Étude comparative du comportement à l'impact de systèmes absorbeur d'énergie

Comparative analyses of impact behavior of energy absorbing circular tubes

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Abstract :

Many systems are submitted to violent loadings like shock or collision with other surrounding systems. Depending on their application, different means could be developed as a protecting system. In the present work, DCNS focuses on the crushed cylindrical tubes as energy-absorbing components. First, nonlinear finite element calculation is performed to simulate the elastic-plastic behavior of tubes with different shapes (stiffened tubes, circular tubes with buckling initiators, circular tubes with corrugated surface). Regarding results, a specific post-treatment was performed to evaluate the crush mode and the resulting force. Then, the work focuses on tubes with a corrugated surface which provide softer resulting force. The influence of different parameters has been studied like thickness or wavelength. Thanks to these finite element calculations, only tubes with corrugated surface have been manufactured and tested on an impact machine at different impact velocities. Through a force sensor measurement and a high-speed camera, the numerical and experimental correlation could validate the finite element approach and some future energy-absorbing system would be numerically tested.

Keywords : energy-absorbing tubes, corrugated surface, axial crushing

1 Introduction

In shipbuilding, many types of equipments on board need to be protected from shock and collision. Several means could be applied but one of the most widely used in transport industry is thin-walled circular tubes. Indeed, these components are employed for their high energy absorption capacity. When tubes are submitted to axial loading, the kinetic energy is dissipated through plastic deformation or inelastic buckling. Many authors have already studied the behavior of different shapes of tubes. Salehghaffari et al. [1] focuse on the numerical behavior of externally stiffened crush tubes.

Buckling is the predominant deformation mode. Therefore, it seems fair to be able to control this phenomenon in order to increase the dissipated energy. The efficiency of adding buckling initiators have been experimentally studied by Zhang et al [2]. Another way to control the buckling deformation mode is to modify the tube surface for example by using a corrugated surface (see Chen et al. [3]). Most of these papers provide some interesting responses as absorbing-energy components but all the proposed configurations have specific dimensions. These differences prevent any comparison to find the best solution for a specific application. Indeed, tube dimensions, especially the diameter, have a great influence on buckling.

Therefore, this study focuses first on a numerical comparison on three different configurations of tube with the same internal diameter. Depending on results, the following work analyses the influence of different parameters of tubes with corrugated surface. Finally, to validate the numerical approach, some experimental tests have been performed using an impact machine.

2 Samples description

2.1 Stiffened tubes

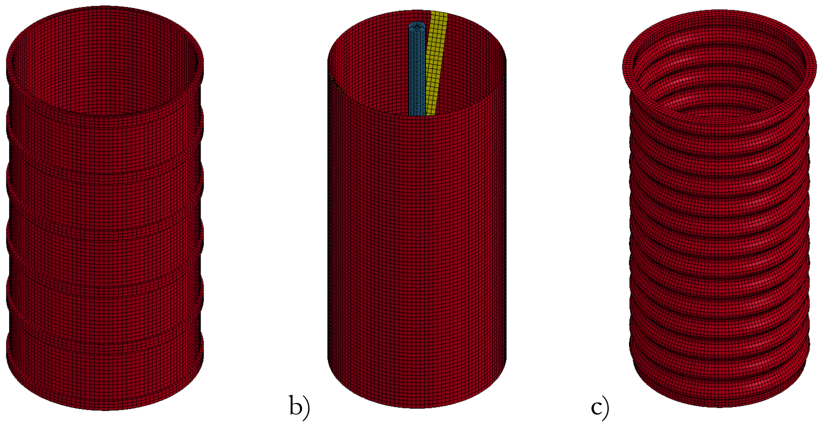
The inner diameter of the stiffener tube is 100 mm and the length is 200 mm. The ratio between the thin walled sections and stiffened areas are based on rules proposed in [1]. Therefore, the stiffened tube used in this study has six reinforced areas of 6.25 mm height each. Moreover, the tube thickness is 1.4 mm and the ring stiffeners induce an extra thickness of 1.8 mm. Regarding the finite element approach, this tube has been modeled with 26 260 hexahedral elements (FIG 1-a).

2.2 Circular tubes with buckling initiators

Based on the experimental tube proposed by [2], a circular tube with buckling initiators has been modeled using 10 864 shell elements (FIG 1-b). The global dimensions of this tube are: inner diameter D = 100 mm, length L = 200 mm and thickness t = 1.4 mm. The initiators consist in three pulling strips uniformly distributed around the top edge of the tube and a cylindrical column with a radius of 5 mm. The column is higher than the top edge of the tube by h = 25 mm. The initial angle between the strips and the horizontal level is θ = 60°.

