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The Effect of a Thermal Barrier on the Buckling and Post-Buckling Behavior of Pressurized Aluminum Cylindrical Shells subjected to Shear

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Abstract

This study is devoted to the analysis of the buckling behaviour of a hybrid wall construction where the skin of a very thin light-weight structure, a metallic cylindrical shell is coated with a low density foam material. To gauge the effect of shear or the interaction of shear and bending loads on the buckling behaviour, experiments were conducted on slightly pressurized cylindrical shells. Several experiments were conducted on scaled models, and a numerical analysis was also carried out. The results allow us to gauge the effect of this foam layer on the critical behaviour associated with a linear bifurcation, and also on the post-critical behaviour. A significant increase in the bearing capacity is demonstrated with the foam layer which also contributes inhibits unstable post-critical behaviour.

Keywords: buckling, shell, multilayered shell, shear, bifurcation, thermal barrier.

1 Introduction

The buckling design of the EPC (Main Cryogenic Tank) of the launcher Ariane5 is based on the NASA SP8007 rule established at the end of the sixties. This rule is recognized as being too conservative for low pressure and the constant increase of the weight of satellites to be sent into orbit requires an improvement of this rule and a better understanding of the phenomena due to the instabilities in the case of loads and complex structures.
Many space structures such as Cryogenic launcher stages always need thermal protection. This layer of extremely light material presents excellent properties of heat insulation but very weak mechanical characteristics. Theses loads configurations represent the case of a rocket on the launching pad, waiting to be launched; extreme mechanical loads correspond to the effect of the wind.

2 Experiments

2.1 Scaled models

Experiments are conducted on slightly pressurized cylindrical multilayered shells. The details of the shear set up are shown in Fig. 1. Scaled models are used, several parameters are studied:

- different size (R/t, L/R)
- sensible choice of material and foam to preserve the representativeness of the parameters.
- low pressurization level 0 and 40mbars and higher pressurization level 1000mbars.
- combined loads (shear and induced bending).

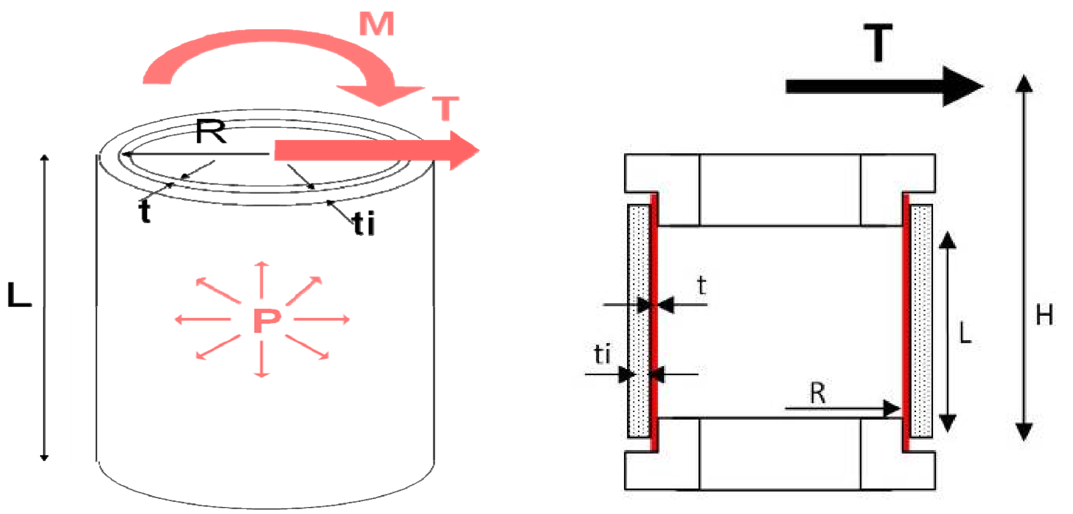

Figure 1: Shell geometry

2.2 Specimen manufacturing

The manufacturing consists in positioning two rings which are going to assure the limit conditions of the shell with the assembly jig. A metallic sheet (steel, copper or aluminum) is then rolled around theses rings. An epoxy glue allows the adhesion; the resin consists of monomers or short chain polymers with an epoxide group at either end. Closure of the cylinder is obtained by gluing the ends. For internal pressures, the airtightness is assured by mastic sealing compound at the extremity of the specimen.

