

EXPERIMENTAL CHARACTERIZATION OF THE ENERGY
ABSORPTION OF FUNCTIONALLY GRADED FOAM FILLED
TUBES UNDER AXIAL CRUSHING LOADS

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ABSTRACT: This paper deals with the energy absorption characterization of functionally graded foam (FGF) filled tubes under axial crushing loads by experimental method. The FGF tubes are filled axially by gradient layers of polyurethane foams with different densities. The mechanical properties of the polyurethane foams are firstly obtained from axial compressive tests. Then, the quasi-static compressive tests are carried out for empty tubes, uniform foam filled tubes and FGF filled tubes. Before to present the experimental test results, a nonlinear FEM simulation of the FGF filled tube is carried out in ABAQUS software to gain more insight into the crush deformation patterns, as well as the energy absorption capability of the FGF filled tube. A good agreement between the experimental and simulation results is observed. Finally, the results of experimental test show that an FGF filled tube has excellent energy absorption capacity compared to the ordinary uniform foam-filled tube with the same weight.

KEY WORDS: Foam-filled tubes, functionally graded foam (FGF), energy absorption, peak crushing force, polyurethane.

1. INTRODUCTION

The honeycomb sandwich structures have exhibited significant energy absorption characteristics under axial crushing loads and consequently, have been received great attention in engineering applications, such as vehicle engineering, shipbuilding, civil engineering and other related industries, see e.g. [1,2]. The use of lightweight materials such as honeycomb cores affects the bending mode of thin-walled hollow cylinder, shortens bending lengths and increases number of lobes [2-4]. Incorporating

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the lightweight foam-fillers into thin-walled sections has proven an effective way to increase the energy absorption. Experimental tests and numerical simulations on foam-filled tubes have also been reported in the literature by some researchers see e.g. [5-8]. In this regard, Hanssen et al. [5,6] conducted several experiments to study the axial deformation behaviour of circular and square aluminium extrusions with aluminium foam, filler under the static and dynamic crushing. The energy absorption performance in axial compression of square aluminium columns with aluminium foam filler has also been assessed by Hanssen et al. [7]. Impact deformation of rigid polymeric foams in uniaxial compressive loading, based on the experiments and FEA modelling was addressed by Gilchrist and Mills in [8].

Further improvement of the crashworthiness characteristics of uniform foam-filled tubes has been achieved by using the FGF material as an alternative to the uniform foam-filled tubes and honeycomb thin-walled structures [9,10]. In this regard, the energy absorption was found to be highly dependent on the foam density. Gupta presented a functionally graded syntactic foam material for high energy absorption under compression loads [11,12]. The studies reported in [13-16] have also dealt with the replacement of uniform foam material by FGF material due to their excellent energy absorption capabilities. Kiernan et al. [14] found that under certain conditions an FGF can outperform uniform foam of equivalent density in terms of reducing peak accelerations. In characterizing the FGFs for flexural properties, Gupta et al. [15] reported that the flexural properties of FGFs, based on wall thickness approach can be controlled more effectively. The energy absorption characteristics of FGF-filled tubes were compared with the uniform foam filled tubes by Sun et al. [16], based on a crashworthiness optimization analysis. In their study, the density of the FGF-filled tubes changes only along the axial direction of the tube. Nouraei [17] investigated the crush behaviour of the FGF-Filled columns, using the nonlinear finite element code LS-DYNA. In his research, the effect of various design parameters, such as density grading, number of grading layers, and thickness of the interactive layer upon the resulting specific energy absorption was investigated. The energy absorption characteristics of two kinds of functionally lateral graded foam-filled tubes (FLGFTs) were investigated in [18] to improve the crashworthiness of foam-filled tubes. It was found that FLGFTs have more energy absorption capacity than the ordinary uniform foam-filled tube with the same weight. Yin et al. [19] conducted a multiobjective crashworthiness optimization for a FGF filled tapered tube in order to simultaneously reduce the peak crushing force (PCF) and enhance the specific energy absorption (SEA) capacity. More recently, the crashworthiness efficiency analysis for two-directional (lateral and axial directions together) functionally graded foams (TD-FGFs) under axial crushing loads was considered in [10].

