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Elastic buckling of pressurized thin-walled cylinders under bending : Effect of thermal barrier layer

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Abstract — The effect of thermal barrier layer (TB) on the buckling of pressurized thin-walled cylindrical shells subjected to bending has been studied with an experimental and numerical approach. The results show that the TB permits to increase the buckling capacity of the shell. As the internal pressure, the TB has also effect on the reduction of imperfection sensibility of the shell. This effect is only observed at the low level of pressure. Two important parameters of the TB: the thickness and the Young modulus were also investigated.

Keywords — Buckling, cylindrical shell, bending, shear, thermal barrier layer.

1 Introduction

This research work was conducted to improve the buckling design of the Main Cryogenic Stage (EPC) of the Ariane 5 and Ariane 6 space launchers. The EPC is composed of different aluminum cylindrical shells which are very thin and therefore are susceptible to buckle. We are particularly interested in the design of the main cryogenic tank under "ground load case" before the flight (Figure 1). In this case, the cylinder is subjected principally to bending and a slight internal pressure ($0 \leq p \leq 100\text{mbar}$). The buckling design is based mainly on the NASA SP8007 standard [1]. Moreover, the EPC is equipped with a thermal barrier layer (TB), which is not taken into account for buckling analysis, knowing that mechanical characteristics of this layer are very low comparatively to aluminum characteristics. Even if this thermal layer is constituted by extremely light material, which exhibits very weak mechanical characteristics, its effects on buckling capacity have to be gauged. The contribution of this layer to the buckling capacity is therefore here questioned.

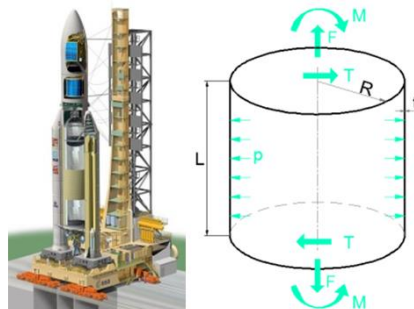


Figure 1. Ariane 5 launcher - "ground case"

In order to fully understand TB effect on the buckling behavior, and to build a database necessary for a new design rule, a large experimental campaign was carried out on appropriate thin cylindrical shells ($440 \leq R/t \leq 1350$, $L/R = 1$). Numerical calculations using ABAQUS (FEM) code was also conducted and a good correlation with the experiments has been observed. The study is then extended to evaluate the influence of different material and geometrical parameters mainly thickness and Young modulus of the TB layer.

2 Buckling stresses

The study [2] shows that the theoretical buckling stress under pure bending is equal to the bifurcation stress for a shell under uniform axial compression ([3],[4],[5]), which is called also classical stress:

$$\sigma_{CL} = \frac{E}{\sqrt{3(1-\nu^2)}} \frac{t}{R} \quad (1)$$

The tests ([6],[7]) confirmed the similarity between uniform compression buckling and pure bending buckling of a thin cylindrical shell. For both cases, the buckling is characterized by bifurcation point, with unstable post-buckling behavior. The buckling mode is by blister, which appears at the compressed site, the whole surface of the shell for axial compression, along and near the compressed generator for bending case. The critical buckling stress of a real cylinder is lower than the theoretical critical stress and obtained experimental critical stresses are very scattered. Several research studies have been conducted to find the reason of this disagreement, and finally the authors attributed the origin to mainly the three following factors: geometric imperfections, boundary conditions, inelastic effects. The geometric imperfections are the main source of dispersion [8] and explain the gap between classical theoretical value and obtained experimental values.