2.3 Circular tubes with corrugated surface

Thanks to works of many authors [3-[4], introducing corrugations on tube surface seems to be a good way to control the compressive stress and the buckling mode of cylindrical tubes. In this study, different tubes with corrugated surface have been considered. All of them have an inner diameter D = 100 mm and a length L = 200 mm (FIG 1-c). The influence of different parameters has been evaluated such as the thickness, wavelength of the corrugation and the material properties. Moreover, these tubes have been numerically and experimentally tested with different impact velocities. Regarding finite element calculations, all tubes have been modeled with shell elements.



a) b) c)

FIG 1: FE models of different tubes (a- stiffened tube, b- tube with initiators, c- tube with corrugated surface)

3 Finite element calculation

All finite element (FE) calculations were performed using the explicit code LS-Dyna version 971. Two different methods were employed to simulate the impact. First, a moving rigid wall with a specific mass (200 kg) was used. The impact test machine also provides an increasing force. To take this force into account, the rigid wall was replaced by a solid quadrilateral part with the same specific mass on which an initial velocity was imposed.

All the samples, used in the first stage of this study, were modeled using S355 Steel properties. The elastic-plastic behavior is modeled by piecewise linear law based on experimental tensile data. The second stage on the study consists in taking into account the influence of different parameters on the mechanical behavior of tubes with corrugated surface. The experimental tests were mainly focused on this second stage. Due to manufacturing constraints, tubes could only be produced in aluminium 5083H111. Consequently, the elastic-plastic behavior of this other material was also modeled in the FE analysis using a piecewise linear law based on [5].

4 Numerical comparison between different tube shapes

All tubes are developed in order to absorb shock energy and reduce transmitted load. FIG 2 compares the evolution of transmitted force during impact for three different shapes of tube. Regarding results, all proposed configurations let damp the collision by the fact that the rigid wall is repulsed at the end but they seem to be oversized. Indeed, the mass (200 kg) and the initial velocity (4 m/s) induce only the deformation of the top of the tube (FIG 3). Nevertheless, depending on the tube shape, different responses could occur.

When the tube is stiffened, the peak load reaches the maximum value (168 kN) as soon as the rigid wall gets in contact with the tube. Then, due to buckling, the energy is progressively dissipated by plastic deformation of the first thin section. The initiators modify the mechanical response and transmitted load evolution. Indeed, at the beginning the energy is immediately dissipated by the deformation near the pulling strips. This phenomenon is mainly due to the fact that the cylindrical column is higher than the top edge of the tube. When the column is enough pushed down, the rigid wall gets in contact with the tube which immediately increases the transmitted force (FIG 2). At this stage the peak load reaches a maximum value of 103 kN.

Tube with corrugated surface provides a softer behavior during impact. Indeed, the corrugation enables the tube to crush progressively by the deformation of one period after another. As a result, the transmitted load remains constant (among 40 kN) during the impact till all kinetic energy is dissipated. This configuration seems to provide the best performance regarding damping by reducing all load peaks.