The above studies on FGF filled tubes are majorly focused on the numerical approaches as the experimental production of continuous FGF is not trivial. In this paper, the objective of the work presented is the experimental characterization of the energy absorption of FGF filled tubes with Polyurethane foams, which is carried out. The polyurethane foams are produced with different densities ranging from 80 to 400 kg/m³. Then, an aluminium tube is axially filled by the produced foams in an ascending density order. The foam-filled aluminium tube is then used as an FGF filled tube in the experimental test. A nonlinear FEM simulation of the FGF filled tube is also carried out in ABAQUS software, to provide a reliable confidence about the accuracy of the experimental setup and the measured properties of the foams.

2. CRASHWORTHINESS

The study on the crashworthiness of thin-walled structures and optimization of their performance is usually started from the definition of the crashworthiness indicator. The force displacement curves of a typical thin-walled structure can measure the impact characteristics to a certain extent. The absorbed energy E is equivalent to the mechanical work, performed by the impact force $F(x)$ during the crush distance d and therefore, is calculated as:

$$(1) \quad E(d) = \int_0^d F(x)dx .$$

3. POLYURETHANE FOAM PRODUCTION

The production of rigid polyurethane foam requires two main liquid components (a polyol and a polyisocyanate) [20,21]. The poly addition reaction, that takes place when the polyol and polyisocyanate are mixed together, results in macromolecules with urethane structures (polyurethanes). According to the polyurethane foam properties, equal amount of raw materials are mixed. A considerable amount of heat is released during the reaction. As a result, the reaction mixture is expanded and its volume is increased to form foam. In this study, for producing foams in different densities, raw materials are mixed and filled in a closed mould to control volume. By adjusting the amount of raw materials and filling in a constant volume, the foam with required density is produced. By this method, the polyurethane foams are produced in 10 different densities from 80 to 400 kg/m³.

The FGF filled tube in this paper is composed of polyurethane foams with different densities, shaped in cylindrical form. The foam outer diameter is equal to the inner diameter of the aluminium tube. The foam height is adjusted by selecting a desirable number of FGF layers, which can be putted axially in aluminium tube by ascending or descending density order. The extraction of the main mechanical

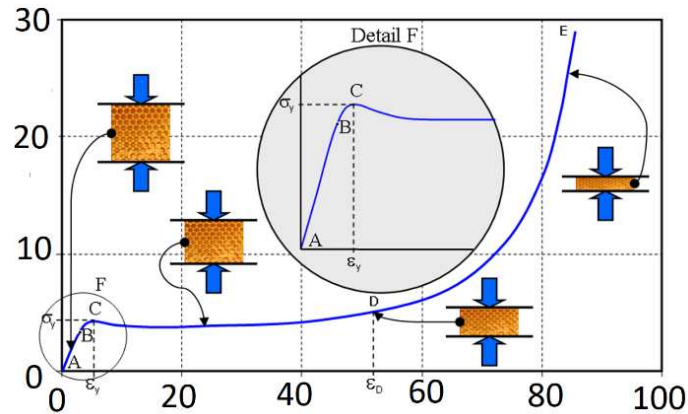


Fig. 1. Typical stress – strain curve for rigid polyurethane foam [22].

properties of the polyurethane foams with different densities in a static compression test is presented. The main parameters studied in compression include the Young's modulus, the yield stress, the plateau stress and the densification strain (Fig. 1).

