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Numerical Simulation of Impact Behaviour of Structures with Internal Pressurization for Crash-Adaptive Concept

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This study presents an alternative approach for the absorption of impact energy that uses the internal pressurization of structures in the framework of a crash-adaptive response. Numerical simulations were conducted on the axial impact of thin-walled tubular structures with circular cross-section that serves as an approximation to a front crash box of a motor vehicle. The main objective of this work consists in studying the effect of internal pressurization of tubular structures in a crashworthiness application, as well as the possibility to obtain a reduction in wall thickness thus improving weight efficiency. A numerical study is presented for an internal pressure of 20 bar and tubular structures of circular section and 1.14 mm thickness. Numerical simulations were performed by making use of the LS-DYNA explicit dynamics software, while considering for the material a stainless steel alloy that is a material with interest for crashworthiness applications and manufacturing requisites due to its balance between strength, ductility, and energy absorption. The results obtained allow the conclusion, that with respect to internal pressurization it is feasible to reduce the wall thickness and have an impact resistance identical to the original while improving overall efficiency.

Key words: numerical simulation, LS-DYNA, energy absorption, crashworthiness.

1. Introduction

Currently there is an increase in vehicle speeds, as is frequently reflected in an increase of accidents. In order to reduce the impact on occupants as well as the financial cost, manufacturers have been investing in the development of vehicle structures while considering increasing requirements of crashworthiness. With technological progress, new solutions for systems that absorb impact energy have been presented.

Moreover, reducing the weight of a vehicle structure has become a major concern in the automotive industry. In fact, a weight reduction of car structures will cause a reduction in fuel consumption and therefore a decrease of pollutant emissions. Theoretical studies show that a 100 kg reduction in the weight of a car could save 0.2 to 0.5 litres of fuel per 100 km, assuming a normal propulsion mechanism and depending on the usage scenario [1].

However, to date, thickness reduction of a given component must involve the use of materials of higher strength and frequently higher manufacturing cost. In order to counteract this, the need arises for the use of alternatives for structural design, drawing up new strategies and devices for energy absorption. These devices can be reversible or irreversible [2]. Reversible devices are characterized by absorbing and returning energy at impact, not suffering any permanent damage to its structure. The irreversible device absorbs impact energy becoming deformed permanently, for example, as a thin-walled tubular structure with circular cross-section.

Up to now, crash adaptive safety applications are introduced in passenger cars mainly for interior, restraint, and seat applications. The optimization and pre-activation of restraint systems in advance of a physical impact lead to various benefits, such as lower speed deployment of the driver and passenger airbags, as well as improved belt action due to pre-strengthening. Having sensor information available, one has the ability to prepare vehicle structures in advance of an impact and obtain a controlled crash response resulting on a tailored crash pulse.

Having crash performance, weight restrictions, and packaging aspects in mind, one technical solution that appears as an attractive approach to create overall benefits is the use of pressurized structures. Two approaches can be used [3, 4]:

- In the first approach the initial structural shape of the crashworthy components remains unchanged during pressurization, therefore, pressure has to be adjusted carefully.
- In the second approach the implementation is performed in a way that the structure expands from a small cross-section to a larger one when being pressurized. This effect can provide great benefits, such as packaging benefits or extending the crash length.

In this work, emphasis is given to a mechanism for energy absorption of irreversible type and corresponding to the first approach (pressurization without plastic deformation – Fig. 1). The study is performed according to numerical simulation of the impact behavior of a thin-walled tubular structure, consisting in this approach to a front crash box of an automobile. This structure has circular cross section and internal pressurization will be implemented in order to allow a reduction in wall thickness (Fig. 1). Consideration will be given to the impact speed of the EuroNCAP frontal crash test (64 km/h) and a common Drop Test (36 km/h). As regards to the impact mass, this is set numerically as a moving rigid wall of 76 kg. The material used to simulate the component will be a austenitic stainless steel (Nirosta H400) due to its excellent mechanical properties that give it a possible use in structures designed for crashworthiness [5]. The simulations are performed using LS-DYNA, a well known software used to solve various engineering problems in areas such as, crashworthiness, occupant protection in vehicles, metal deformation, drop test, impact at high speeds, and biomedical and seismic analysis, among others [6].