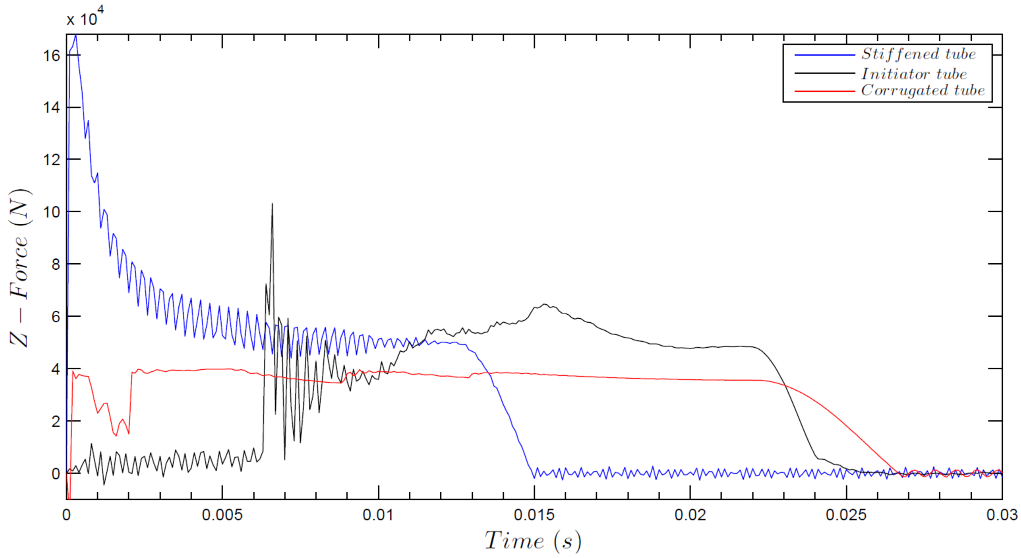


FIG 2: Comparison of Z-Force during impact

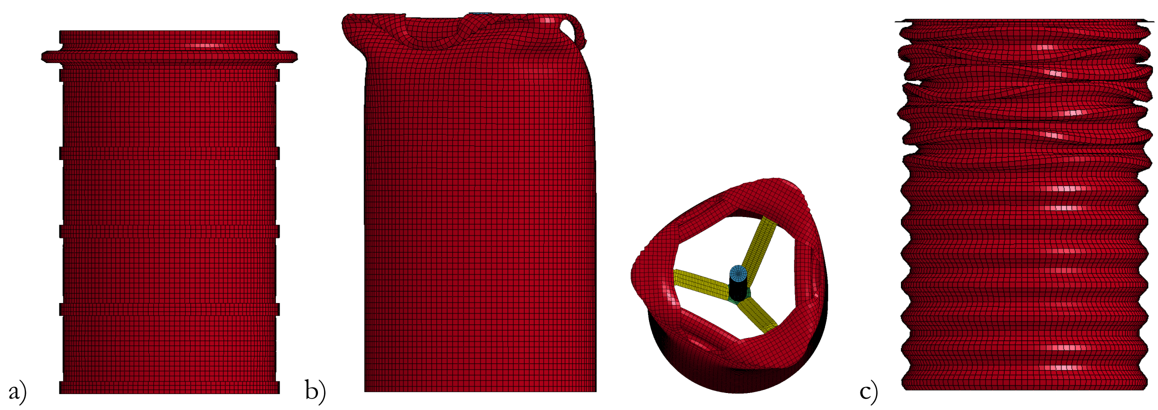


FIG 3: Deformation of different tubes after shock (a-stiffened tube, b- initiator tube, c- corrugated tube)

5 Impact tests

The first numerical stage of this study points out that the best configuration to absorb energy is a tube with corrugated surface. To validate the numerical approach, only this configuration has been experimentally tested on an impact machine.

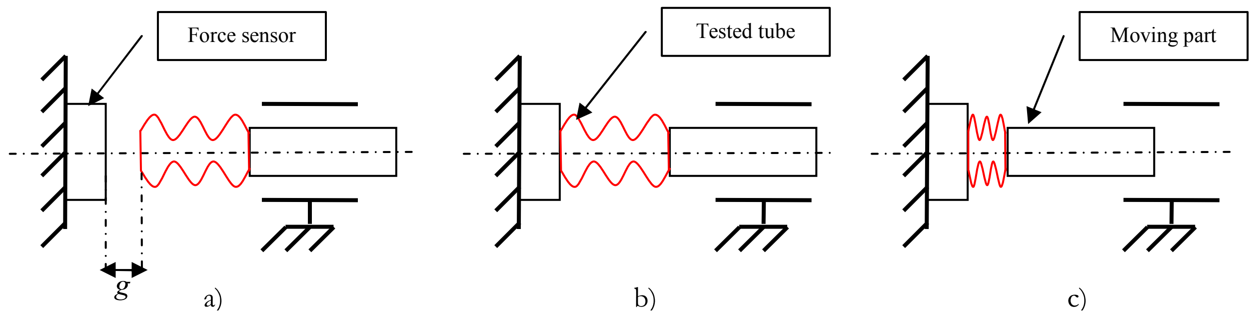


FIG 4: Principle diagram of the impact machine used

All tests were carried out with an initial gap "g" between the tube and the fixed support (FIG 4 – a and FIG 6 - a). Thanks to this, the impact velocity could be modified. As a matter of fact, the impact velocity increases with the gap. Moreover, due to the technology of the test machine, an additional force is applied on the impact tube. The evolution of this force depends on the impact velocity i.e. the initial gap. In the present study, tests were carried out with two different gaps (50 mm or 130 mm) as shown in FIG 5.