For the design, imperfection sensitivity is taken into account via a reduction factor, or knock-down factor, applied to the theoretical stress. Hence, the NASA SP8007 rule defines the buckling stresses under bending:

$$\sigma_{cr} = \alpha_M \cdot \sigma_{CL} \text{ with } \alpha_M = 1 - 0.731(1 - e^{-\frac{1}{16}\sqrt{\frac{R}{t}}}) \quad (2)$$

3 Experimentation

Experiments are conducted on scaled models. The cylindrical shells are fabricated using the rolling-bonding process. Two rings are positioned at the extremities of the shell, to ensure the boundary conditions and permits loads introduction via assembly jig. To obtain a cylindrical shell with thermal barrier, a layer of extruded polystyrene foam is bonded with double-sided tape to the metallic external skin. Several geometrical and material parameters are studied. The radius $R = 132\text{mm}$ and $L=135\text{mm}$ are unchanged for all tested specimens. Nominal thickness varies between 0.1 and 0.3 mm. The main geometrical characteristics are therefore $L/R \approx 1$, and $440 \leq R/t \leq 1320$. For the shells, three metallic materials are considered: aluminum (Al), steel (St) and copper (Co). The TB layer (polystyrene) has a constant thickness $t_c = 3.7\text{mm}$, one to three layers have been considered. For each constitutive material (metallic shell and polystyrene), mechanical tensile tests were conducted to characterize the stress-strain curve.

Figure 2 shows the scheme of the experimental setup. The possible variation of the height of the lever arm allows loading the shell mainly in bending or shear, or bending-shear interaction. For this study, the lever arm length is chosen to guaranty buckling under bending load. The specimen is clamped on bottom by 36 bolts, and fixed in the same way with a thick steel ring at the top. The transversal load is generated by a pneumatic jack. The internal pressurization of the shell is obtained with compressed air and controlled with a pressure transducer. Four displacements transducers (LVDT) fixed on the two end rings permit to determine the relative motion between the top and the bottom of the shell. A camera captures the deformation of the shell during the test.

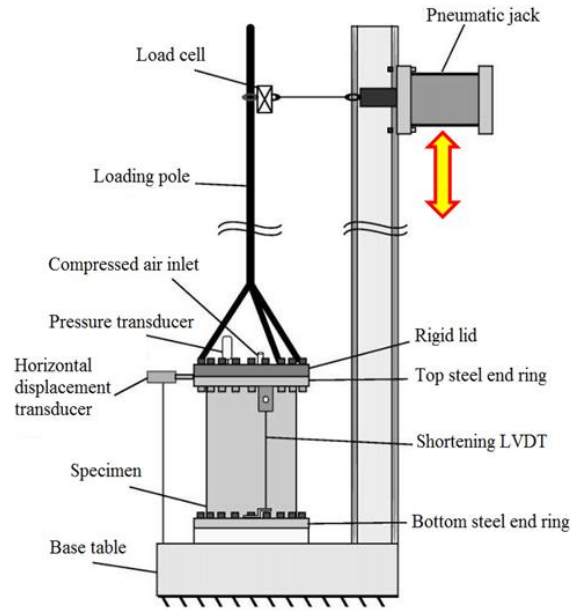


Figure 2. Scheme of the experimental set-up

4 Numerical modeling

Numerical simulations were conducted using the commercial finite element program ABAQUS [9]. Figure 3 and Figure 4 show the numerical model for perfect and imperfect configurations. Boundary conditions adopted for the simulation are selected to be consistent with those for the experiments. A reference point RP was created at the center of top edge of the shell to define loads and boundary conditions. A coupling constraint (or beam-type multi-point constraint MPC) connect this reference points to the end nodes of the shell to generate a rigid body. The weight of experimental equipment and the tensile load induced by the internal pressure (bottom effect) are taken into the axial load (N). The modeling was performed via 4-noded linear curved shell elements (six degrees of freedom per node) with reduced integration. The element aspect ratio is fixed at 1:1. The shell with TB is considered as a multilayered shell (metal/polystyrene composite material). This is consistent with the assumption of perfect adhesion between the skin and the foam (TB).