During the assembly on the experimental setup, a 4mm foam sheet is sticked with two-sided adhesive tape. In the case of these experimental studies, this foam consists in extruded polystyrene foam.

2.3 Experimental setup

The experimental setup allows loading the shell in bending and shear, in function of the height of the application force, with an internal pressure. The transversal load is generated by a pneumatic cylinder with a constant flow.
The information resulting from all the sensors (1 pressure sensor, 1 strength sensor, 4 LVDT sensors 1 horizontal LVDT sensor measuring respectively the vertical movement and the horizontal movement of the upper ring), is treated by the conditioners which pass on the data to a software for their acquisition.
A CCD camera captures an image every 10 seconds and allows following the deformations of the shell.

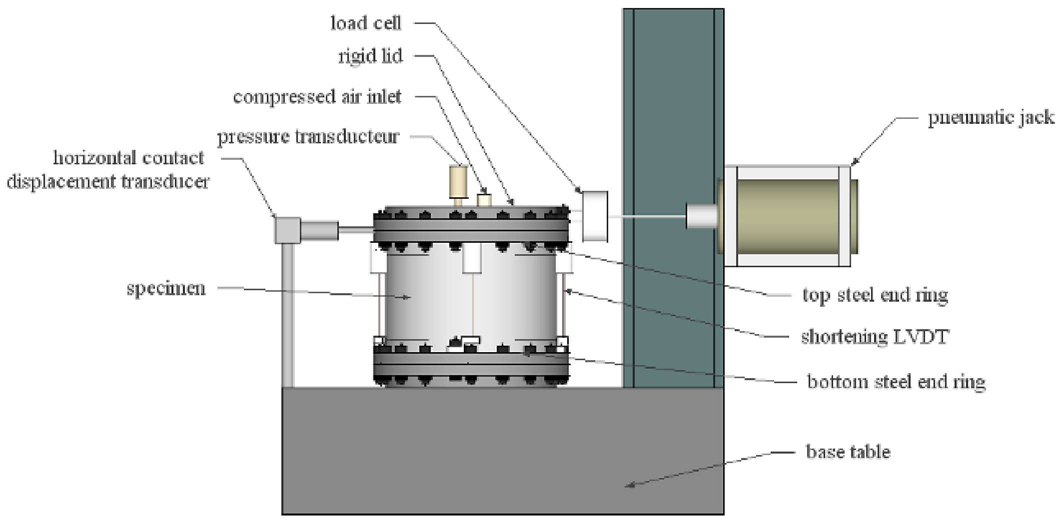

Figure 2: Set up for transverse shear buckling experiments

Shells made of metal strips with different materials (stainless steel, copper, and aluminum) and thicknesses (0.1, 0.2 and 0.3mm) were tested to show the influence of the material and geometrical parameters on the buckling of thin pressurized shells under a transverse load. A series of experiments is presented here, showing important consequences of the thermal barrier on the buckling.
For some experiments, the Vic-3D stereo-correlation system was used, in order to visualize the development of the buckling modes.

2.4 Shear behaviour

We present here a typical shear buckling experiment conducted on shell CL162 in stainless steel, with L/R=1 and R/t=1350 (0.1 mm thickness). This shell was not pressurized.

