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On the energy absorption of tube reinforced foam materials under quasi-static and dynamic compression

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ABSTRACT

Theoretical and numerical analyses are carried out to reveal the role of metal tube reinforcement in the enhancement of the energy absorption capacity of foam materials with different densities and strength. A theoretical model is proposed to estimate the strength increase of the reinforcement due to the confined tube, which buckles. Using this model, the contribution of the reinforcement is obtained to the mean quasi-static tube force and also to the total quasi-static average force of reinforced materials comprising different foam and reinforcing components. The proposed model is also used to estimate the efficiency of the reinforced foam materials in the quasi-static loading regime.

FE simulations are carried out to verify the theoretical quasi-static model and to examine some essential dynamic effects due to the inertia of the foam and reinforcing tubes on the energy absorption of the material when subjected to impact loading. Attention is paid to the force enhancement at the impacted end and to the dynamic load transfer to the distal end of blocks of reinforced materials.

1. Introduction

There has been a growing interest in recent years in finding design solutions for efficient energy absorbing lightweight structures and materials. Among the numerous possibilities, structures combining traditional elements such as tubes with various sections and foam, as well as reinforcements based on metals and polymers have been examined to obtain their characteristics under quasi-static and dynamic loading. In particular, the crushing behaviour of fully or partially foam-filled thin-walled structural elements has been studied to determine their energy absorption capacity employing experimental, theoretical and numerical methods of analysis.

A nearly constant force over a large stroke is the major characteristic of an efficient energy absorber. Therefore, efforts have been directed towards the design of structures with an increased mean force while maintaining a low weight. The foam-filled tubes are good candidates for efficient energy absorbers as their length can significantly be reduced under axial compression at a nearly constant force while the added foam contributes to the increase of their strength. Researchers have analysed various tube elements filled with foam to examine the role of the filler on the tube deformation and to estimate the combined mean force. Reid et al. [1] conducted an experimental study on axial crushing of thin-walled square and rectangular metal tubes filled with polyurethane foam with various densities in order to estimate the mean force. Simple theoretical models were proposed to quantify the interaction between the foam and tube. Abramowicz and Wierzbicki [2] studied the effect of low density polyurethane on the crushing behaviour of metal tube. In the proposed theoretical model they assumed that the energy dissipated by the foam core is a function of its volumetric reduction. The axial crushing behaviour of very thin (diameter–to-thickness ratio > 600) empty and foam filled circular tubes under quasi-static and dynamic loading conditions was studied experimentally and theoretically by Reddy and Wall [3]. They concluded that the observed increase in the crushing force of the filled tubes is due to the foam compression and buckling mode change – from non-symmetric in the empty tube to axisymmetric in the foam-filled tube.

An empirical formula for the mean crushing force of foam-filled square tube was proposed by Santosa and Wierzbicki [4] based on numerical and experimental investigations. In their study, no interaction between the foam and tube was taken into account. The influence of the added adhesives was discussed in [5] pointing out their contribution to the increase in the mean force. Hanssen et al. [6,7] conducted a series of experiments on the axial crushing of aluminium extrusions with aluminium foam filler and proposed another empirical formula for the mean crushing force, which

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takes into account the contribution to the mean crushing force from, respectively, the non-filled aluminium extrusion, uniaxial resistance due to the aluminium foam core and the interaction effect between the foam and tube. Recently, a theoretical model was proposed in [8] for a circular tube with a partial infill in order to quantify the influence of the foam properties on the increase in the mean force under quasi-static compression. Tubular structures filled with compliant core have also been studied in [9–12], in which an increase in the mean force and energy absorption have been reported.

The influence of the foam filling on the deformation of thin aluminium tubes was studied by Aktay et al. [13] focusing on the buckling mode. They found that the number of folds increased in foam-filled tubes regardless of the buckling mode – axisymmetric or non-symmetric. Kavi et al. [14] also studied the buckling mode change and energy absorption of foam-filled thin-walled circular tubes based on an experimentally obtained strengthening coefficient. They observed that the foam filling changes the deformation mode from non-symmetric for an empty tube to axisymmetric mode in a foam-filled tube, which confirms the findings in [3].

The effect of foam filling on the strength of filled honeycomb and lattice panels was recently studied under quasi-static and dynamic loading. The effect of foam filling on the mechanical properties of hexagonal cell aluminium honeycomb under a quasi-static loading was studied experimentally in [15] where it was shown that the filling increases the energy absorption capacity up to 300%. A theoretical model to obtain the mean crushing strength of foam-filled hexagonal honeycomb due to a quasi-static loading was proposed by Mahmoudabadi and Sadighi [16], assuming that the energy dissipated by the foam core is a function of its volumetric reduction. The model compared favourably with the experimental data. In addition to the strength enhancement, the experimental results showed that filling honeycomb cells with foam decreases the ratio of the peak force to the mean crushing force.