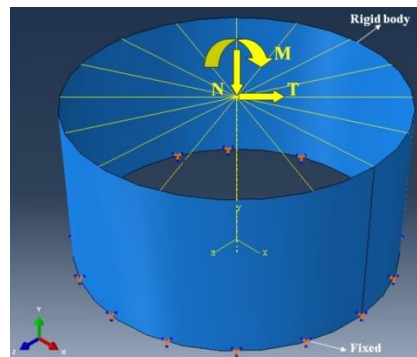


Figure 3. Scheme of the numerical model

The linear bifurcation analysis (LBA) and nonlinear analysis with the modified Riks nonlinear solution algorithm, without imperfection (GNA-Geometrical nonlinear analysis) or with imperfection

(GNIA-Geometrical nonlinear imperfect analysis) were conducted. The behavior and also the buckling load of the cylindrical shell depend not only on the size of the defect but also on its shape. Many forms of defects have been proposed, such as the localized inward bump or single blister type defect [10], the generalized axisymmetric defect, called also Koiter defect [11] and studied also by Hutchinson [12] [13], or the localized axisymmetric defect proposed and studied by different researchers ([14] [15],[16], [17]). For this study, a simplified modeling approach is considered, with the input of an inward axisymmetric triangular defect [15] [16] (Figure 4) into the shell geometry. This simplified geometry allows us to conduct numerous simulations and shows relevant results.

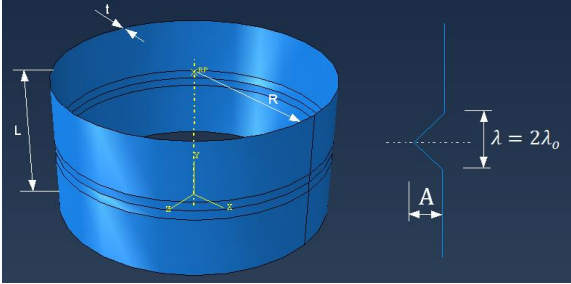


Figure 4. Axisymmetric triangular defect for bending case study

5 Results

The load-displacement curves obtained for copper shells under bending, with (CM437) or without TB (CL467) are shown in Figure 5. The load corresponds to the horizontal force applied at the top of the lever arm. For all cases, a linear pre-buckling path is terminated by a bifurcation point (marked with a circle) where the load decreases very rapidly. The post-buckling is unstable and corresponds to a dynamic process. One point after the buckling is kept to show the far post-buckling response. As the rigidity of the TB is very low, it does not influence the overall rigidity of the structure. It can be seen here that the initial rigidity represented by the slope of the load-displacement curve is identical. However, experimental and numerical results show that the TB improves the bearing capacity of the shell.

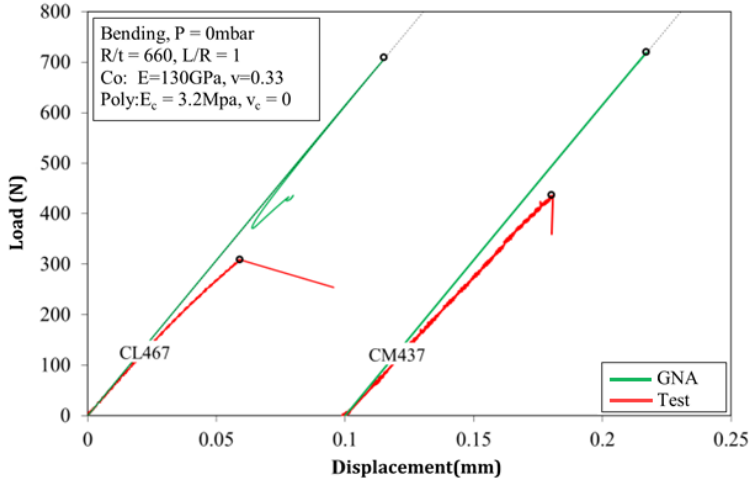


Figure 5. Load displacement curves for shells with and without TB

The thermal barrier doesn't change the shape of the buckling mode as we can see in Figure 6.

