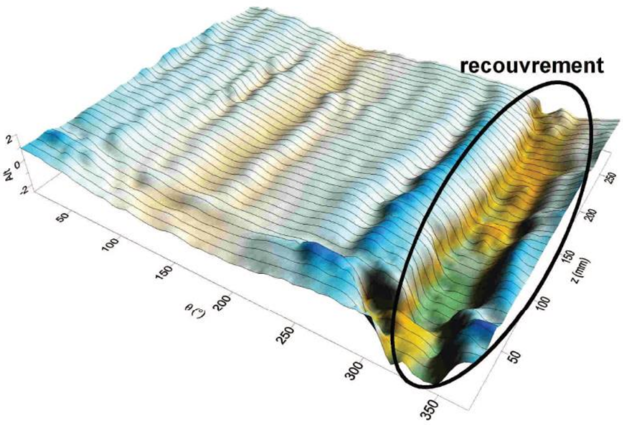

Figure 12: Measurement of geometrical imperfections (aluminium shell, t=0.2mm)

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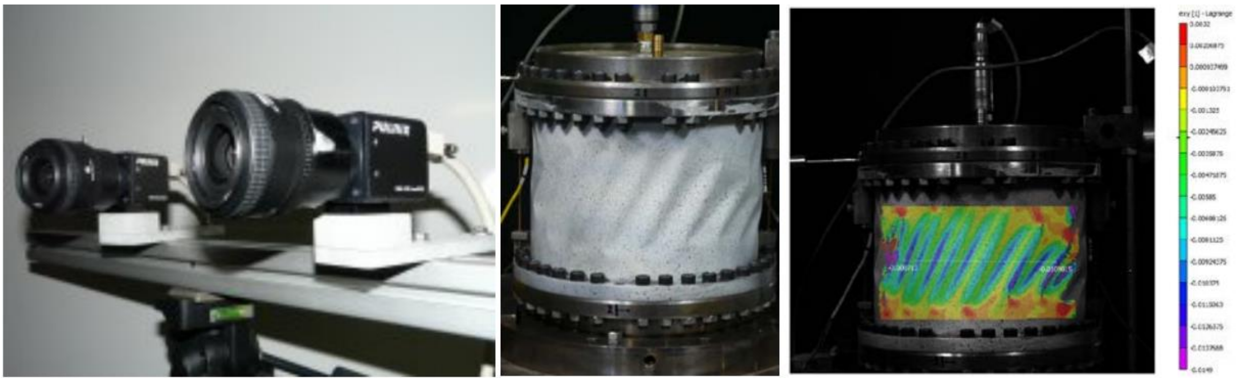

Figure 13: Shape monitoring during testing through Digital Image Correlation

Some examples of buckling behaviour for compression, bending and shear are presented on Figure 14.

