

Experimental and FE Analysis of Quasi-Static Bending of Foam-Filled Structures

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ABSTRACT

Three-point bending under quasi-static loading was carried out on empty and partially foam-filled tubes. ALPORAS® aluminium foam was used as an insert with aluminium alloy tube in the experiment. The experiment was modelled using the finite element (FE) code software package LS-DYNA®. The Deshpande-Fleck constitutive model was implemented in the simulation to model the foam. Its material parameters were calibrated against experimental data. The material parameters for the tube were also derived experimentally. Experimental data showed increase in specific energy absorption of approximately 17% whilst the lowest generator of the tube was found to increase by approximately 14% with inclusion of partially filling foam. The FE simulations compared well with the experiments, with the load-displacement and LG-indenter displacement agreeing within approximately 15%. Visual inspection of the foam showed local densification around the point of indentation. Similar features were seen in the FE simulation with high strains and large deformation present near the point of indentation. The results thus indicated a localised effect in energy absorption of the foam in the scenario being studied.

INTRODUCTION

The ability of the aluminium foam to deform largely with relatively small increase in stress has made it an ideal

candidate for use as an energy absorber. Indeed, search of the words “energy absorption foam” in any academic database yields a multitude of hits. Study on the effect of foam inclusion has produced mixed results. All agree on the increase in the overall energy absorption (EA) from the use of aluminium foam insert. However, with the weight specific energy absorption (SEA) of the overall structure, some works have shown no beneficial use from the inclusion of the foam.

Much work has been done on aluminium foam-filled tubes being axially compressed [1,2,3,4], with one of the early work done by Reddy and Wall [5]. Oblique loading of foam-filled circular tubes has been studied by Børvik et al. [6] and Reyes et al. [7]. It was stated that the SEA for the axially crushed tube showed some increase while for the oblique loading the opposite effect was recorded. However, the authors have noted that no SEA optimisation study was carried out for the foam-filled tube. Recently, Zarei et al. [8] has started work on the optimisation study for dynamic axial crushing of foam-filled square tubes. The study of the effect of foam insert against the bending has also been carried out by Hanssen et al. [9] and Santosa et al. [10, 11].

The comparison across the various works is made more difficult with the various foams now available on the market including ALPORAS, CYMAT and Hydro Aluminium. Each is produced with different methods giving some variation in behaviour amongst the various foams [12]. Much of the

characteristic behaviour is now tied in with the density of the foam and this gives further complexity in comparison of results across various works. For example, CYMAT and ALPORAS foam both at 10% relative density may behave differently.

However, the majority of the work points to the potential use of foam-filled structures in the automobile industry, primarily in the field of structural strength enhancement. Finite element analysis (FEA) has become an invaluable tool in this industry and such an approach is now commonly applied in research work involving the analysis of foam-filled structures. The aim is to produce finite element (FE) models that are capable at mimicking large structures such as the chassis of a vehicle. Such work has been done by Hanssen et al. [13] on inclusion of aluminium foam in the A-pillar of a vehicle. It was stated that overall EA was increased by 30% with only 3% increase in weight from the foam inclusion. As stated by Hanssen et al. [13], the complexity of the analysis is increased by the use of solid elements to model the foam, when traditionally shell elements are only used for such analysis of the pillar.

Various FEA code packages have also been used including PAM-CRASH, Abaqus and LS-DYNA. Shabeyk et al. [14], for example, has used Abaqus to carry out numerical study of an axial, dynamical crushing of foam-filled square tubes. However, the modelling of the aluminium foam has seen a distinctive move towards the use of the constitutive model first introduced by Deshpande and Fleck [15]. The model mimics foam as an isotropic material with its parameters given as a function of the foam density.

The present work utilises the software package LS-DYNA to mimic the three-point bending experiments of the empty and foam-filled circular tubes. The aim was to see the amount of overall energy absorption increase from the use of a partial foam insert, and more specifically the increase in weight specific energy absorption of the structure. The ability of the FE code to simulate the experiments by comparing against the experimental data is presented as a first step in the validation of the model for further use in the future.

EXPERIMENTAL DETAILS

Three-point bending was applied to both the empty and foam-filled tubes. Tests were carried out on a mechanical testing machine, MTS model 819. The specimen is placed on two 90° angled vee-shaped supports. The indenter velocity is set at a constant speed of 0.005mm/s. The diameter of the indenter and the supports are 10mm. Span between the supports is set to 260mm (or h-span=130mm). Linear motion potentiometer (LMP) was placed directly below the indenter to measure the lowest generator (LG) of the beam in bending. The experimental set-up is shown in [Fig. 1](#).



Figure 1. A foam-filled tube under three-point bending.