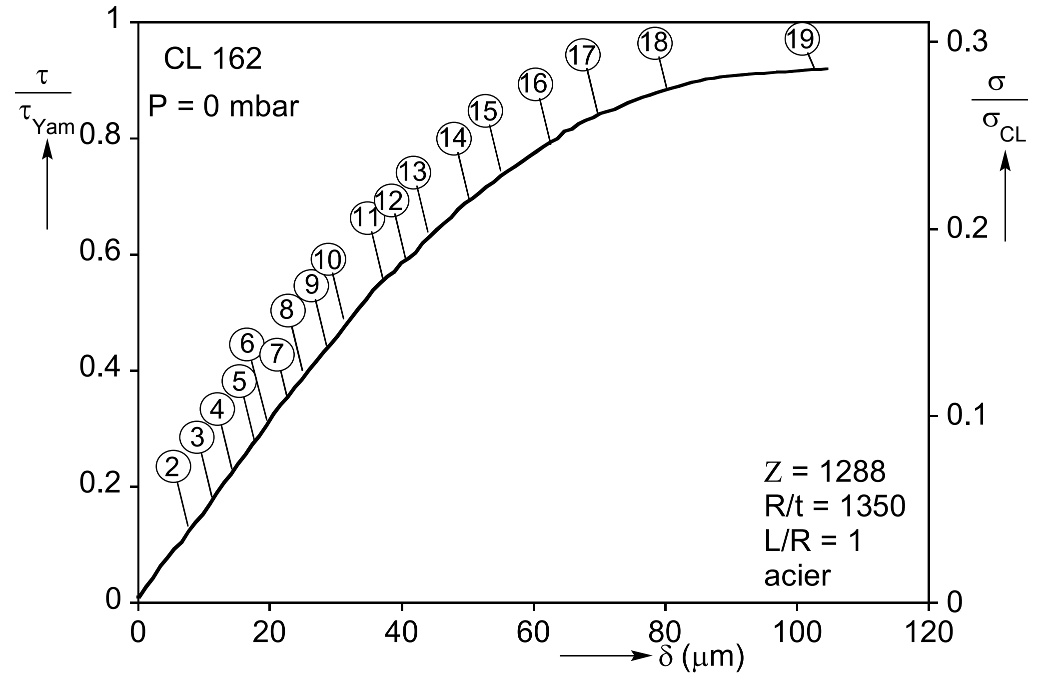

Figure 3: Load displacement curve, CL 162

The load-displacement curve is shown on Fig. 3, with the horizontal displacement δ in µm on the x-axis and shear stress τ divided by the Yamaki theoretical buckling stress τ_{yam}, on the y-axis. The numbers in flags correspond to side view configurations recorded with the Vic-3D system, showing the specimen at different levels of deformation (1 being the initial state and 20 the post-buckling mode) on Fig. 4. For each configuration, the displacement was extracted on a straight line at cylinder mid-height, and plotted on Fig.5 (magnified 5 times).

The initial behaviour (2 to 11) is linear, reaching roughly 60 % of the theoretical shear buckling stress. During this phase, the out-of-plane deformations are barely visible (smaller than 70 microns, that is 70% of the cylinder's thickness), concentrated around the generator where the shear stress is maximum, and in the shape of tilted buckles. Deformations increase then rapidly during the following non-linear regime, corresponding to the development of the buckles and their propagation on the side of the specimen. At a shear stress of about 17,36Mpa, a limit-point is reached, leading to the collapse of the structure. The post-buckling mode (configuration 20) features large inclined buckles on the entire side of the cylinder, with amplitudes up to 60 times the thickness of the shell.