The energy absorption capacity of foam-filled lattice composite panels under out-of-plane loading was studied in [17]. Overall, it was demonstrated that due to the energy absorbed by the lattice itself, the lattice composite panels exhibited better performance than the foam core sandwich panels. However, its large resistance to buckling led to a significant increase of the peak force, which is an undesirable behaviour for energy absorbers.

The above studies of structures, which comprise foam and tubular elements, point out the benefit of their combination for energy absorption. In general, these studies are concerned with the analyses of either single tubes or foam-filled honeycomb. On the other hand, regularly arranged tubes with different cross-sections have been also considered as a possible lightweight core material capable of energy absorption under quasi-static and dynamic loading [18,19]. For that reason, embedding regularly spaced tubes in foam can lead to an enhancement of the energy absorption capacity of a tube core due to the confinement. Recently, Alia et al. [20] reported an experimental study on the energy absorption of polymer tube-reinforced foam structures. Several polymer types were used to establish the influence of the foam density and tube arrangement on the crush behaviour of these structures. It was shown that the energy-absorbing characteristics of the above structures exceed the corresponding values associated with other core materials, such as aluminium honeycombs, polymer honeycombs and metal foams.

The study reported in [20] was focused on a reinforcement comprising the out-of-plane loaded tubes where the increase of the energy absorption was caused by the interaction between the tube buckling and foam compression. Another idea to use tubes as reinforcement was proposed in [21] where empty tubes were placed in a layer-like manner, thus experiencing lateral compression when the reinforced material was subjected to the analysed quasi-static indentation.

The majority of the studies reported in the literature on the out-of-plane loaded foam-filled tubular elements are, however, concerned with partially or fully filled tubes when the tube buckling deformation is constrained only on the inside, therefore, a strong confinement and significant tube-foam interaction cannot be achieved. In the case of a tube embedded within foam, the tube is constrained at both the inner and outer sides and a strong interaction and considerable strength increase of the tube are expected.

In the present study, a reinforced material comprising foam and circular thin-walled metal tubes is analysed. First, a theoretical model of the foam-tube interaction is proposed to obtain the enhancement of the mean force of the tube due to the confinement caused by the surrounding foam, as well as the energy absorption capacity of the reinforced material under quasi-static compression. The model is further verified by numerical simulations using FE code ABAQUS. The constructed FE model is finally used to reveal essential dynamic effects in the reinforced material caused by the inertia sensitivity of the constituent components.

2. Theoretical analysis

2.1. A tube embedded in foam

The present theoretical model is based on a model developed by Huang and Lu [22] for a progressive axisymmetric folding of an empty circular tube with radius R and wall thickness h. The shape of the deformation zone described by this model is presented in Fig. 1a. Three segments are included: two equal radius arcs connected by a straight segment, which is tangent to the arcs. The total length of the four arcs is equal to the effective hinge length aH, where H is the half fold length to be determined in the analysis. The independent model parameter a varies between 0 and 1, thus defining the fold shape. Note that for $a=1$ the present model coincides with the model with continuous deformations proposed by Wierzbicki et al. [23] while for $a \to 0$ it formulates the model with stationary hinges described in [23].

The shape of the instantaneous position of the deformation zone at a given crushing distance can be defined by the two angles α and β, which are related to the instantaneous radii

$$r_1 = aH/2\alpha, \tag{1a}$$

$$r_2 = aH/2\beta. \tag{1b}$$

During the deformation, both angles increase corresponding to the axial crushing δ. Following [22], angles α and β can be related to an eccentricity factor m (Fig. 1b), which specifies the proportion between the inside and outside parts of the fold,

$$\begin{aligned}&\left[\frac{a}{\alpha}(1-\cos\alpha)+(1-a)\sin\,\alpha\right]-\left[\frac{a}{\beta}(1-\cos\beta)+(1-a)\sin\beta\right]\\&\quad=m\left[\frac{a}{\alpha_f}(1-\cos\alpha_f)+(1-a)\sin\alpha_f\right]\end{aligned} \tag{2a}$$

$$\begin{aligned}&\left[\frac{a}{b}(1-\cos\beta)+(1-a)\sin\beta\right]-\left[\frac{a}{\alpha}(1-\cos\alpha)+(1-a)\sin\alpha\right]\\&\quad=(1-m)\left[\frac{a}{\alpha_f}(1-\cos\alpha_f)+(1-a)\sin\alpha_f\right]\end{aligned} \tag{2b}$$

and the final angle α_f can be obtained from the geometry of the fully collapsed model by solving the following equation

$$\cos\alpha_f = \frac{a}{2(1-a)}\frac{1-2\sin\alpha_f}{\alpha_f}. \tag{3}$$