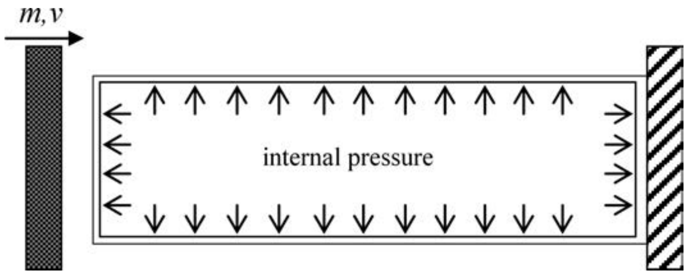

Fig. 1. Concept of pressurized cylindrical tubular structure.

Initially, a first study is performed as a numerical simulation of a tubular structure with circular cross-section of 1.14 mm thickness, which fits the hypothesis of using the same internal pressurization. The purpose is to study the influence of pressure in the interior of a structure for crashworthiness applications.

In the following step is analyzed the possibility to obtain a reduction in wall thickness of the tubular structure, using an internal pressure of 20 bar in order to attempt to compensate for the reduction in material thickness. This pressure value is usually obtained in airbag applications. Comparisons are performed between different thicknesses and internal pressure combinations. A measure of the structural efficiency for crashworthiness purposes (η) is used in the analysis through Eq. (1.1) [2], where P_m is the mean crushing load, A is the section area, and σ_y is the yield stress of the material. The mean crushing load is defined by Eq. (1.2) with δ_f as the total displacement and E_a the absorbed energy,

$$\eta = \frac{P_m}{A\sigma_y}, \tag{1.1}$$

$$P_m = \frac{E_a}{\delta_f}. \tag{1.2}$$

2. Numerical model

The crushing behaviour of thin-walled tubes was investigated with an explicit elasto-plastic finite element code: LS-DYNA. This code uses a Lagrangian formulation with a finite element mesh fixed in the material that distorts with it.

The equations of motion are integrated in time explicitly using central differences. The method requires very small time steps for a stable solution, thus it is particularly suited for impact and crash simulations though less appropriate for equilibrium structural analyses.

The finite element model is presented in Fig. 2. In the model considered, triggers are present to initiate the deformation on a prescribed position, and therefore obtain a more controlled crushing process and reduce the maximum force. The tubular structure is assumed to deform under the following constraint conditions: one end is fixed, with all degrees of freedom constrained in the distal surface nodes, and the other end is impacted by a rigid wall having a mass m and travelling with initial impact velocity v. The model was constructed using 4 node quadrilateral Belytschko-Tsay shell elements with 5 through-thickness Gauss points. An average element size of 5 mm was used. Geometric imperfections were introduced in the form of nodes displaced 0.5 mm out of plane in sympathy with the expected mode of collapse in order to trigger the analysis. Material model number 24 ("Mat_Linear_Isotropic_Plasticity") from the LS-DYNA model library was used. The true stress-strain curves were introduced in LS-DYNA, the material curve used is presented in Fig. 3 [5]. The strain-rate dependence was included through the Cowper-Symonds coefficients D and p [5]. A summary of the material properties used is presented in Table 1. The contact between the mass (rigid wall) and the specimen was modelled using a "Contact_automatic_nodes_to_surface" interface with a friction coefficient of 1.0 to prevent any sliding between specimen and wall. To account for the contact between the lobes during deformation, a "Contact_automatic_single_surface" algorithm with friction coefficient equal to 0.1 was specified.

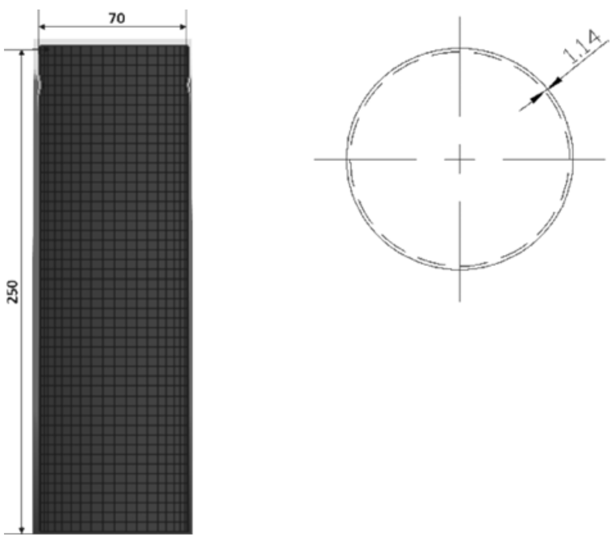

Fig. 2. Numerical model LS-DYNA and tubular section.