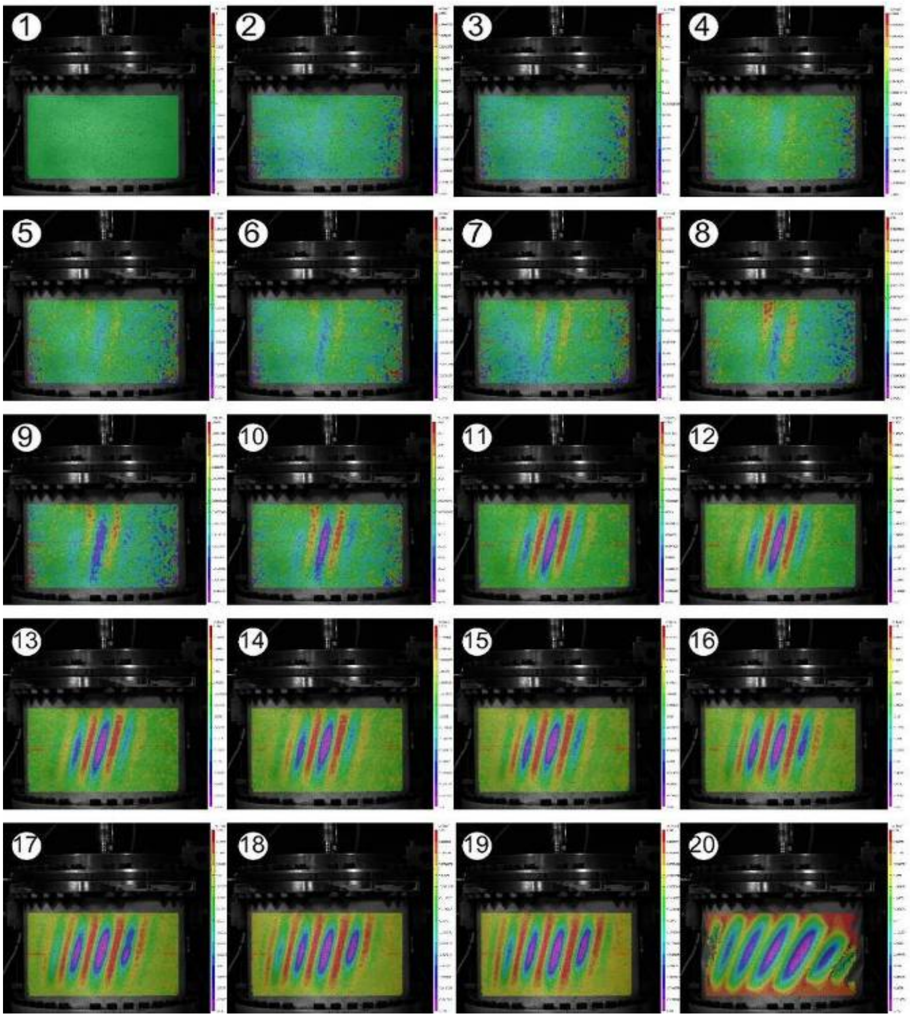

Figure 4: Pictures showing a typical shear buckling experiment conducted on shell CL162 in stainless steel. (VIC 3D)

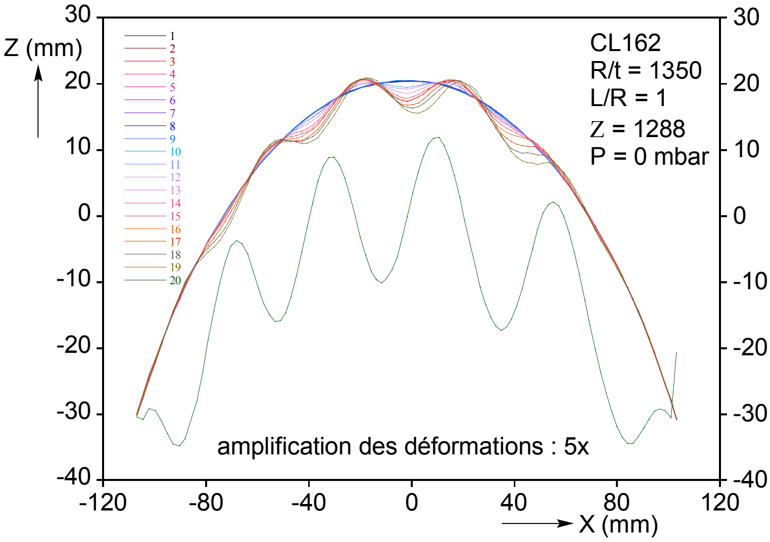

Figure 5: Straight line deformation at cylinder mid-height, CL 162

3 Influence of thermal barrier on the behaviour under transverse shear

Two series have been made to appreciate the buckling of thin pressurized aluminium shells covered with a polystyrene layer under transverse shear load. In order to compare the behaviour of shells with different material and geometrical properties, a dimensionless pressure parameter (1) is used, as is customary in shell buckling studies.

$$P^* = \frac{P}{E} \cdot \left(\frac{R}{t} \right)^2 \tag{1}$$

3.1 Aluminum shells behaviour

The curves Fig.6 present the evolution of normalized stresses with theoretical stresses as a function of the horizontal displacement of the upper rigid part of the shell for two series of stress-displacement responses.
A first series corresponds to aluminum shells with a nominal R/t equals to 675 (corresponding to a 0.2 mm thickness) and a nominal L/R equals to 1. The pressures studied in each case are from 0 to 1000mbars.
A second series of stress-displacement responses directly compares the first series with similar aluminum shells covered with a 4 millimeters polystyrene sheet.

