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TESTING AND SIMULATION OF EXTRUDED POLYSTYRENE FOAM AT LOW TO MODERATE STRAIN RATES

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pp. 326-331

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Abstract: This paper presents a study into the behaviour of extruded polystyrene foam at low strain rates. The foam is being studied in order assess its potential for use as part of a new innovative design of portable road safety barrier the aim to consume less water and reduce rates of serious injury. The foam was tested at a range of low strain rates, with the stress and strain behaviour of the foam specimens being recorded. The energy absorption capabilities of the foam were assessed as well as the response of the foam to multiple loadings. The experimental data was then used to create a material model of the foam for use in the explicit finite element solver LS-DYNA. Simulations were carried out using the material model which showed excellent correlation between the numerical material model and the experimental data.

Key words: Energy absorption, polymeric foams, LS-DYNA, Fu-Chang

1 INTRODUCTION

Australia‘s annual economic cost of road crashes is in the billions of dollars with an average loss of 1464 lives and over 22,000 serious injuries to all road users (Langford & Newstead, 2008). Road crashes disproportionately affect younger members of society and lead to enduring consequences incurred as years of productive life are lost. Many serious injuries have long-term impacts involving loss of quality of life, with high medical and rehabilitation support being significant costs to the community.

Road safety barriers are used widely as a crash severity mitigation measure, with different functional barrier designs being used in different road environments. The performance goal of a road safety barrier is to control an errant vehicle in a manner which reduces its velocity over a short distance, without causing serious injury to the occupants and minimising the chance of an accident with other road users. One type of road safety barriers is the plastic water-filled barrier which is often used around road work sites and during temporarily changed road conditions. These barriers are useful in safely controlling the post-impact behaviour of errant vehicles by utilising the physical displacement of the barrier and the sloshing effect of the water. The empty High Density Polyethylene (HDPE) barriers are also easy to transport to site and relatively simple to place and install.

Collisions with road safety barriers make up a significant component of the statistics associated with vehicle accidents. Commonly used road barriers on Australian roads and around the world could be causing deaths rather than preventing them, as they are either too rigid or too light to absorb sufficient impact energy to reduce the severity of crashes (Larsson, Candappa, & Corben, 2003). Revisions to barrier designs have been only partially effective under different road and driving conditions; run-off-road crashes into roadside hazards including rigid objects and roll-over comprise nearly 40% of road fatalities (Grzebieta, Zou, Jiang, & Carey, 2005).

In addition to these shortcomings, water filled temporary barriers can consume up to 550 litres per two metres of protection (Energy Absorption Systems Inc., 2009) and can often be incorrectly installed due to complicated installation procedures. To address these issues, a new innovative design of road safety barrier is to be designed, reducing the amount of water consumption by integrating an energy absorbing polymeric foam within the internal frame of the barrier and using advanced numerical simulation techniques to optimise the design.

A number of studies have been published regarding the functional behaviour of polymeric foams and there potential for use impact energy absorbing devices (Aktay, Toksoy, & Güden, 2006; Mills, Fitzgerald, Gilchrist, & Verdejo, 2003; Slik, Vogel, & Chawda, 2006). Such studies consistently show that polymeric foams have the material properties necessary to safely absorb and redirect a wide range of impact loads.

In order to meet the functional and design requirements of such a barrier, it is necessary to assess the behaviour of commercially available polymeric foams and to develop a material model of these foams for use in explicit finite element studies. This paper will detail the process of assessing the behaviour of an extruded polystyrene foam at low strain rates and the methods used to develop the numerical material model of the foam for use in a crashworthiness simulation using explicit finite element techniques. The explicit numerical solver LS-DYNA (Livermore Software Technology Corporation [LSTC], 2010a) will be used to assist in creating the material model and to make use of the model for further development work.

2 BACKGROUND INFORMATION

2.1 Comparison of Foams

Various polymeric foams have previously been studied in order to assess their ability to act as impact energy absorption devices. Polyvinylchloride (PVC) foams have been thoroughly analysed for the potential use in composite sandwich structures (Atas & Sevim, 2010), expanded polystyrene (EPS) foams have been used as the impact absorbing material in motorcycle crash helmets (Di Landro, Sala, & Olivieri, 2002) and polyurethane foams have been used as impact limiters for hazardous materials (Li, Tam, & Liu, 2009).

While most polymeric foams exhibit a similar loading behaviour that features an three distinct loading phases of initial elastic loading, a densification plateau and solidification section, the density and base polymer of the foam have a great effect on its behaviour. With denser foams, the densification plateau becomes shorter and the reaction forces observed becomes higher (Di Landro et al., 2002). Understanding these behaviours plays an important role in design of devices using the foams.

The SAFER racetrack barrier is a composite structure which has been installed on a number of large oval racing tracks in the United States. The barrier is constructed out of thick walled steel frames and extruded polystyrene (XPS) foam, which are mounted to existing concrete walls. An errant vehicle is safely controlled and redirected by the barrier, with the kinetic energy being absorbed through a combination of displacement of the steel box frame and the crushing of the XPS foam (Reid, Faller, Holloway, Rohde, & Sicking, 2003). A key functional property of the SAFER barrier is the ability to permanently absorb a portion of the impact energy, while the rest is dissipated as the errant racing vehicle is redirected. The behaviour of the XPS foam is essential in the performance of the barrier as it allows for the sustained increase of momentum of the steel and provides continued energy absorption and cushioning of the vehicle as it is redirected. The density of the XPS foam is around 26 kg/m^3 and is commercially known as Foamular 150 (Reid & Bienlenberg, 2008).

