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CRASHWORTHINESS PERFORMANCE OF FOAM-FILLED TUBES UNDER IMPACT LOADING

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Abstract- **This paper aims to explore the crashworthiness performance of designed foam-filled tubes under dynamic compression loading. The impact of empty and foam-filled thin-walled tubes was simulated by Abaqus software. The Kelvin cell is manipulated to enhance the crashworthiness performance of empty tubes. Detailed deformation features and energy absorption characteristics during the crushing process were presented. The numerical results showed that the foam-filled tubular structures presented new deformation modes, and have energy-absorbing effectiveness higher than those of the empty tubes. Furthermore, the obtained reaction force-displacement curves of foam-filled tubular structures exhibit three different stages, starting with a short linear stage, followed by a long plateau region at the second stage, and finished by a densification stage. Based on the numerical results, foam-filled structures were demonstrated as the best lightweight crashworthy structures.**

Keywords – Impact, Foam-filled thin-walled tubes, Kelvin cell, Deformation, Energy absorption

I. INTRODUCTION

Install energy absorption devices in vehicles became the most common approach to minimize the loss of life and property in an impact accident. The energy absorbers performance is usually evaluated through a crush test, by calculating the amount of absorbed energy during the impact [1-2]. An ideal shock absorber has a long constant stress plateau during the crash test.

Due to their high manufacturability and low cost, thin-walled tubes have been extensively employed as energy-absorbing devices to absorb kinetic energy through plastic deformation. Structural efficiency enhancement leads the researchers to study different materials and geometrical aspects of thin wall structures [3]. To improve the crashworthiness of thin-walled tubes without adding weight to the structure, cellular materials in particular lightweight foam material became the best candidate, it is employed as a filler for thin-walled tubular structures, due to its ability to absorb energy under compressive loading in a highly efficient manner. To this end, a large number of studies focusing on the crushing response of empty and foam-filled thin-walled tubes especially for circular and square cross-sections under axial loading have been published [4-5-6-7-8-9-10].

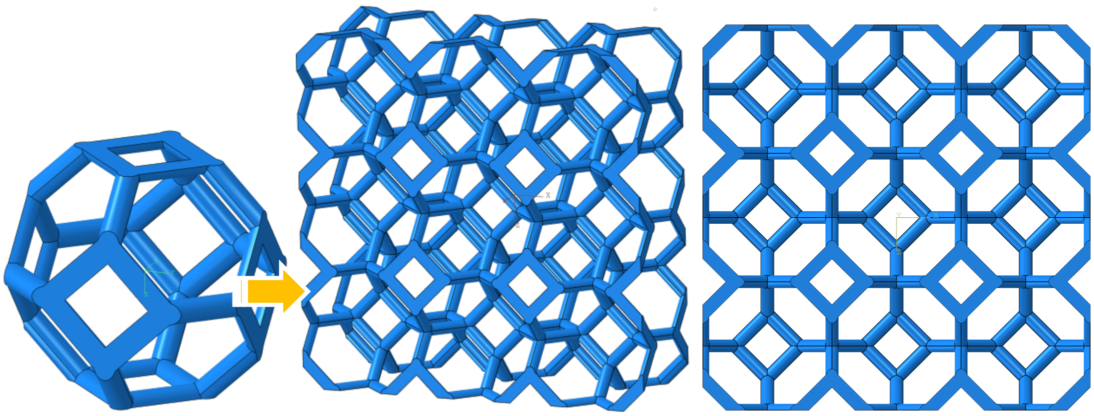
In this paper, the response and the energy absorption capability of designed foam-filled tubes based on Kelvin cells have been investigated numerically under dynamic compression loading, using the Abaqus software. The effect of cell diameter on the response mode has been studied by comparing the detailed deformation features and energy absorption characteristics during the crushing process. The paper is organized as follows:

- The description of the proposed foam-filled tubes structure and the finite element modeling are presented in section 2.
- The dynamic compression results are presented and discussed in section 3.
- The concluding remarks are given in section 4.