ALPORAS® aluminium foam [16] was used as the foam insert. The solid cylindrical block of foam with length of 150mm was fabricated from a larger block using the wire-cutting method. The foam specimens were cut to a dimension to produce a “push-fit” with the empty tubes and placed at the centre of the tube to produce a partially-filled tube. Relative density of the foam, with respect to the standard density of aluminium of 2.7g/cm³, was found to be 8.2%. AA6060T5 MF 40 × 1.6mm tube was used in the experiment. For ease of reference the partially foam-filled tube will be referred to as foam-filled tube throughout this text.

CONSTITUTIVE MODEL

The commercially available software LS-DYNA® was used in the FE analysis. The proceeding sections describe the constitutive models and their parameters used in the analysis.

EMPTY TUBE

The empty tube was modelled using the isotropic plasticity model, *MAT_018 in LS-DYNA [17]. Strain hardening behaviour is described via the power law hardening rule.

DESHPANDE-FLECK FOAM MODEL

The aluminium foam is modelled using the pre-existing Deshpande-Fleck model, *MAT_154 [17]. The “yield stress” or the strain-hardening behaviour is described by [Eq. \(1\)](#).

$$\sigma_y = \sigma_{pl,ini} + \gamma \frac{\hat{\epsilon}}{\epsilon_c} + \alpha_2 \ln \left(\frac{1}{1 - \left(\frac{\hat{\epsilon}}{\epsilon_D} \right)^\beta} \right) \quad (1)$$

$\sigma_{pl,ini}$ is the initial plateau stress. $\hat{\epsilon}$ is the equivalent strain. Calibrated against an axial compression test, $\hat{\epsilon}$ is the empirical true strain. γ , α_2 and β are material parameters. ϵ_D with the description of “densification strain” is used instead of ϵ_c in the LS-DYNA documentation [17]. This description in [17] is incorrect and symbol ϵ_c has been substituted in its place in Eq. (1) for clarity between the densification strain ϵ_D and compaction strain ϵ_c . Furthermore, the author would also like to note the use of the initial plateau stress $\sigma_{pl,ini}$ and not the plateau stress σ_{pl} in Eq. (1). The definition of these two stresses will be clarified below.

The compaction strain, ϵ_c , in which true compressive strain is taken as being positive in sign, is given by the expression in Eq. (2).

$$\epsilon_c = -\ln \left(\frac{\rho_f}{\rho_{f0}} \right) \quad (2)$$

Here, ϵ_c is a theoretical value that states the strain at which the foam has been fully densified (i.e. with no voids). The derivation of Eq. (2) is presented in Appendix A.

The material parameters are given as a function of the relative densities through the power law expression [15, 18, 19] presented in Eq. (3).

$$\left\{ \sigma_{pl,ini}, \alpha_2, \gamma, \frac{1}{\beta} \right\} = a \left(\frac{\rho_f}{\rho_{f0}} \right)^b + c \quad (3)$$

The yield shape factor for the mode α , is given by the expression in Eq. (4) [18],

$$\alpha = \frac{9(1-2\nu)}{2(1+\nu)} \quad (4)$$

However, the measurement of elastic Poisson's ratio ν , for aluminium foam is said to be difficult with the value being very close to zero [18]. According to Hanssen et al. [18], Deshpande and Fleck then considered the use of the plastic

Poisson's ratio defined by $\nu_p = -\dot{\epsilon}_{22}^p / \dot{\epsilon}_{11}^p$. Directions 1 and 2 are the direction of uniaxial loading and another

perpendicular to that of direction 1, respectively. Implementation of the definition of ν_p to a uniaxial compression test is then said to give the expression of Eq. (5) [18],

$$\alpha = \frac{9(1-2\nu_p)}{2(1+\nu_p)} \quad (5)$$

However, it is assumed that $\nu_p = 0$ for aluminium foam [6, 7]. Thus, $\alpha = \sqrt{(9/2)}$. The assumption of taking $\nu_p = 0$ is also in line with the assumptions taken to derive the theoretical expression for the compaction strain (refer to Appendix A).

Fracture of the foam is defined using volumetric failure strain ϵ_{cr} . Failure is set to occur when $\epsilon_m \geq \epsilon_{cr}$ [20]. This failure criterion has been confirmed through simple test simulations in LS-DYNA.

MATERIAL PARAMETER DERIVATION

EMPTY TUBE

Tensile testing was carried out on a dog-bone shaped tensile test specimen cut from tube of dimension 101.6×1.6mm (Fig. 2). The test was carried out at a speed of 0.02mm/s and a true stress-strain curve was obtained (Fig. 3). The determination of the original cross-sectional area of the gauge section was made using the expression given in Appendix D of Australian Standard® AS 1391-2007 [21]. The steepest gradient of 67.85GPa was obtained within the elastic region, and the nominally value of 70GPa reported in literature [6] was used

in the numerical model. The power-law equation, $y = ax^b$, was then fitted to the empirical data post-0.02% yield stress using the MATLAB and its Curve Fitting Toolbox. The power law parameters values of 282.9MPa and 0.08067 was derived for ‘a’ and ‘b’ of the power law equation respectively.