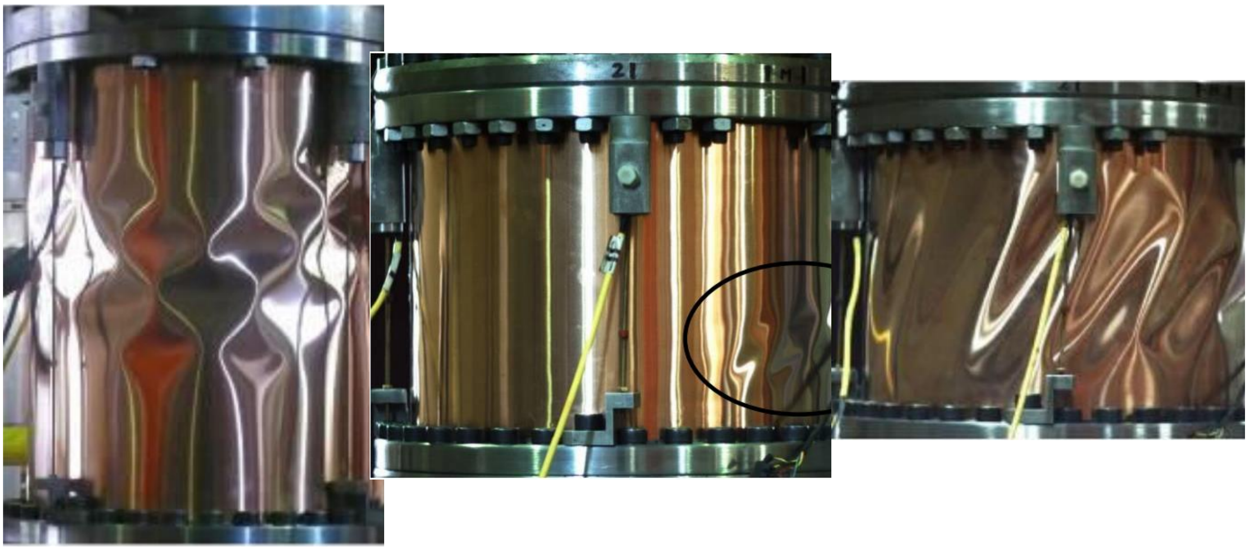

Figure 14: Buckled specimens in compression, bending and shear ([9])

2.5 Numerical simulations

Numerous simulations have been carried out to support and complement the experimental results (confirmation of observed trends). Classical Linear Buckling Analysis and Non Linear Geometrical Analyses have been used. An example of such simulations are presented on Figure 15.

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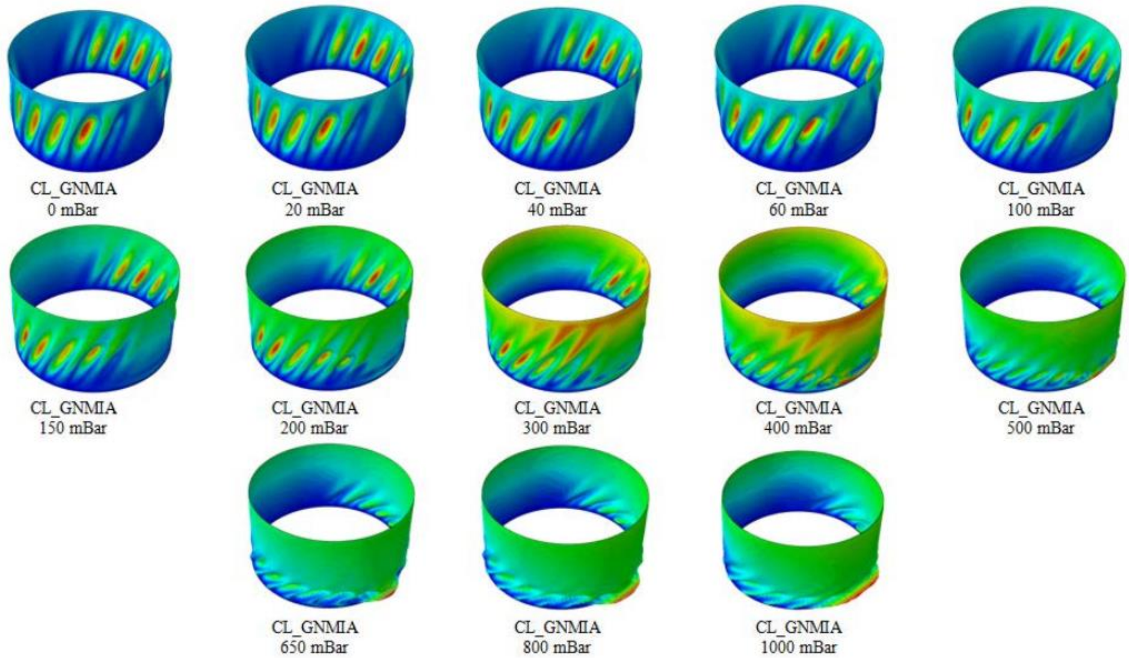

Figure 15: Buckling behavior as a function of pressure – Aluminium shell ([10])

2 options have been used for the inclusion of the imperfections:
- mapping of the measured imperfections on the mesh,
- use of a “worst defect”: an axisymmetric inward triangle (Figure 16).