II. NUMERICAL MODELING

2.1 Geometry –

Figure 1 illustrates the analyzed open-cell model foam, in which Kelvin's tetrakaidecahedral cells are periodically arranged in a body-centered cubic lattice.



a *b*

Figure 1. Geometrical illustrations of the analyzed open-cell model foam. (a) Unit Kelvin cell, (b) Kelvin cell structure.

The designed kelvin cell structure with two different cell diameters d = 5mm and d = 10mm are used as a filler for thin-walled tubular structure as shown in Figure 2.

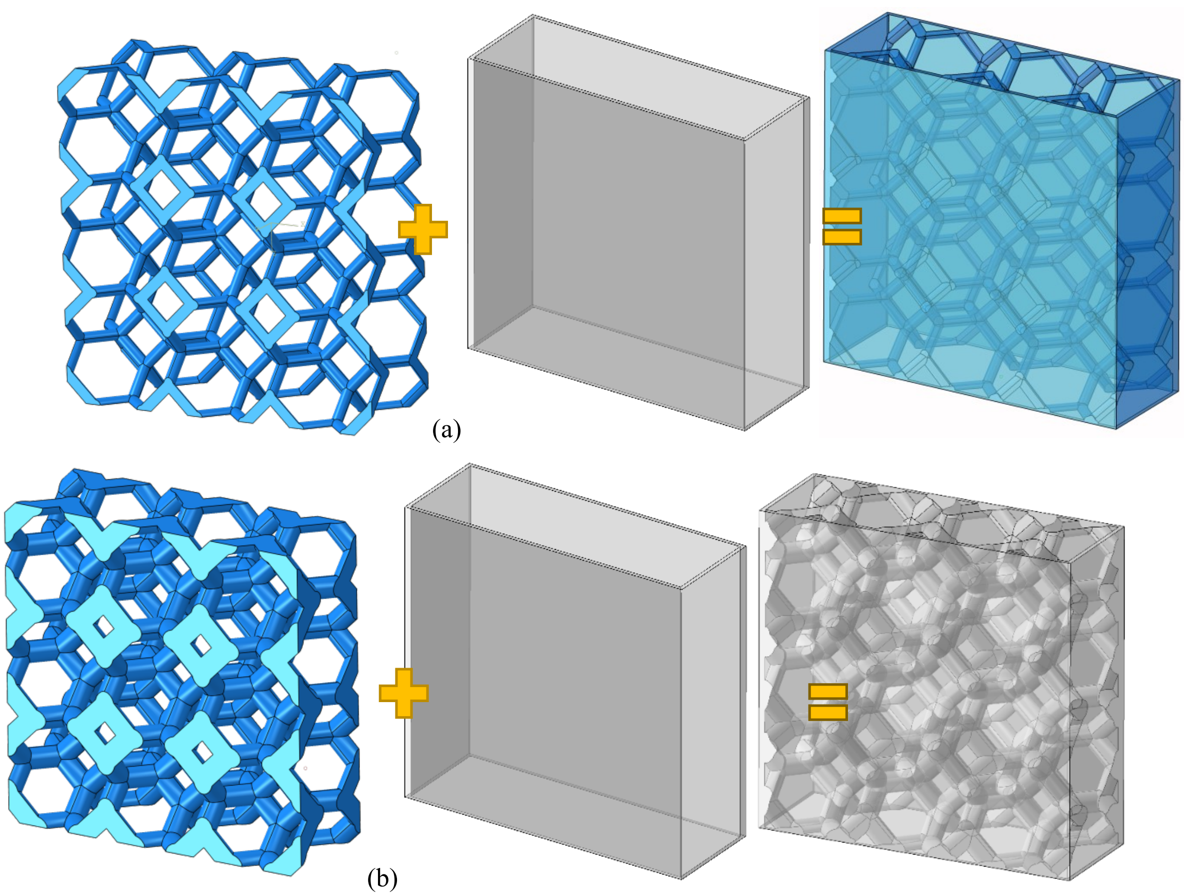


Figure 2. 3D CAD Model of the foam-filled thin-walled tube a) Cell diameter d=5mm and b) Cell diameter d=10mm.