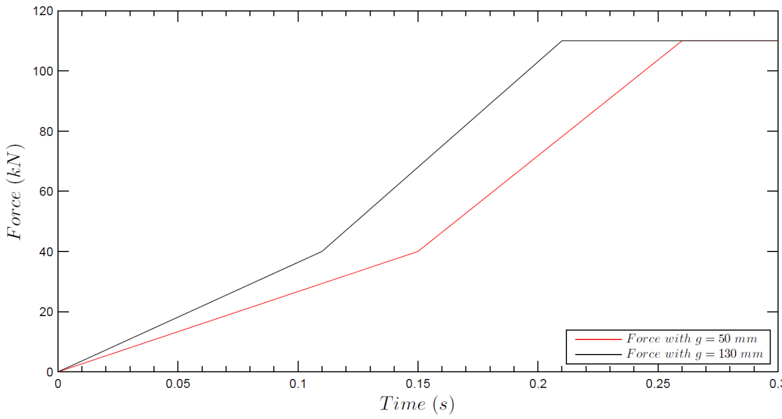


FIG 5: Evolution of additional force

The force sensor is placed on the fixed support in order to measure the applied force during impact. An actuator initiates the motion of the moving part until contact occurs between the tube and the force sensor (FIG 4 – b).The test ends when all kinetic energy is dissipated by the plastic deformation and buckling (FIG 4 – c). During the test, the force applied by the impact tube and the velocity of the moving part is monitored. FIG 6 - b shows two different samples: a tube before impact (on left) and after impact test (on right).

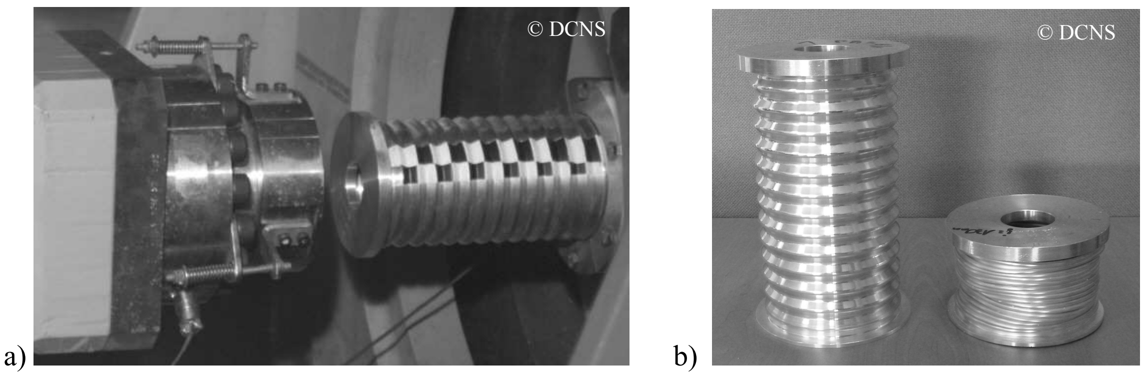


FIG 6: Overview of impact tests

6 Comparison between experiments and numerical response

When tubes have totally crushed, the elastic recovery induces an opposite displacement of the solid part which bounces several times. Experimentally this phenomenon could not occur due to the actuator which avoids the opposite motion. Consequently, the comparison between experiments and numerical response will only be studied until collapse.

Two different tests were performed with different initial gaps in order to determine the influence of impact velocity. Moreover, the same configurations were modeled to obtain the numerical response. FIG 7 compares both results regarding transmitted force and tube's velocity. As already observed (§ 4), corrugations reduces all load peaks. Moreover, these results point out a good correlation between experimental and numerical curves. With the lower velocity ($g = 50$ mm), the crush occurs gradually which induces oscillations (black curves). Increasing the impact velocity seems to facilitate the tube deformation and to reduce force and velocity variations.