4. CHARACTERIZATION OF THE ENERGY ABSORPTION

4.1. EXTRACTION OF THE FOAM PROPERTIES

In this section, the mechanical properties of the produced foam are studied. Uniaxial compression test is the most common test, which provides basic stress-strain relation of the material, elastic modulus, yield stress, etc. In this study, foams are produced in 10 different densities, from 80 to 400 kg/m³. Before filling the aluminium tube by foams, their properties should be obtained from a compressive test. Foams in cylindrical shape are produced and then, the static compressive tests are performed.



Fig. 2. Specimens used in the experimental program.



Fig. 3. Specimens after test in the experimental test: (a) from left to right, density is 80, 123, 147, 175 and 200 kg/m^3 ; (b) from left to right, density is 235, 251, 300, 350 and 400 kg/m^3 .

A foam specimen before the compression is shown in Fig. 2. In addition, Fig. 3 shows the deformed foam specimens after plastic deformation.

The engineering stress-strain curves are obtained for the produced polyurethane foams and shown in Figs. 4 and 5. The trend of stress variation in terms of the strain observed from these figures is the same, as reported in Fig. 1.

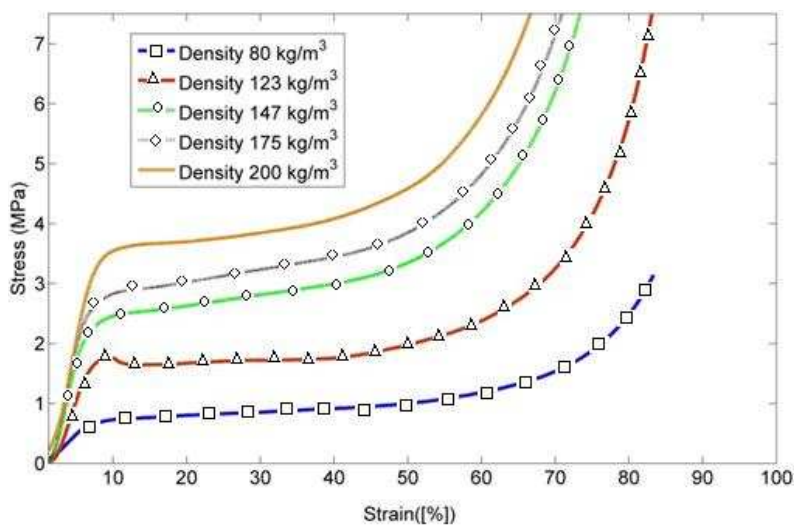


Fig. 4. Stress-strain curves for the specimens of Fig. 3(a).

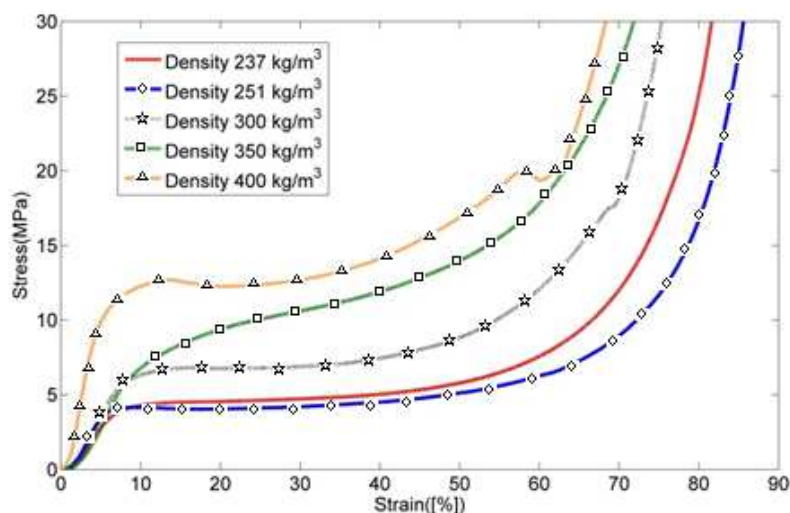


Fig. 5. Stress-strain curves for the specimens of Fig. 3(b).