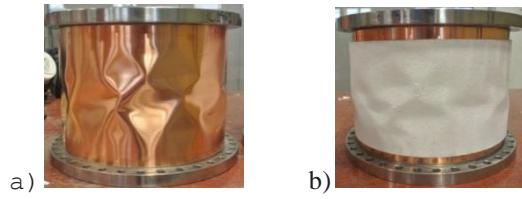


Figure 6. Bending modes, a) without TB, b) with TB

The Figure 7 and Figure 8 show the gain (%) of bearing capacity induced by the foam in function of the thickness (t_c) and the modulus (E_c) of the TB. The two parameters are normalized according to the geometrical metallic shell characteristics. The experimental results are compared to linear and nonlinear analysis without defect (LBA and GNA). We see well that the thinner the shell, or the higher the relative thickness (t_c/t) or relative stiffness (E_c/E), the higher the gain.

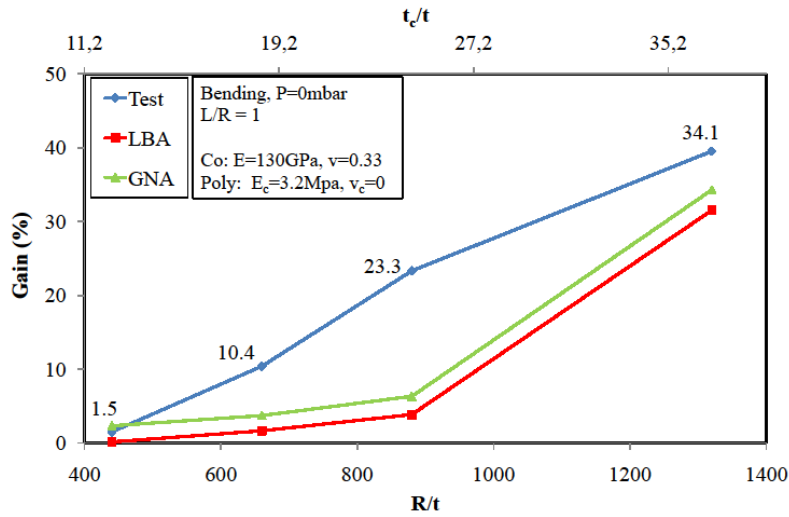


Figure 7. Gain for bending case: Effect of t_c/t

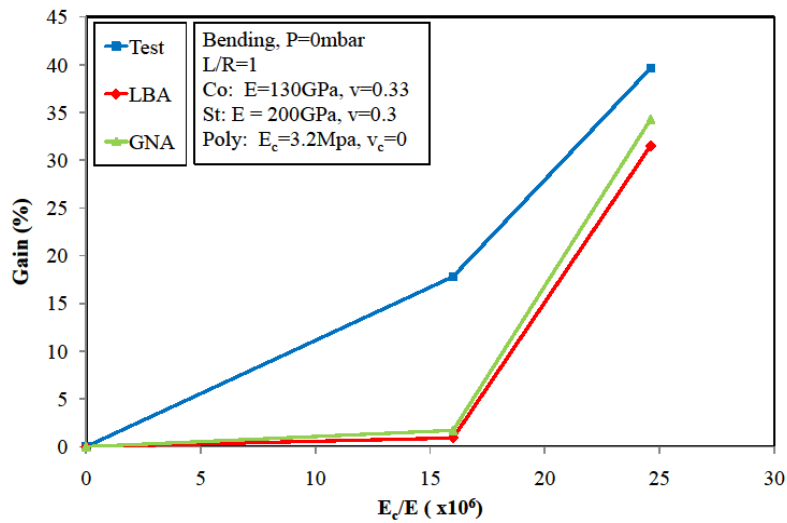


Figure 8. Gain for bending case: Effect of E_c/E

However, the experimental gain seems greater than observed on the simulations. So the

nonlinear analysis with defect is conducted to evaluate the imperfection sensitivity of the shell with TB. The Figure 9 confirmed that the critical load of the multilayered (foam-metallic) shell is always greater than the smooth shell for any amplitude of the defect. Furthermore, the TB contributed to decrease the imperfection sensitivity. For the perfect shell ($A/t = 0$), the TB conducts to a gain of about 15% for the configuration studied here. And the gain is more important for the imperfect shell. For example, for $A/t = 1.5$, the gain can reach 30%.