III. FINITE ELEMENT ANALYSIS AND RESULT

To investigate the axial crushing performance of the proposed foam-filled thin-walled tube model, a 3D finite element (FE) model was developed in commercial code ABAQUS/ Explicit as shown in Figure. 3. The structure was supported by a rigid fixed lower platen and loaded by a rigid moving upper platen at a constant velocity of 15.2 m/s [11].

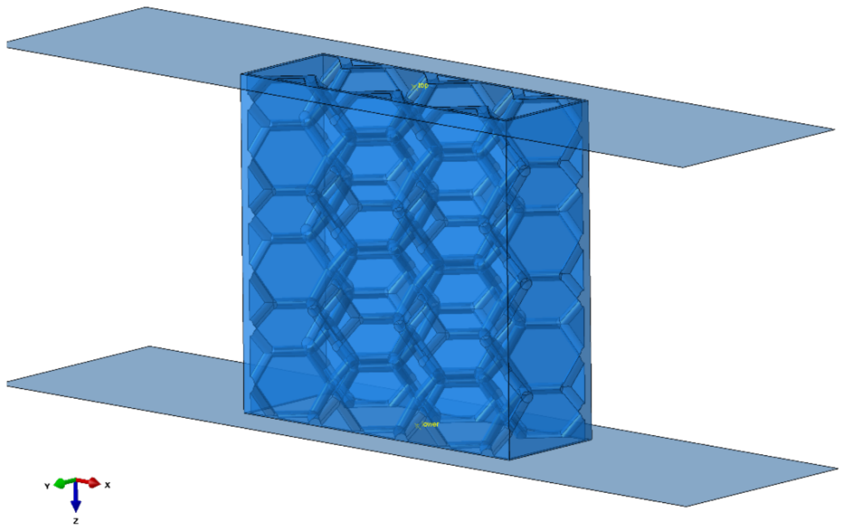
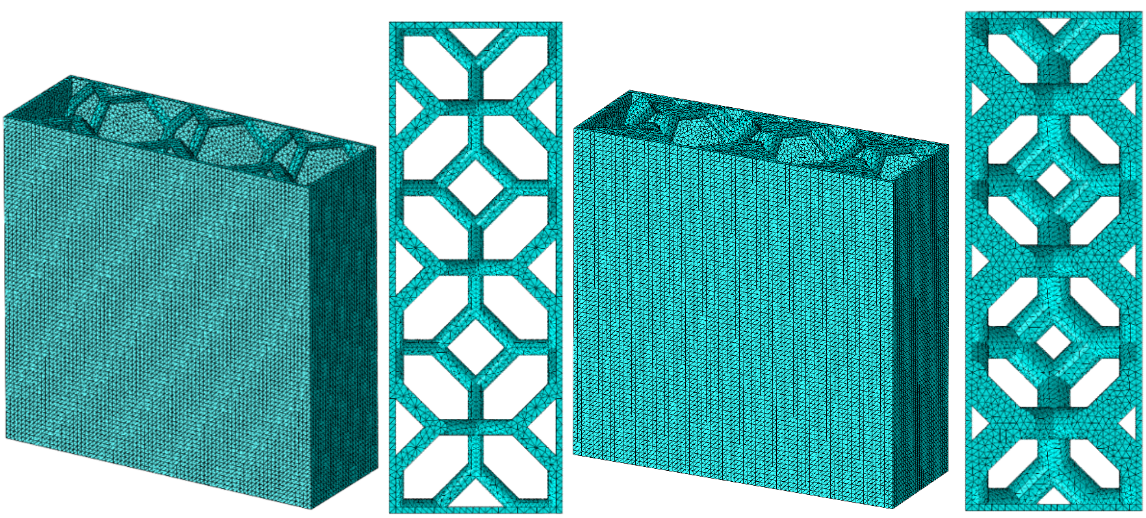


Figure 3. Numerical model of the foam-filled thin-walled tube and initial boundary conditions.

The foam structure is discretized using tetrahedralelements, and the thin-walled tubeis meshed withhexahedral elements, while the two remaining plates are meshed with shell elements as shown in Figure4.



(c) (d)

Figure 4. 3D FE model of foam-filled thin-walled tube. (a) d = 5mm (b)d = 10mm.