The mechanical properties obtained from the experimental test are reported in Table 1. It is observed, that by increasing the foam density, we obtain a significant increase of mechanical properties, which means that the density has an important role in determining the dynamic compressive behaviour. Test results show that by increasing the foam density, the mechanical properties such as the yield stress, the elasticity module and the plateau stress are increased, too.

Table 1. Mean values of the mechanical properties as a function of density

Density [kg/m ³]	Diameter [mm]	Height [mm]	Young's modulus [MPa]	Yield stress [MPa]	Plateau stress [MPa]	Densification [%]
80	38	28	5.085	0.608	0.857	53.72
123	38	30	22.251	1.629	1.689	59.94
147	38	30	33.139	2.103	2.746	54.1
175	38	30	37.693	2.461	3.185	52.47
200	38	24	43.322	3.098	3.82	52.31
237	38	24	53.922	3.78	4.817	56.45
251	38	30	64.34	3.89	4.111	58.89
300	38	28	72.367	5.782	6.819	64.31
350	38	24	70.141	6.282	10.791	64.77
400	38	30	191.461	10.18	12.44	64.432

4.2. CONSTRUCTION OF THE FGF FILLED TUBES

After obtaining the foams mechanical properties, a tube made of an aluminium alloy (AA6061-T4) should be filled by these foams. We create here two sample tests; the first with 10 layers and the second with 8 layers of the FGFs, see Fig. 6. The aluminium tube is used with length 110 mm in the first sample and with length 90 mm in the second sample. The inner and outer diameters of the tube are 38 mm and 40 mm, respectively and with density $2.7 \times 10^3 \text{ kg/m}^3$, the Young's modulus $E = 68.20 \text{ GPa}$, the Poisson's ratio $\nu = 0.28$, the initial yielding stress $S_y = 80 \text{ MPa}$, the ultimate stress $S_u = 173 \text{ MPa}$ and the elongation 17.4%.

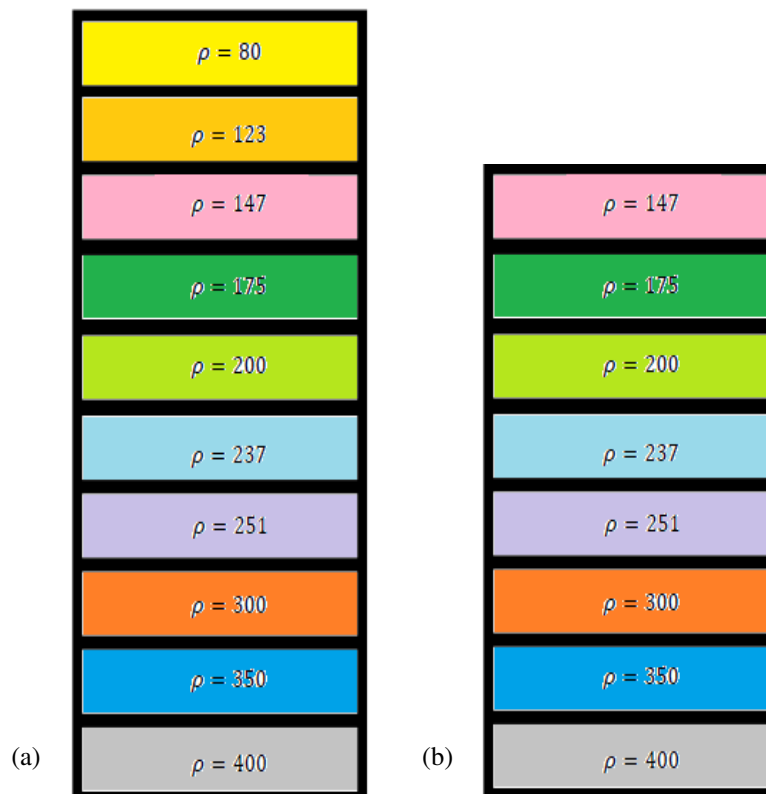


Fig. 6. The FGF filled sample test tubes: (a) 10 layers with length 110 mm (first sample test); (b) 8 layers with length 90 mm (second sample test).