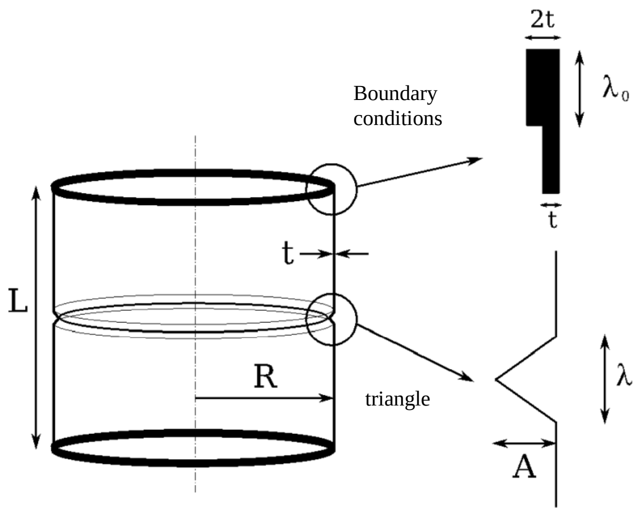

Figure 16: axisymmetric inward triangle imperfection

2.6 Examples of results

This work has brought vast information on all the studied topics. Among the achieved results are the following points:

Effect of pressure (Figure 17 and 18)

Pressure has a strong positive effect on the buckling behavior. This effect is more pronounced that proposed by the SP-8007. However, for large pressure levels, a plastic behavior is observed at the edges, which lowers the buckling critical load.

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Effect of Thermal insulation (Figure 19**)**
The thermal insulation layer brings an improvement to the buckling behavior (increased critical load). This effect is especially strong for structures with a large R/t ratio and when pressure is very low.

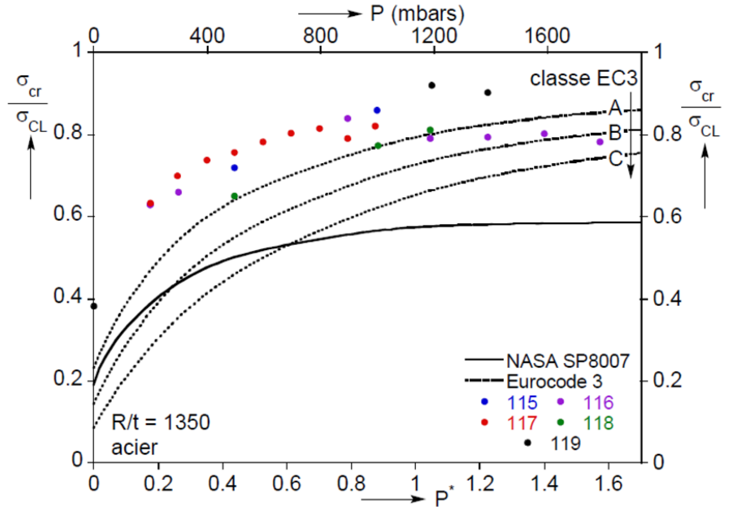

Figure 17: Effect of pressure on apparent KDF – Compression ([9])

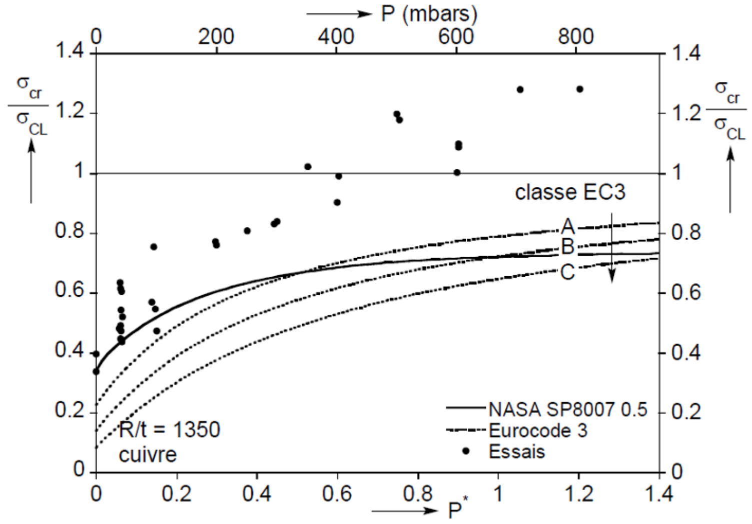

Figure 18: Effect of pressure on apparent KDF – Bending ([9])