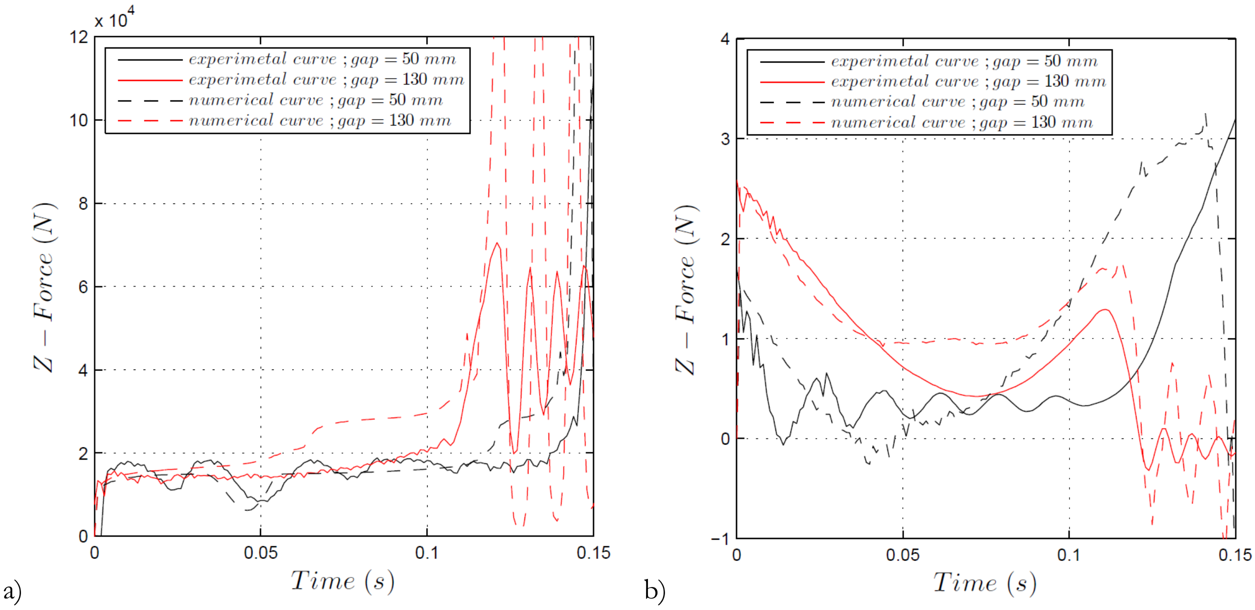


FIG 7: Experimental and numerical curves: influence of gap (Evolution of force (a) and velocity (b))

FIG 8 compares the evolution of force and velocity for tubes with different thicknesses. A higher thickness induces a higher stiffness. Consequently, the crush occurs with more difficulty. Indeed, the global energy (kinetic energy and energy induced by additional force) needs to reach a threshold to cause deformation. Before this threshold, some oscillations are observed (red curve). This phenomenon seems to decrease with a 1.4 mm thickness. To validate this trend, other tubes should be tested. Unfortunately, machine tools availability does not allow to manufacture thin tubes. Nevertheless, as above, results provide a good correlation between numerical response and experiments. The validation of the influence of thickness could be numerically carried on.

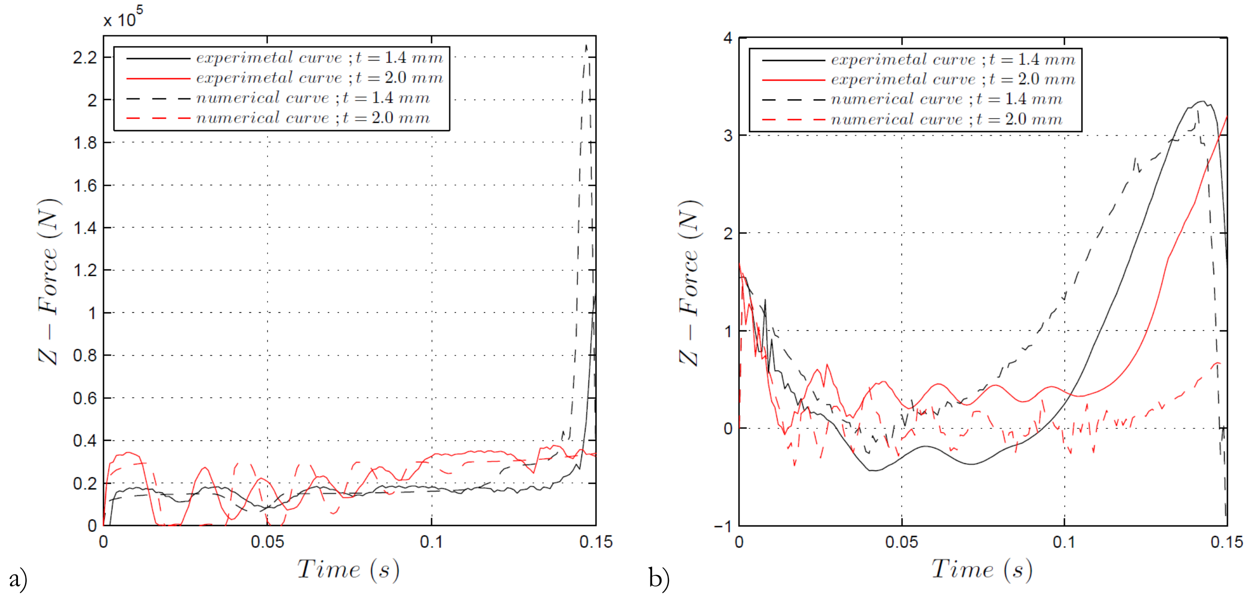


FIG 8: Experimental and numerical curves: influence of thickness (Evolution of force (a) and velocity (b))