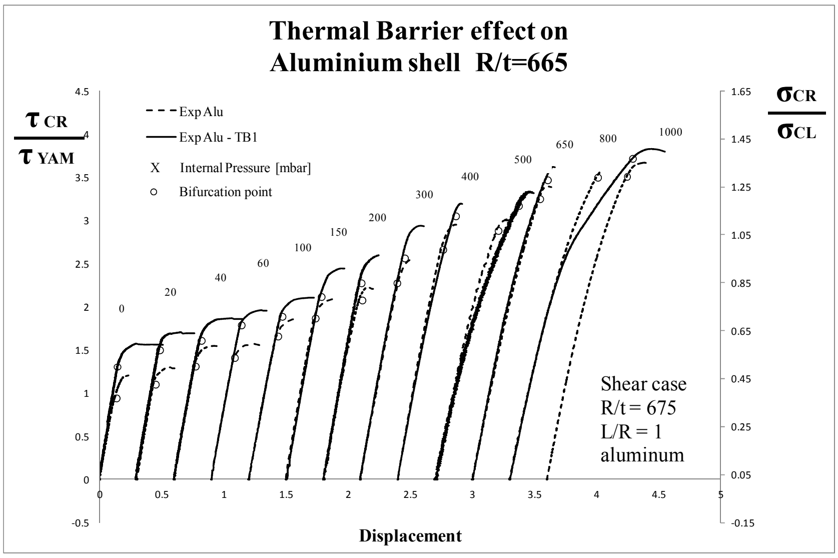

Figure 6. Load displacement response for several internal pressures (0 to 1000 mbars)

The first experiments curves are conducted with no internal pressure. As previously noted, the behaviour of the shells are initially linear, up to the theoretical critical stress, at which point the post-critical path becomes non-linear and the stiffness is progressively reduced until collapse.

We notice that the critical stress of shear is close to its theoretical value for simple aluminum shells in low pressures, showing a lower sensibility of the geometrical defects than that observed for the other types of load [1][2][3][4][5].
It is clearly shown that the isolated shells have the same behaviour but with a higher resistance stress, we can realize right now that the foam has a significant effect on the resistance of the structure for a certain level of pressure. This point will be detailed after.
Little change in the behaviour is observed for pressurized shells, however the critical stress increases steadily for high pressures.

The related buckling modes (pictures taken after the collapse of the shell) are presented on Fig. 7 for the non covered shells, showing a side view of the specimen (orthogonal to the transverse load). We initially see on the side of the cylinder large buckles, taking up the entire height of the specimen, where the shear stress is maximum. Little progress is seen with increasing pressure on the side view; although we can still visually perceive some level of reduction in the depth and size of the buckles, leaning more and more towards the bottom of the shell. At first, large diamond-shaped buckles recalling compression or bending buckling modes appear during the collapse of the structure. As the pressure increases, these buckles tend to reduce, and are more concentrated at the lower part of the specimen like a bending buckling, and become an outward bulge or "elephant's foot" like typical compression buckle mode for high pressure.

Figure 7. Corresponding non covered shells buckling modes (side view)

The Fig.8 presents related buckling modes for multilayered shells. The general behaviour seems to be the same as the one observed for non covered shells, however the foamed shells present more and thinner shear blisters, the foam layer contributes to inhibit unstable post-critical behaviour, delaying the collapse moment and in the same way increasing the critical stress.