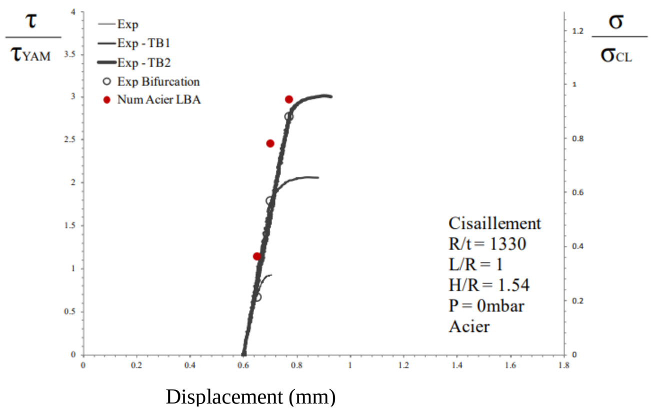

Figure 19: Effect of thermal insulation on buckling behavior in Shear ([10])

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2.7 Industrial Exploitation

One significant part of the work has been dedicated to the derivation of updated sizing rules to be used for the developments of new launchers with isotropic barrels. This task has not been easy since laboratory specimens have little to do with industrial structures. Numerical simulations have been extensively used for this work.
These new rules will not be presented here. They offer a significant improvement with respect to the SP-8007 for the following aspects:
- effect of pressure on compression and bending buckling behavior,
- KDF for shearing loads,
- interaction laws for combined compression, bending, shearing and internal pressure,
- effect of thermal insulation on the buckling behavior.

The new rules have been implemented in an in-house software for early phases of project developments.

A side effect of this work has also been a strong improvement of our in-house simulation capabilities to carry out advanced non linear buckling computations, which are more and more used at different level of the development.

2.8 Current & Future work

R&T work is currently focused on stiffened tanks. Several tests have been carried out on 3D printed specimens (Figure 20) with and without pressure. Initial tests were not so successful because of the low quality of the printed specimens (Figure 21). A work on the printer parameters and the improvement in the technology allows getting more satisfactory results, even though the obtained specimens are more fragile than the one used so far. A stronger emphasis than before will be placed on the numerical simulation.

Figure 20: 3D-printed polymer stiffened shell

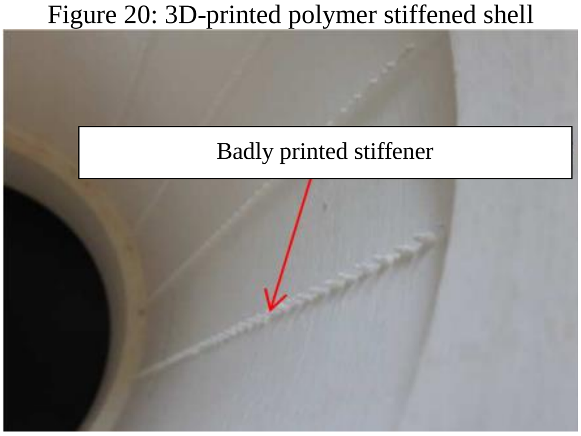

Figure 21: Low quality of the initial 3D-printed specimens

3. Conclusion

An overview of 30 years of R&T work carried out in common by ArianeGroup and CNES has been given. A significant number of PhD Thesis have been produced in order to cover the different aspects of the buckling of isotropic shells.

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This huge task has allowed to derive updated sizing rules for buckling, which contribute to our efforts to get lightweight and cost efficient design for European launchers.
As a concluding remark, we would like to highlight the difficulty to carry out such a task on such a long period, especially since a number of persons have been successively involved in this task. It is not easy to keep the momentum, have in mind the global picture and identify the right direction to go. We achieved this thanks to our R&T organizations which has been able to prioritize these actions, the dedication of our technical experts and to the pivotal role of Prof. Ali Limam.

Acknowledgments

The authors want to express their deepest thanks to Prof. A. Limam for his long-term work in cooperation with ArianeGroup and CNES. We salute the memories of the late Prof. J.-F. Jullien and of our colleague J. Fougeras. We also thank our colleagues who contributed to this research project over the years: D. Lestrat, V. Taponnier, M. Jacquesson, B. Tang, T. Bouilly for CNES and E. Greco, F. Lorioux, J. F Pelliccia for ArianeGroup.

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