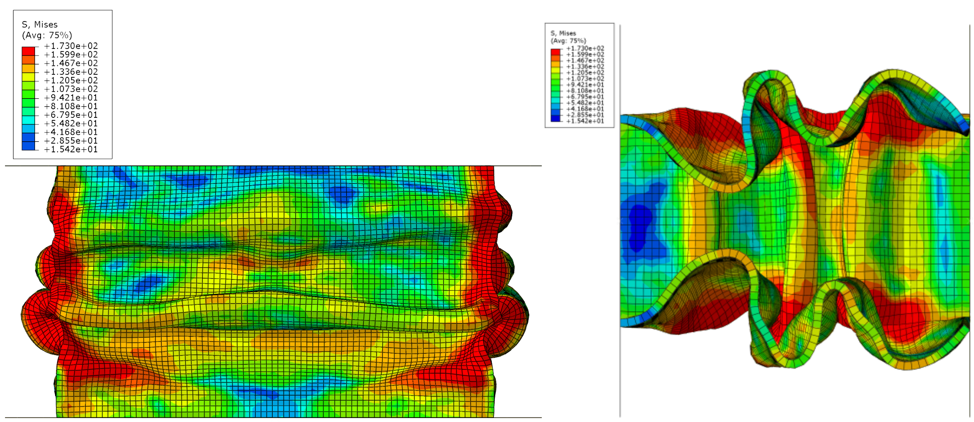
The foam-filled thin-walled tube parts are made from aluminum. The mechanical properties of the employed Aluminum are listed in Table 1.

Table 1. Material properties of Aluminium used in FE study [12].

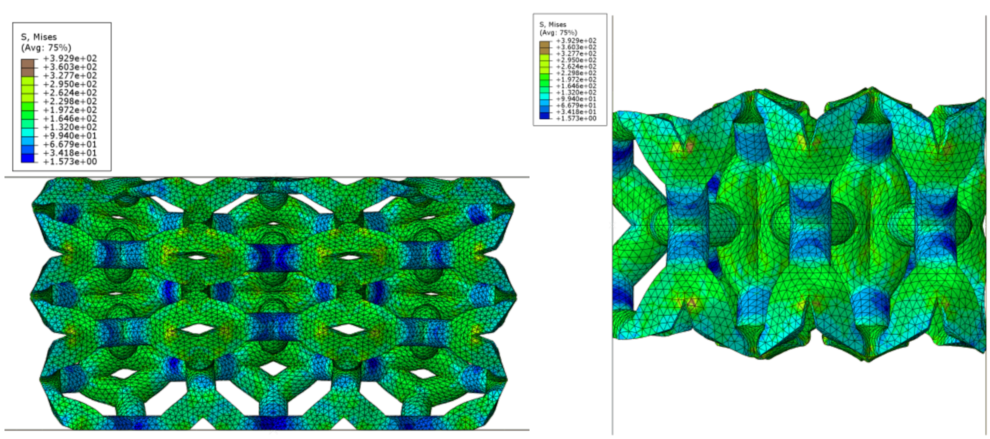
Density (tonne/mm3)	$2.71*10^{-9}$
Poisson's ratio	0.3
Young's modulus (GPa)	68.2
Yield-stress (N/mm2)	80
Plastic-stress (MPa)	**Plastic-strain**
80	0
115	0.024
139	0.049
150	0.079
158	0.099
167	0.124
171	0.149
173	0.174

The results of the numerical simulations presented below show the evolution of the Von Misses stress for the different studied configurations after an impact of 0.004s (Figure 5) and 0.008s (Figure 6).