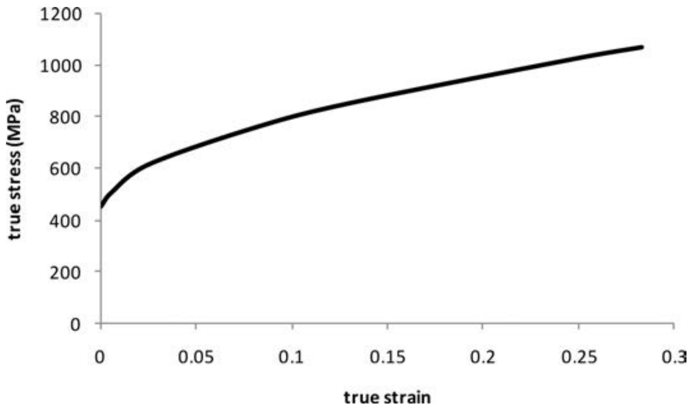

Fig. 3. Characteristic curve of austenitic stainless steel H400 [5].

Table 1. Material parameters used in numerical simulation [5].

	E [MPa]	ρ [Ton/mm^3]	σ_y [MPa]	σ_r [MPa]	Cowper-Symonds Constants	
					D [s^{-1}]	p
Stainless Steel H400	210e+5	7.38e-9	453	799	1150	7.75

The internal pressure was applied using the keyword *load* and option SHELL_SET to apply pressure to the internal shell surface within the prescribed duration time of the test, corresponding to a constant pressure application.

3. Results and discussion

3.1. Influence of internal pressure

Table 2 shows the tests initially carried out on tubular structures with a thickness of 1.14 mm. At this stage the target is to study the influence of internal pressurization at 20 bar. It should be noted, that with reference to additional internal pressure, this means that the internal pressure at 0.0 MPa is atmospheric (0.1 MPa which is approximately 1 bar). The nomenclature used is the following: **Test Name = Thickness_Impact Speed_Aditional Inside Pressure.**

Table 2. Tests carried out initially on 1.14 mm thickness structure.

Test name	Thickness [mm]	Impact velocity [mm/s]	Pressure [MPa]	Impact mass [kg]
1.14_10014_0.0	1.14	10014	0.1	76
1.14_10014_2.0	1.14	10014	2.0	76
1.14_17777_0.0	1.14	17777	0.1	76
1.14_17777_2.0	1.14	17777	2.0	76

Results for this study can be observed in Table 3, where δ_f is the total displacement, E_a is the energy absorbed, P_m is the mean crushing force, and η is the efficiency of the structure for crashworthiness purposes, as defined by equation (1.1) [2]. The percentage improvement of P_m is also given. Considering the tests conducted the same impact velocity, we can observe that the total displacement was reduced with the introduction of internal pressure while the mean load and the efficiency of the structure also increased. Figure 4 illustrates the load vs

Table 3. Results for initial tests conducted on structure with 1.14 mm of thickness.

Test name	δ_f [mm]	E_a [kJ]	P_m [kN]	P_m improv. [%]	η [%]
1.14_10014_0.0	54	3.9	72.4	–	64.8
1.14_10014_2.0	46	3.7	82.0	13.3	73.5
1.14_17777_0.0	159	12.1	76.0	–	68.1
1.14_17777_2.0	131	11.9	90.7	19.33	81.3