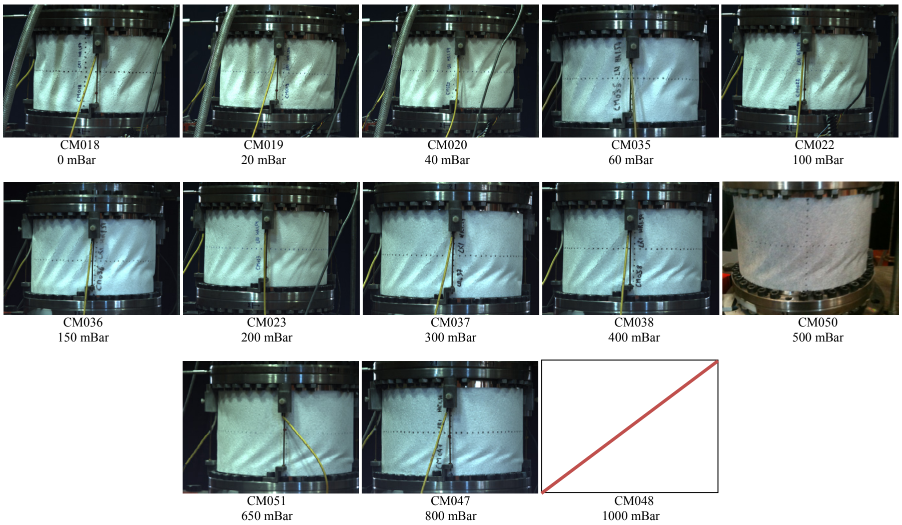

Figure 8. Corresponding covered shells buckling modes (side view)

3.2 Effect of the thermal barrier

As seen on the previous point and on the Fig.6, the foam brings some resistance at the shell. The Fig.9 shows the gain in the case of foamed shells comparatively to non covered simple shells, in function of the pressure.

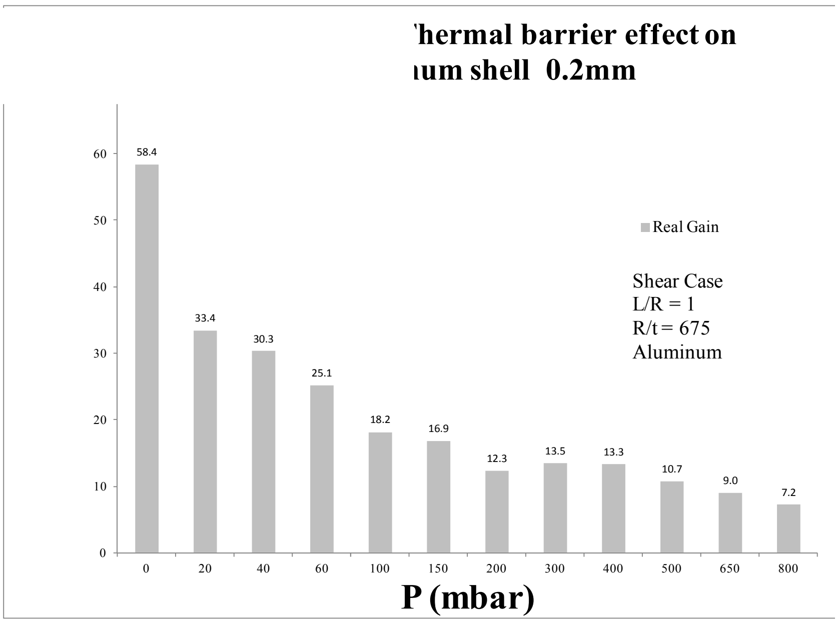

Figure 9. Foam gain compared to non covered shells

Without pressure, the foam increases the resistance of the shell of about 60%. As the pressure increases, the foam has no more so much effect and tends to increase the critical load to 7% for high pressure.

4 Numerical shear analyses

The numerical analyzes are conducted with finite element codes using the software Abaqus. The analysis also indicates that a suitable gain on the bearing capacity can be obtained with this concept of multilayered foam-metallic shells. A classical approach with multilayered shell elements is proposed and gauged comparatively to the experiments.

In the case of a perfect adherence between the two layers, and considering a perfect shell simulation, experimental and numerical results in shear case are in good agreement.

The graphic Fig. 10 presents the evolution of normalized stresses with Yamaki [9] stresses in function of the adimensional pressure.