- After an impact of 0.004s



(a)



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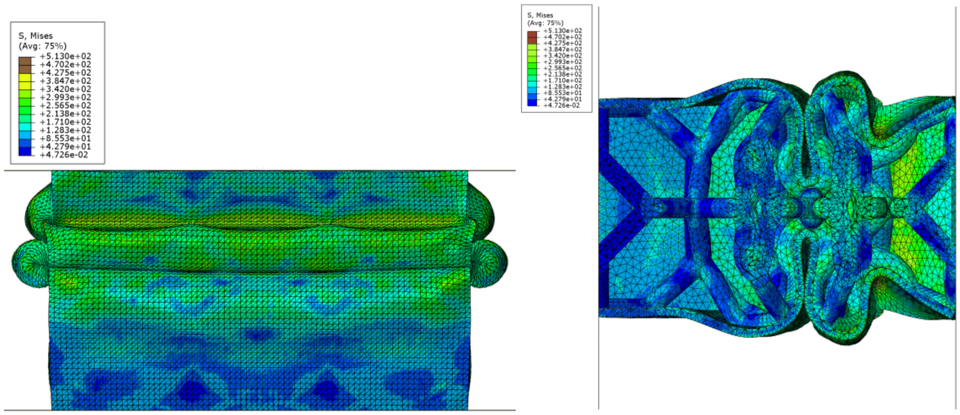

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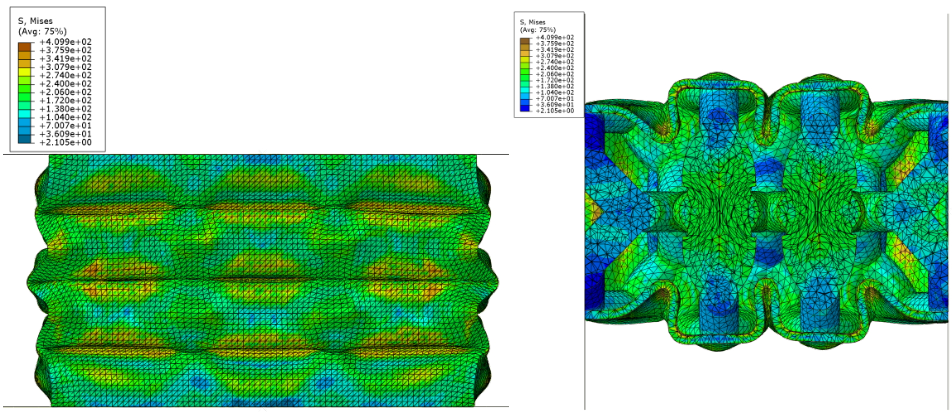
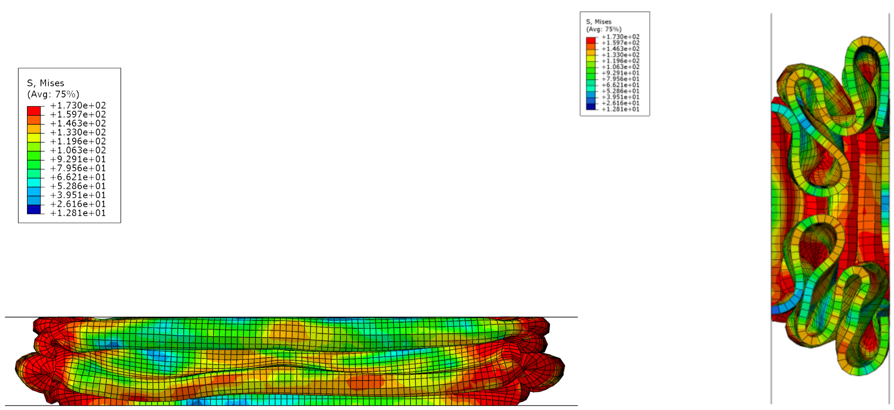