Figure 2. Tensile testing of a dog-bone specimen cut from a tube.

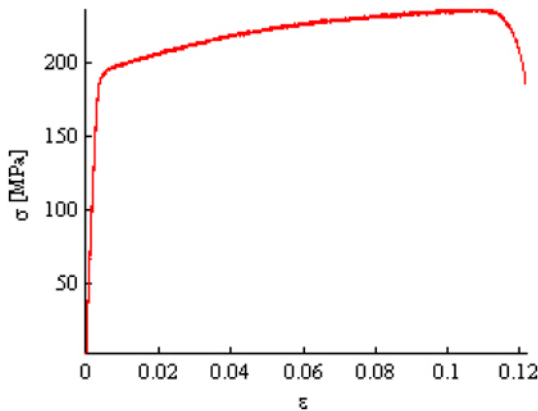


Figure 3. Tensile test result of the specimen cut-out from the empty tube.

FOAM

The plateau stress can be found by the expression of Eq. (6) [22, 23], where ϵ_D is calculated using the concept of energy absorption efficiency [22, 23]. Both σ_{pl} and ϵ_D is found from the nominal stress-strain curve [22, 23]. However, Eq. (6) does not take into account the gradient of the stress-strain behaviour into consideration and thus can predict σ_{pl} that is higher than the upper yield point σ_{UY} .

$$\sigma_{pl} = (\epsilon_D - \epsilon_{UY})^{-1} \int_{\epsilon_{UY}}^{\epsilon_D} \sigma(\epsilon) d\epsilon \quad (6)$$

The primary purpose of the plastic hardening expression of the Deshpande-Fleck model, Eq. (1), is to describe the stress-strain behaviour of the foam in the post-elastic region. Its purpose is to fit the empirical stress-strain curve and such a fit is presented in Fig. 4. Figure 4 shows a fit of Eq. (1) on the empirical true plastic stress-strain plot of a foam with $\rho_{rel} = 8.21\%$. For clarity experimental data points at increments of 25 readings are plotted. The fit was achieved using the Curve Fitting Tool Box in MATLAB. An analogous plot has also been presented by Hassen et al. [18] for Hydro Aluminium foam and by Styles et al. [24] for ALPORAS foam. The lowest stress from such a fit depicts the initiation of the plateau region of the foam behaviour and is appropriately termed as the initial plateau stress $\sigma_{pl,ini}$ in certain work [18], while in others [7, 20] the general term of plateau stress is used. For clarity throughout this text, $\sigma_{pl,ini}$ will be defined as being the lowest stress achieved from a curve fit of the plastic hardening empirical data, and this will be the value to be implemented in the first term of the Deshpande-Fleck hardening expression presented in Eq. (1).

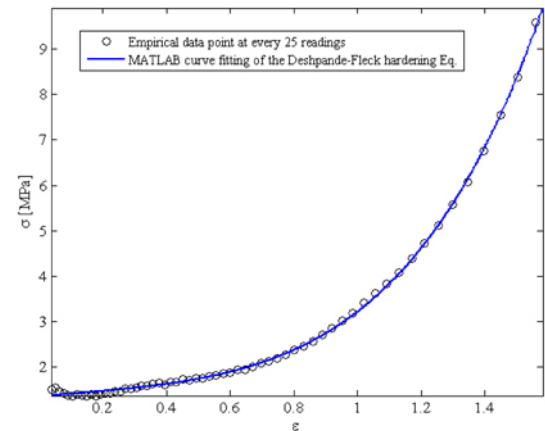


Figure 4. Fit of an empirical logarithmic stress-strain plot using Deshpande-Fleck models hardening equation for foam with $\rho_{rel} = 8.21\%$.

The point of initiation of the plastic region must now be defined. The most distinctive and easily definable feature in the stress-strain plot was the first peak referred to as the upper yield point σ_{UY} or first yield point. For the work presented, the Deshpande-Fleck model's hardening expression was fitted to the empirical stress-strain data post- σ_{UY} .

The above process was repeated for five sets of data for foam specimens with the relative densities of 8.21%, 9.59%, 9.89%, 10.08% and 10.31%. The five cylindrical blocks of ALPORAS foam were compressed at $\dot{\epsilon} = 1 \times 10^{-3} s^{-1}$, with the average dimensions of the cylinders given by diameter of 29.9mm and height of 40.0mm. True plastic