In each sample test, three models are produced including the empty tube, the uniform foam filled tube and the FGF filled tube, as shown in Fig. 7. Since the density of the FGF tube is varied in the axial direction, the uniform foam filled tube



Fig. 7. First sample test with: (A) FGF filled tube; and (B) empty tube. Second sample test with: (C) FGF filled tube; and (D) empty tube.

of the same weight as the corresponding FGF tubes is constructed for comparing the energy absorption capability. The equivalent foam density of the uniform foam tube is calculated as

$$(2) \quad \rho_{\text{eqv}} = \sum_{i=1}^{N_G} \rho_i / N_G ,$$

where N_G denotes the total number of foam layers in the axial direction of the FGF, and ρ_i is the density of the i -th layer. The equivalent foam density of the uniform foam tube is about 226.3 kg/m^3 in the first sample test and 257 kg/m^3 in the second sample test. Due to the construction limitations, the uniform foam with density 237 kg/m^3 is used in the first sample test. To investigate the effect of density,



Fig. 8. Deformation pattern for the empty tube.



Fig. 9. Deformation pattern and crushing process for the FGF filled tube.

the uniform filled tube in the second sample test is constructed with a density of 332.8 kg/m^3 , which is higher than its equivalent value (257 kg/m^3). Figures 8 and 9 show the deformation patterns for the empty and the FGF filled tubes in crushing process under uniaxial compressive test, respectively.

4.3. FEM SIMULATION

Before to present the experimental test results, a nonlinear FEM simulation of the FGF filled tube with 10 layers (see Fig. 6(a)) is carried out in ABAQUS software, to gain more insight into the crush deformation patterns, as well as the energy absorption capability of the FGF filled tube. In addition, it can provide a reliable confidence about the accuracy of the experimental setup and the measured properties of the foams, tabulated in Table 1. All the required mechanical properties of this model are given in Sections 4.1 and 4.2. Four-node quadrilateral shell elements are considered for the tube. To model foam materials, solid elements with one integra-

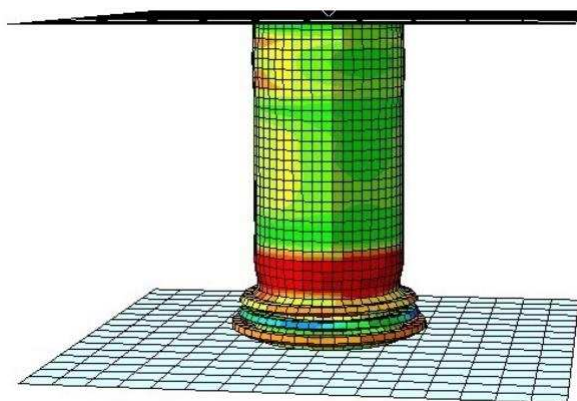


Fig. 10. Deformation patterns of the FGF filled tube in FEM analysis.

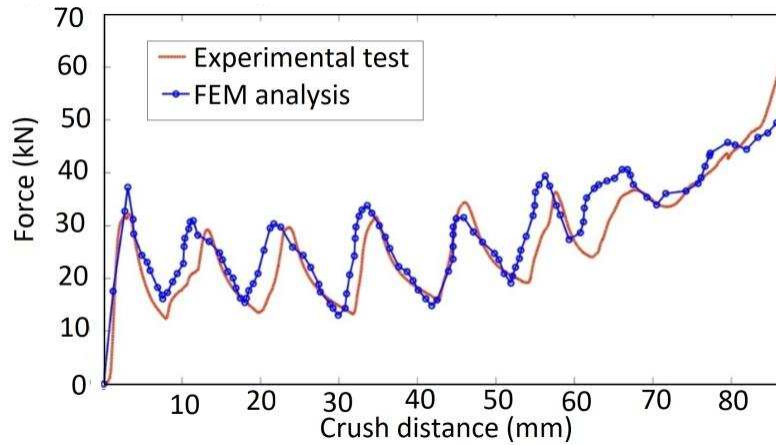


Fig. 11. Force vs. displacement for the experimental test and the FEM analysis.