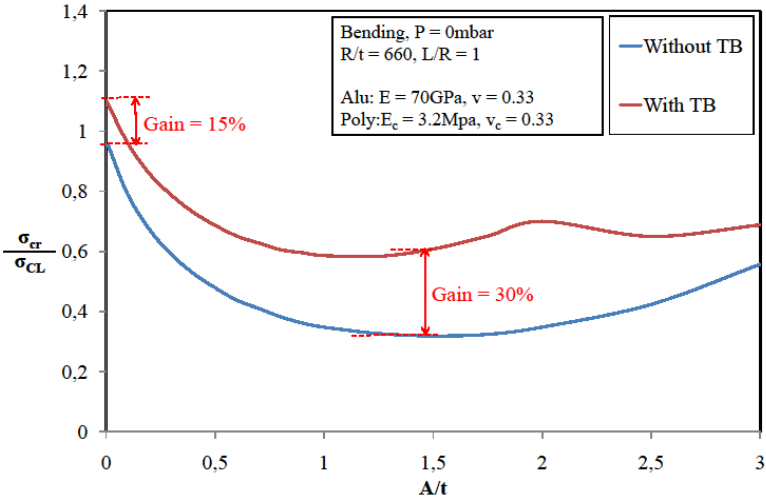


Figure 9. Gain in bearing capacity induced by the TB, depending the imperfection amplitude (GNIA)

All the test and GNIA calculations with and without TB at the different levels of pressure are grouped in Figure 10. The dimensionless pressure parameter $P^* = P/E(R/t)^2$ was also presented, and here $P^* < 0.225$ which corresponds to a low internal pressurization. The results confirm that both TB and internal pressure have a strengthening effect on the buckling stress. The gain induced by the TB seems more important at the low pressures and decreases as the pressure increases because the pressure has also the effect of reduction of imperfection sensitivity. The experimental results and their numerical confirmation show that the NASA design standard is too conservative and can be greatly improved.

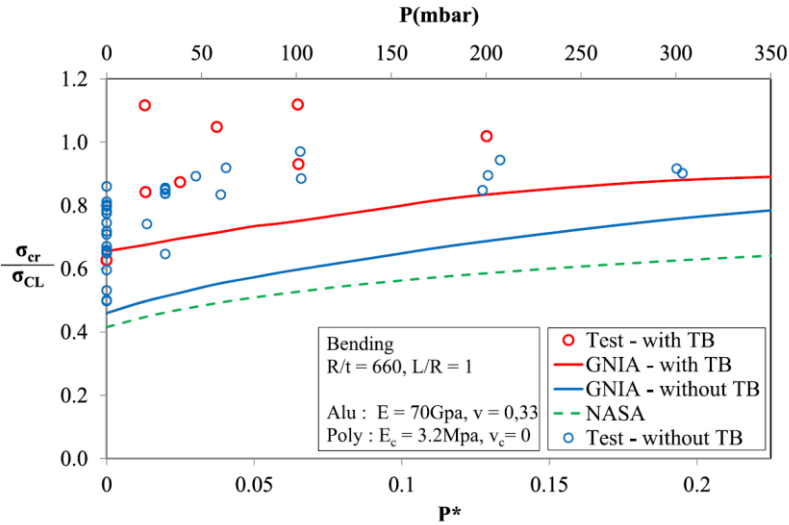


Figure 10. Effect of internal pressure and TB

6 Conclusions

This numerical and experimental study leads to the following conclusions. The effect of TB and internal pressure improve clearly the buckling capacity of the cylindrical shell under bending. As the pressure, the TB reduces the imperfection sensitivity of the shell. This effect of TB is valid at the low pressure. Finally, the NASA design standard is too conservative and can be greatly improved.

7 Abbreviations and acronyms

R	: mean radius of cylinder
L	: length of cylinder
t, tc	: wall thickness of cylinder and TB
E, ν	: Young's modulus, Poisson's ratio of skin
E _c , ν_c	: Young's modulus, Poisson's ratio of TB
T	: shear load
M	: bending moment
P	: internal pressure
P*	: dimensionless pressure parameter

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