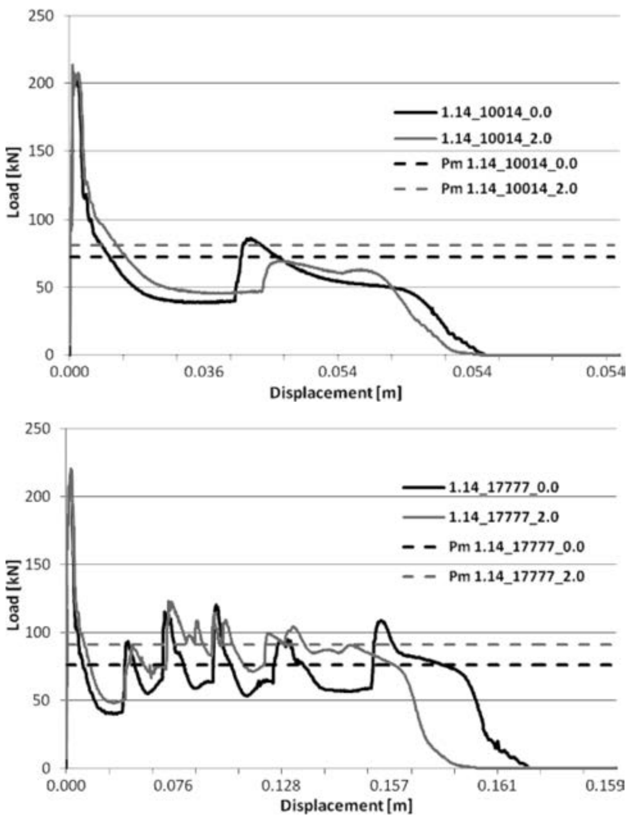

FIG. 4. Load vs. Displacement curve as tests results for 1.14 mm wall thickness structure.

displacement curves for these initial tests as well as the associated mean crushing forces. Figure 5 presents deformed shapes observed during the simulation test, where it is noted that the collapse mode does not change significantly with the introduction of internal pressure.

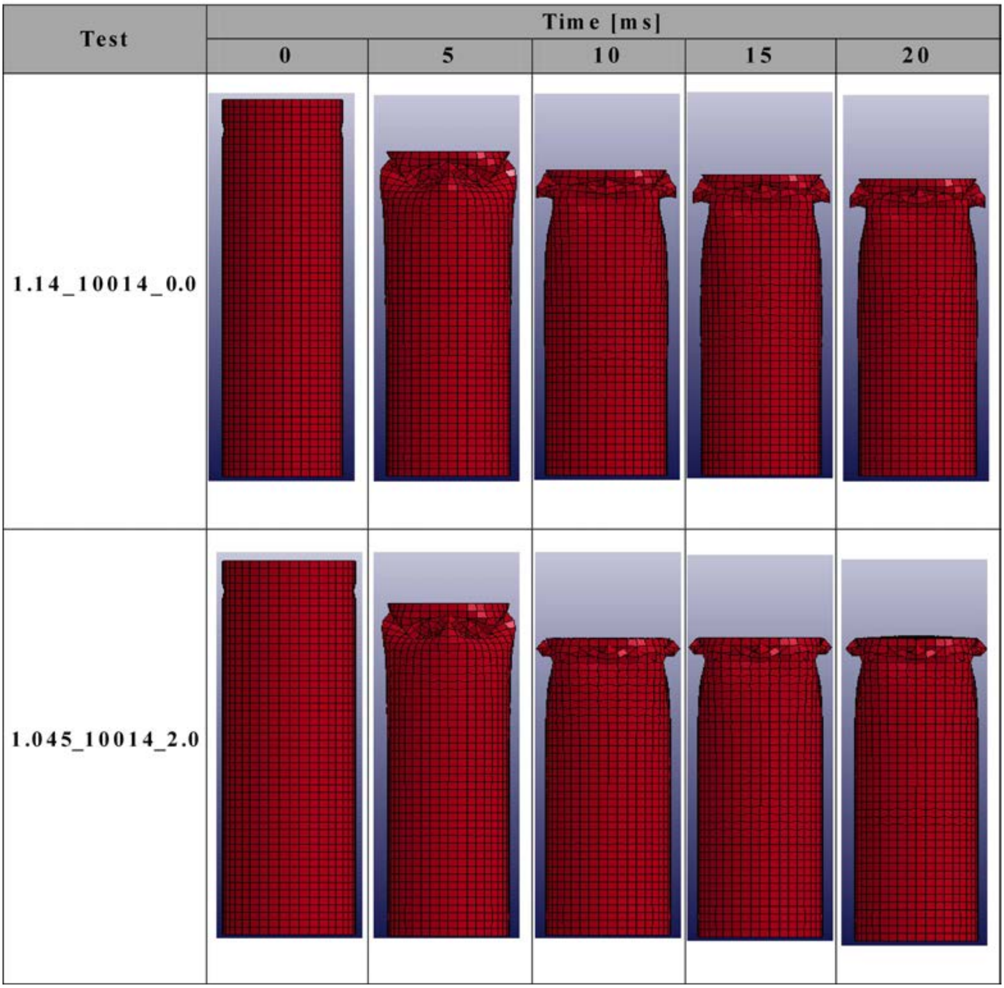

Fig. 5. Deformed shapes during simulation.