Corrugated surface is used to facilitate deformation by controlling the compressive behavior. Consequently, the wavelength seems to have a great influence. To estimate this phenomenon, two different tests were performed with 11 mm and 14 mm-wavelength tubes (FIG 9). Both results point out a very good correlation between simulations and experiments. The too limited variation of wavelength does not permit to estimate the influence of this parameter and further calculations need to be performed with more significant variations.

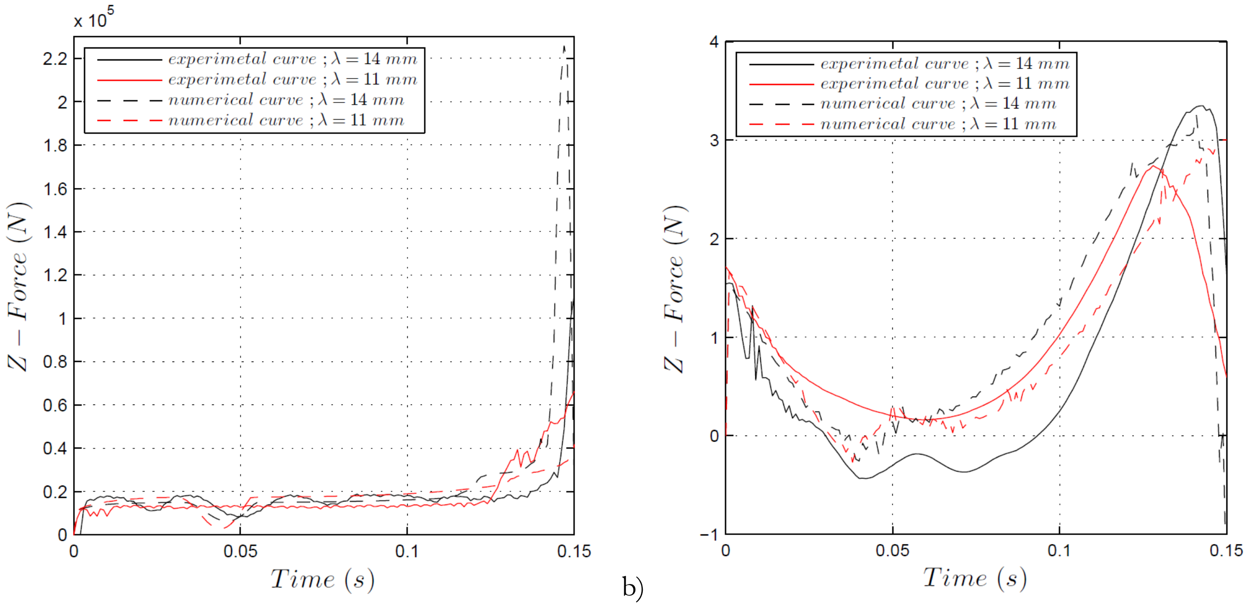


FIG 9: Experimental and numerical curves: influence of wavelength (Evolution of force (a) and velocity (b))

7 Conclusions and prospects

In this paper, the crush behavior of different energy-absorbing tubes was investigated using both explicit non-linear finite element calculation and experiments. The numerical comparison of the force evolution points out that tubes with corrugated surface provide best results to avoid all load peaks. .To validate the numerical approach, some experiments were performed on tubes with different thicknesses or different wavelengths. To estimate the influence of impact velocity, these tests were carried out with different initial gaps. All results indicate that a specific tube (coupling of thickness and wavelength) provides efficient behavior only for a specific impact velocity. However, the global aim of these energy-absorbing tubes is to protect equipments from various undefined shocks. The observed phenomena points out that finding a suitable tube for a wide range of shocks would be difficult. Nevertheless, good correlation between numerical and experimental data permits to numerically carry on investigations in order to define a tube with optimized parameters

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