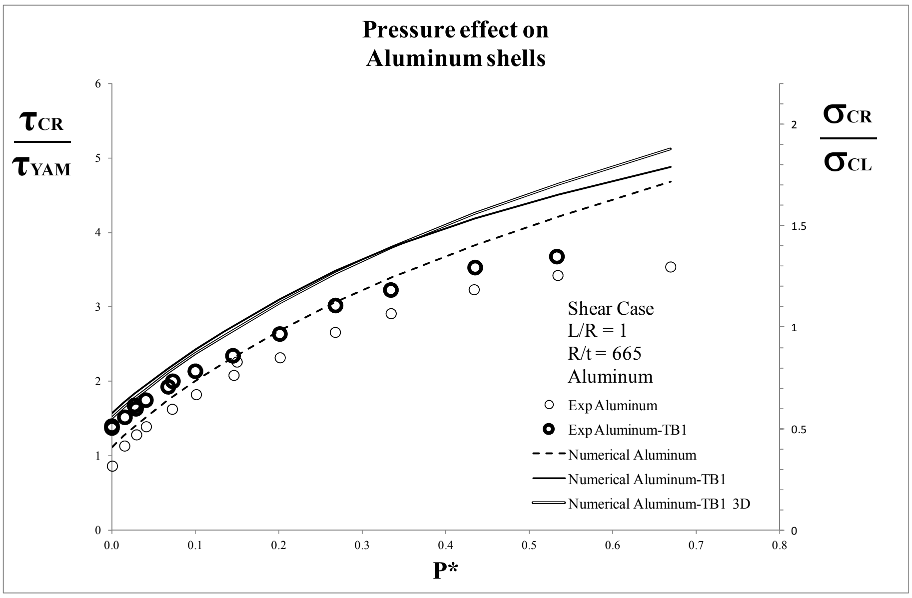

Figure 10. Numerical and Experimental Shear curves, R/t = 675, L/R = 1, aluminum

As well as the experimental results, the curves show the increasing of resistance for isolated shell compared to the non covered shells. Also, the higher the internal pressure is, the less the foam has an effect on the resistance of the shell.

These two series of experiments clearly show that using foam has a positive effect on the resistance of slightly pressurized shells, and these phenomena are not accounted for in the NASA SP8007 design recommendation. Results on Fig. 10 easily show that the critical point of bifurcation is twice higher than the theoretical Yamaki constraint for medium pressures (200 mbars), and increases until more than 3 and 5 times respectively for aluminum and steel shells in high pressure. Moreover, a simple internal pressure about 100 mbars can increase twice the bearing capacity of the structure going thru 300 percent and 800 percent in high pressure. Getting the upper hand over the geometrical defects, pressure has however an effect not so much efficient and could be fatal in high level due to a deformation of the skin.

5 Conclusions

Behaviour of thin pressurized shells under shear load is not really affected by the "membrane effect", the shell can actually be weakened at a level of pressure depending on the geometry of the shell and its material properties. Shear stresses are localized on the lateral side and move towards the compressed side and near the boundary conditions when the pressure increases.
With exactly the same characteristics, and the same calculus conditions, we can see that the foam increases the resistance of the shell; moreover, the foam moves the limit position of load or the limit pressure where the interaction falls from the shear to the flexion.
The foam layer contributes also to inhibit unstable post-critical behaviour. The enhancement of the buckling load hence goes with a decrease to the imperfection sensitivity. The numerical analysis conducted with finite element codes also indicates that a suitable gain on the bearing capacity can be obtained with this concept of multilayered foam-metallic shells. A classical approach with multilayered shell elements clearly shows the effect of this foam in the resistance of the shell, and is in good agreement with experimental tests.

Notation

E	Young's Module	δ_b	Shell displacement
R	Radius	σ_{cr}	Bending stress
t	Thickness of the scaled model	σ_{CL}	Theory stress
ti	Thickness of the foam	τ_{cr}	Shear stress
L	Lengh of the scaled model	τ_{YAM}	Yamaki stress
H	Height of transversal load		
P	Internal pressure		
P*	Adimensional pressure		

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