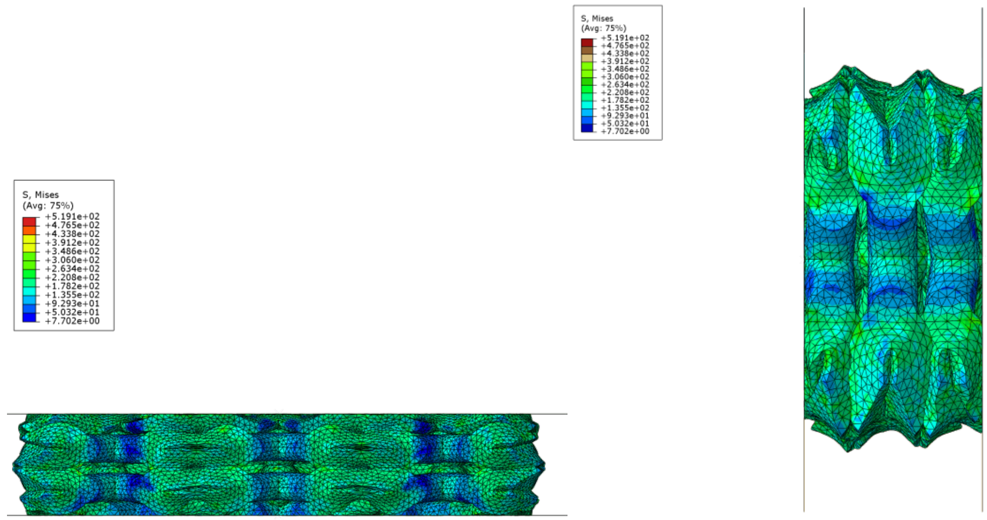
(d)

Figure 5. Comparison of deformation mode and Von Misses stress obtained in the studied structures, after an impact of 0.004s. (a) Empty tube(b)Kelvin cell structure, d=10mm (c) Foam-filled tubular structure, d=5mm (d) Foam-filled tubular structure, d=10mm.

- After an impact of 0.008s.



(a)


S, Mises
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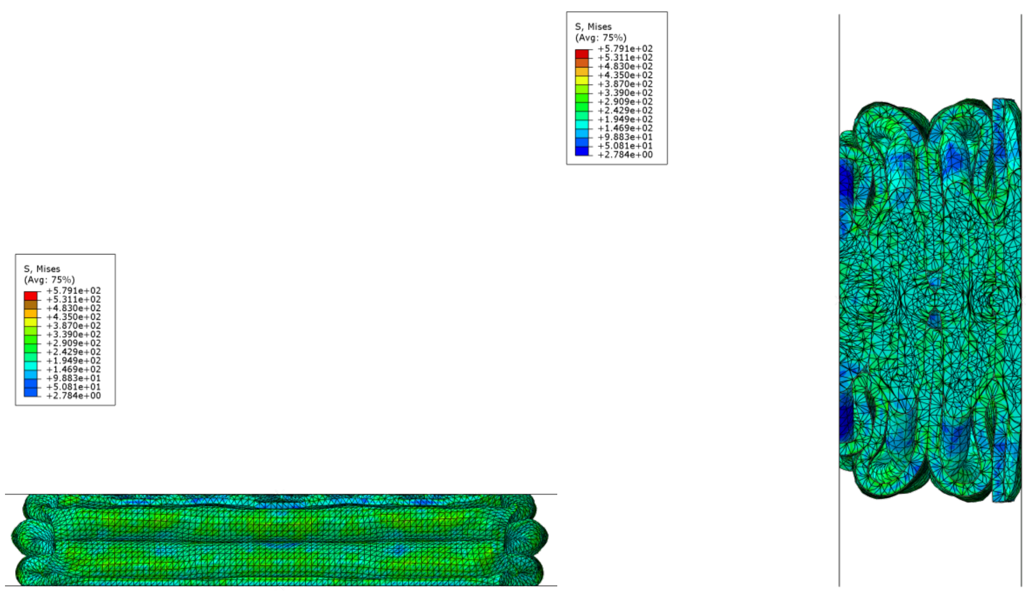
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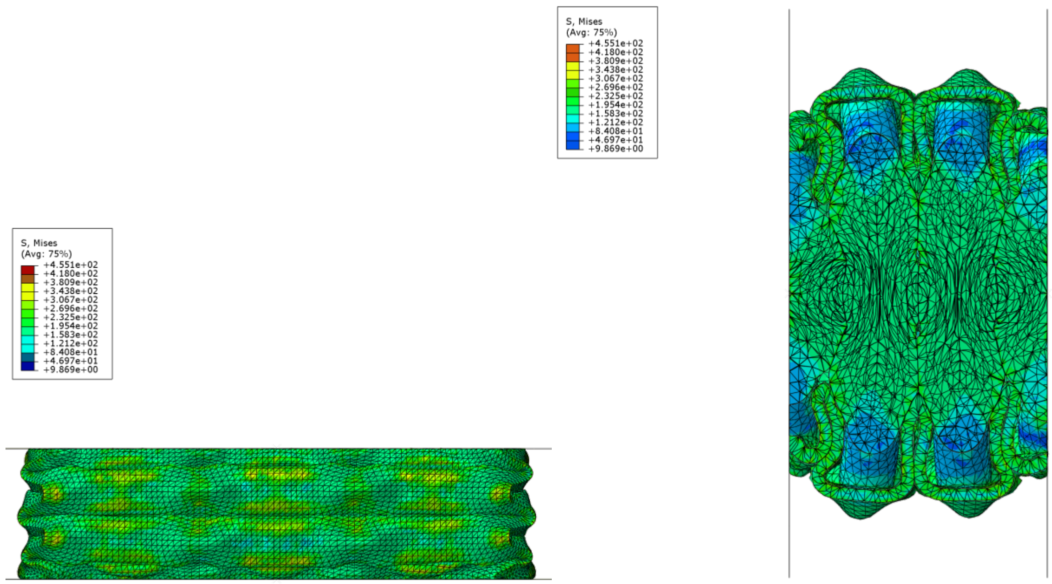