tion point are used and the interface between the foam and the wall is modelled as a surface-to-surface contact. A self-contact is prescribed to avoid interpenetration of the tube walls, generated during bending. Moreover, a contact is defined between the rigid plane and the top of the tube to model the compressive forces. The static and dynamic friction coefficients of 0.2 between all surfaces in contact are assumed. The foam core is divided into 10 layers along the axial direction. According to Fig. 6(a), a unique density value is assigned to each layer. The other material properties can be calculated, based on the corresponding density value of each layer.

Figure 10 shows the deformation pattern of the tube, which when compared with the deformation pattern of the experimental test in Fig. 9, can approve generally the experimental setup. In this paper, the FGF is produced by axially sorting of the polyurethane foams with different densities. The force vs. crush distance for both the experimental test and the FEM analysis of the FGF filled tube is illustrated in Fig. 11. Although some deviations between the results of force variation obtained from the FEM analysis and the experiment can be observed, the general trend is the same. Based on this, the results prove the reliability of the approach exploited for producing the FGF filled tube and measuring the properties of the foams.

4.4. EXPERIMENTAL RESULTS

In this section, the experimental characterization of the energy absorption of both models, introduced in Section 4.2 is presented. Variation of the force vs. displacement for the empty, the uniform and the FGF foam filled tubes in both the first and the second sample tests are depicted in Figs. 12 and 13, respectively. According

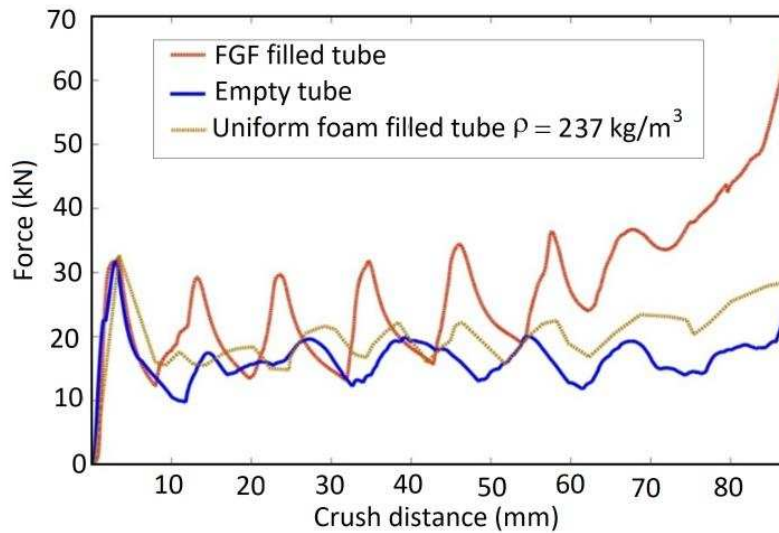


Fig. 12. Force vs. displacement for the empty, uniform and FGF foam filled tubes in the first sample test.