3.2. Thickness reduction

In this second stage, a study was conducted as regards the possibility of reducing the wall thickness of the structure. It was desired to maintain the same impact performance by introducing an internal pressure of 20 bar in the structure so as to offset the reduction in material thickness. Several tests were conducted at the higher speed of 17777 mm/s, which gradually reduced the wall thickness to internal pressurisation of 20 bar. The objective was to compare the displacement of the structure with a thickness of 1.14 mm without the aditional internal pressure and the displacement of the new thinner structure with internal pressure of 20 bar. The results are presented in Table 4 and Fig. 6.

Table 4. Strategy for determination of new thickness.

Velocity [mm/s]	17777					
Internal pressure [bar]	1 bar	20 bar				
Wall Thickness [mm]	1.14	1.08	1.06	1.05	1.045	1.04
δf [m]	0.159	0.152	0.155	0.158	0.159	0.160

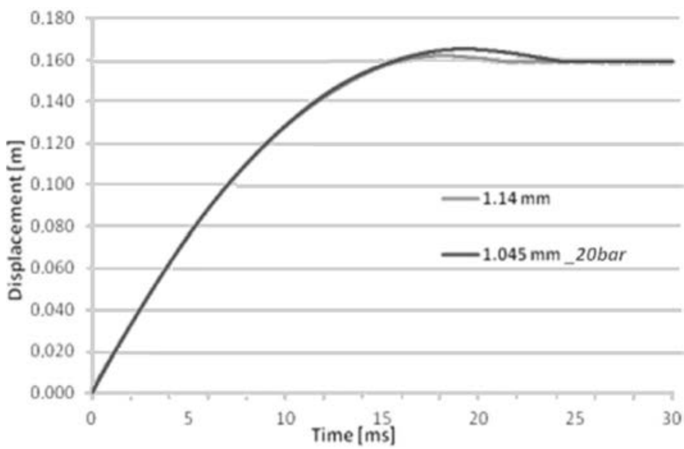

Fig. 6. Displacement vs. time curve used to determine new wall thickness.

The same total displacement was obtained for the structure with a thickness of 1.14 mm without internal pressure and the structure with a thickness of 1.045 mm with 20 bar of internal pressure. Therefore a new circular tubular structure with wall thickness of 1.045 mm was considered for further analysis. In Table 5 the results are presented for this new structure, including the per-

Table 5. Results for tests conducted on structure with 1.045 mm of thickness.

Test	δ_f [mm]	E_a [kJ]	P_m [kN]	P_m improv. [%]	η [%]
1.045_10014_0.0	67	3.9	58.6	–	57.1
1.045_10014_2.0	55	3.8	68.8	17.4	67.1
1.045_17777_0.0	189	12.1	64.0	–	62.4
1.045_17777_2.0	159	11.9	74.6	16.6	72.8

centage improvement for the new thickness. Figure 7 illustrates the variation of the mean load and load vs displacement curves for the tests conducted on the tubular structure with a thickness of 1.045 mm (for two velocities, with and without additional inside pressure).

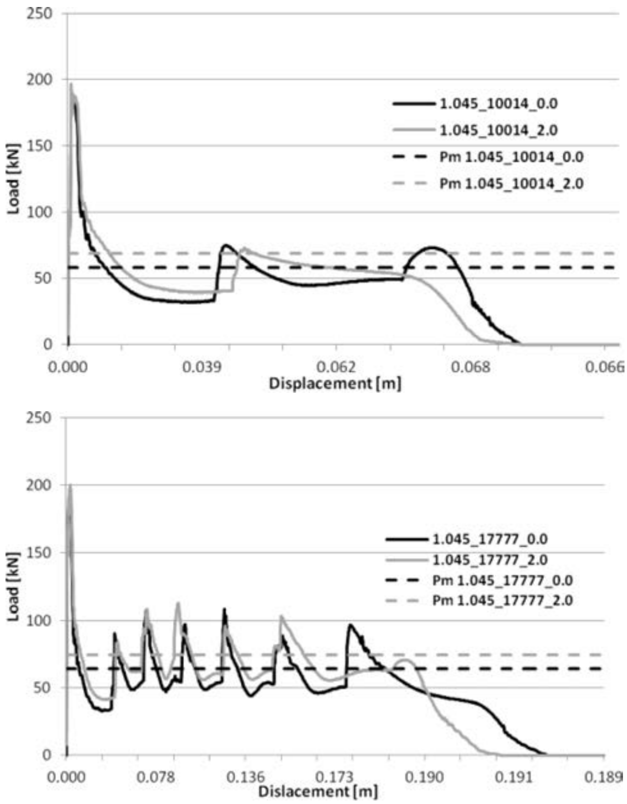

Fig. 7. Load vs. displacement curves as tests results for 1.045 mm wall thickness structure.