(d)

Figure 6. Comparison of deformation mode and Von Misses stress obtained in the studied structures, after an impact of 0.008s. (a) Empty tube(b)Kelvin cell structure, d=10mm (c) Foam-filled tubular structure, d=5mm (d) Foam-filled tubular structure, d=10mm.

In order to allow comparison, the obtained results for the empty tube, the foam alone, and the foam-filled tubular structure (d = 5mm and d = 10mm) are plotted in the same graph.

Figure 7 shows a comparison between reaction force-displacementcurves for the different studied configurations during the impact.

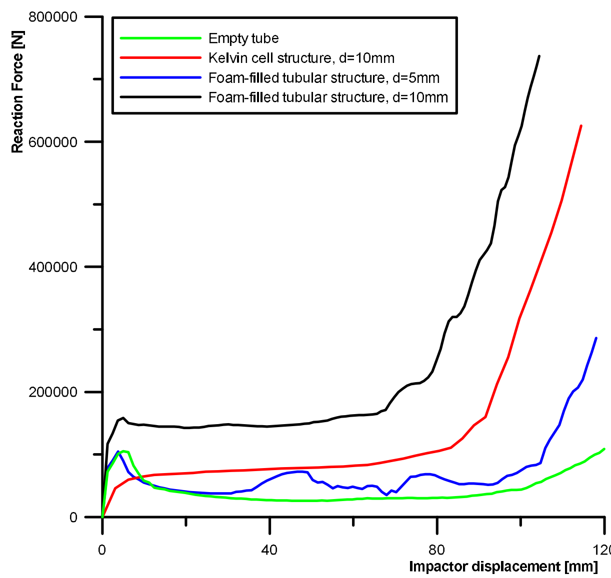

Figure 7. Reaction force-displacement curves1for the different studied configurations.

From the numerical results of the crushing samples, it was shown that:

- The mechanical response of the foam-filled tubular structure in compression can be divided into three stages: elastic deformation, stress plateau, and densification stage.
- For foam structure, when a unit cell is crushed, the load is transferred to the next unit cell, and the force value decreases during the force transfer between cells. The decrease in the force value depends on the number of unit cells in the structure.

IV.CONCLUSION

In order to improve the dynamic compression loading and energy absorption capacities of thin-walled tubes, one kind of foam topology is proposed as a filler material. The dynamic compression loading is simulated by Abaqus software. The numerical results showed that:

- The lowest crashworthiness performance is recorded in the structure of the empty tube.
- The designed kelvin cell can be successfully induced in a thin-walled tube.
- Adding foam into thin-walled tubes increases the energy absorption capacity.
- Increasing the kelvin cell diameter can increase the energy absorption capacity of the structure, but this led to an increase in the structure weight.

The presented numerical simulations provided some useful guide, and give more explanation on the dynamic response and energy absorption capacity of foam-filled thin-walled structures.

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