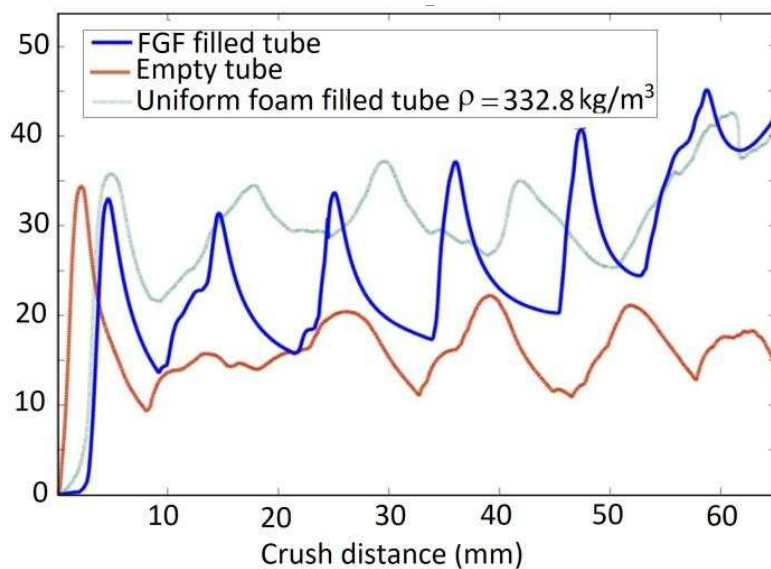


Fig. 13. Force vs. displacement for the empty, uniform and FGF foam filled tubes in the second sample test.

to Fig. 12, it is observed that the FGF filled tube has the highest energy absorption capability, compared to the empty and the uniform foam filled tubes. On the other hand, results of Fig. 13 show that the uniform foam filled tube exhibits higher energy absorption capability than the empty and the FGF filled tubes. The main reason behind this important issue is based on the fact that the density of the constructed uniform foam tube is higher than its equivalent value 257 kg/m^3 in the second sample test. This fact clearly indicates the effect of adjusting higher density in energy absorption capabilities. It is notable, that in the preceding crushing process, the peak crushing force for the FGF filled tube is increased in some displacement values. The reason is ascending trend of the FGF density in the axial direction. In the second test arrangement, the density of the uniform foam tube is intentionally increased about 30% higher than its equivalent value to qualitatively assess the effect of this increase on the amount of total energy absorption. According to the results of Fig. 13, an increase of 25% in the energy absorption can be seen, compared to the FGF filled tube. The main reason for presenting the results associated with this arrangement is just to give the designer how the energy absorption capability can be affected by increase of the density of the uniform foam tube.

In order to reach a final FGF filled tube with desirable crashworthiness characteristics, this study can be supplemented further with a multiobjective optimization procedure to simultaneously achieve maximum specific energy absorption capacity and minimum peak crushing force. Since such optimization has already been implemented for even two directional FGM filled tubes in a previous work of us (see [10]), it was not repeated here for the sake of brevity and focusing mainly on the experimental characterization.

5. CONCLUSION

In this paper, the energy absorption characteristics of functionally graded foam (FGF) filled tube under axial crushing load was analyzed by the experimental method. The polyurethane foams were firstly produced in different densities, and their mechanical properties such as the Young's modulus, the yield stress, the plateau stress, and the densification were obtained by the axial compressive test. It was observed, that by increasing the foam density, a significant increase of mechanical properties is obtained, which means that the density has an important role in determining the dynamic compressive behaviour. Test results showed that by increasing the foam density, the mechanical properties such as the yield stress, the elasticity module and the plateau stress are increased, too. Variation of the force vs. displacement for the empty, the uniform and the FGF foam filled tubes was investigated. It was seen that the FGF filled tube has the highest energy absorption capability compared to the empty and the uniform foam filled tubes. In addition, in a second sample test, the uniform filled

tube was constructed with a density higher than its equivalent value to qualitatively assess the effect of this increase on the amount of total energy absorption. The results showed that the uniform foam filled tube exhibits higher energy absorption capability than the empty and the FGF filled tubes. This fact clearly indicates the effect of adjusting higher density in the energy absorption capabilities. In addition, the experimental results of the FGF filled tube were compared with the nonlinear FEM simulation, which was carried out in ABAQUS software. A good agreement between the results was observed. It was concluded, that the experimental method used in this paper for producing the FGF filled tube is acceptable.

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