3.3. Comparison of results

Considering the results obtained in the simulation for the two structures, it is important to obtain a comparison between them, especially the first for non-pressurized tests (original thickness) and additionally the second with internal pressure of 20 bar (structure with 10.45 mm thickness). In Table 6 the comparitive results are compared. Figure 8 presents load vs displacement curves and the associated mean crushing forces.

For the same impact speed, identical results were obtained for both structures (1.14 mm vs pressurized 1.045 mm). The total displacement, energy absorbed,

Table 6. Comparison of results for both structures.

Test	δ_f [m]	E_a [kJ]	P_m [kN]	η [%]
1.14_10014_0.0	0.0539	3.9	72.4	64.8
1.045_10014_2.0	0.0548	3.8	68.8	67.1
1.14_17777_0.0	0.1592	12.1	76.1	68.1
1.045_17777_2.0	0.1593	11.9	74.6	72.8

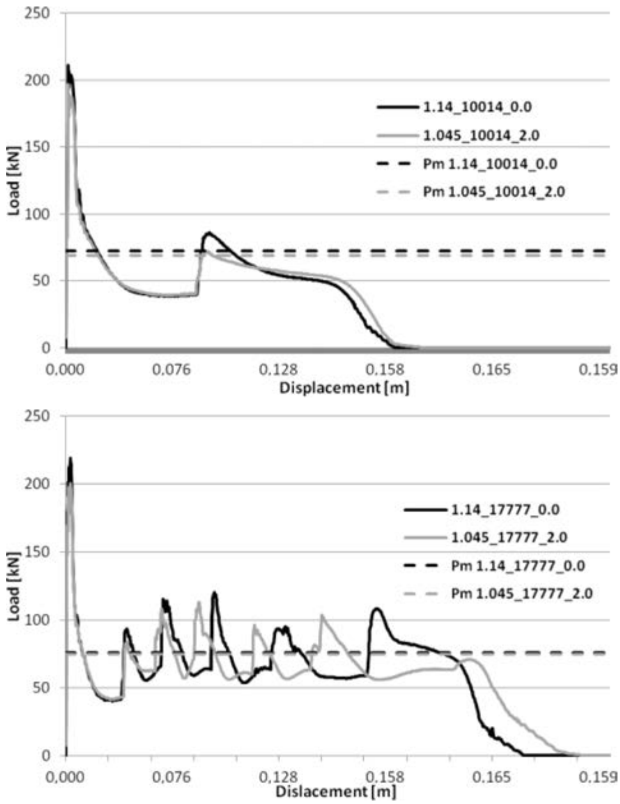

FIG. 8. Results Comparison with load vs. displacement curves for both impact velocities.

and mean load were similar considering the intended purpose, while crash efficiency increased.

4. Conclusions

A numerical study was performed on the simulation of a tubular structure with circular section and thickness of 1.14 mm, which fits in the type of structure for crashworthiness application. The purpose was to study the influence of pressure inside the structure for crashworthiness applications. Based on the available results it can be concluded that it is possible to increase the impact resistance of the structure with the introduction of pressure in its interior which would benefit from its use in crashworthiness applications. The deformation decreased with increased internal pressure and the average load increased. Therefore the structure efficiency increased with the introduction of internal pressure.

Subsequently the possibility to obtain a reduction in wall thickness of the tubular structure was studied using an internal pressure of 20 bar in order to attempt to compensate this reduction. Comparisons were made between the original structure with no pressure in its interior and the thinnest structure with 20 bar of internal pressure. The results obtained allow us to conclude that it is feasible to reduce the wall thickness and have an impact resistance equivalent to the original while improving overall efficiency. For the same impact speeds, the total displacement experienced by the structure is identical, the impact energy absorbed was practically the same and, even considering a decrease of mean crushing force, there is an increase in the efficiency of the structure for impact energy absorption.

The results obtained with numerical simulations show good indications for the validity of an adaptive crashworthiness concept wherein tube pressurization could act as an enhancement of energy absorption. Such final validation is dependent on experimental results, while the implementation of a pressurization scheme and deployement parameters could be better described with a coupled fluid-structure numerical model.

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