2.2 **Explicit modelling of foam materials**

There are a number of material formulations available to model polymeric foams in the explicit numerical simulation solver LS-DYNA. A low density foam model (MAT_57) is available which can model the three phases loading of polymeric foams and also their hysteretic unloading (Hallquist, 2006). Ozturk and Anlas (2009) increased the accuracy of this formulation for a material model of EPS foam by optimising an objective function featuring the absorbed impact energy in order to properly determine the hysteric shape variables of the foam.

A crushable foam material formulation (MAT_163) offers the ability to define a series of stress-strain curves for various strain rates. The ability to nominate stress-strain curves greatly simplifies the process of model creation, although the unloading of the foam is modelled as a linear relaxation, which is not representative of actual behaviour.

The response of the Fu-Chang formulation (MAT_83) can be defined by a series of stress-strain curves for increasing strain rates and is designed to incorporate the actual hysteric unloading of polymeric foams (Hallquist, 2006). The incorporation of these two important material behaviours (i.e. rate sensitivity and hysteric accurate unloading response) means that MAT_83 is an ideal method of modelling polymeric foams for use in impact simulations. Reid and Bienlenberg (2008) compared MAT_163 and MAT_83 in the construction of a material model for an XPS foam. They concluded that both models can model loading with equal accuracy, the Fu-Chang formulation is more useful for modelling impact rebound. Also highlighted has the need for element hourglass energy control and the calculation of interior contact at high strain levels.

The strain rate dependency of foam varies depending on the strain rate region in which it operates. In quasi-static and moderate strain rates (i.e. < 1.0/s) the compressive stress and reaction forces are relatively independent of the strain rate. At higher strain rates the response increases with the strain rate due to the expulsion of air from the cellular matrix of the foam (Gibson, 1997). It is therefore important to model the rate dependency of polymeric foams in impact simulations. While softer polymeric foams (i.e. EPS and HDPE) typically have a reasonably regular exponential correlation between the engineering stress and the strain rate, harder foams, including Polyurethane (PU) foams, have an irregular response due to a reduction in the fracture toughness of the material (Ouellet, Cronin, & Worswick, 2006).

2.3 **Definition of the Fu-Chang material formulation**

The Fu-Chang material formulation is capable of modelling the rate dependant effects of low and medium density foams. The hysteretic effects of the foam are a function of the rate sensitivity. The material formulation is implemented in LS-DYNA so that the constitutive equation becomes:

$$\sigma(t) = \sigma^{*}\left(E^{N}(t), S(t)\right), \tag{1}$$

where E^N is the non-linear strain and S is the state variable. The arrangement dictates that the kinetic equation is equal non-linear true strain rate, which for the formulation is:

$$\dot{E}^{N}(t) = \frac{\sigma^{*}}{|\sigma|} D_0 \exp\left[-\mathrm{c}_0\left(\frac{\mathrm{tr}(\sigma \mathrm{S})}{\|\sigma\|^2}\right)^{2\mathrm{n}_0}\right]. \tag{2}$$

In (2) the components D_0, c_0 and n_0 are material constants with the state variable S being defined by the following:

$$\dot{S} = \left[\mathrm{c}_1(\mathrm{aR} - \mathrm{c}_2\mathrm{S})\mathrm{P} - \mathrm{c}_3\mathrm{W}^{\mathrm{n}_1}\left(\|\dot{\mathrm{E}}^{\mathrm{N}}\|\right)^{\mathrm{n}_2}\mathrm{I}\right]\mathrm{R}, \tag{3}$$

$$R = 1 + c_4\left(\frac{\|\dot{\mathrm{E}}^{\mathrm{N}}\|}{c_5} - 1\right)^{n_3}, \tag{4}$$

$$P = \mathrm{tr}\left(\sigma\dot{\mathrm{E}}^{\mathrm{N}}\right), \tag{5}$$

$$P = \mathrm{tr}\left(\sigma\dot{\mathrm{E}}^{\mathrm{N}}\right), \tag{6}$$

$$W = \int \mathrm{tr}\left(\sigma(\mathrm{dE})\right). \tag{7}$$

In (3), (4), (5) and (6) the components c_1, c_2, c_3, c_4, c_5, n_1, n_2, n_3 and a are material constants. LS-DYNA features the functionality to be able to internally calculate the twelve material constants of the Fu-Chang formulation for a specified material based on a series of stress-strain curves with a range of strain rates applicable to the loading rates involved.

3 EXPERIMENTAL TESTING

Extruded polystyrene (XPS) foam has been selected for the initial study into the effectiveness of polymeric foams in road safety barriers. In order to study assess the effectiveness of the XPS foam for this application, its behaviour under compression has been determined for quasi-static to moderate strain rate loadings. Strain rates of the final design are anticipated to be in the range from quasi static up to moderate impact rates. This study focuses on detailing the behaviour of the foam below 0.5/s, and a future study will detail the behaviour at a strain rate up to 50/s.

3.1 **Low strain rate compression testing**

The main goal of these initial experiments was to develop the response of XPS foam as stress versus strain curves up to 0.5/s. For this purpose, low strain rates tests were performed on the XPS foam using an Instron 5567 tensile testing machine in the Materials Testing Lab at Gardens Point, QUT. This particular machine has a maximum cross head velocity of 8.05 mm/minute in compression, which is determined by the limits of the screw thread drive system. Therefore in order to achieve a reasonable strain rate, the XPS foam was cut in 30x30x30 mm specimens. The density of the foam used in the tests was 35 kg/m^3. While the low strain rate is not indicative of the expected compression rates of vehicular impact, the testing gave valuable data which assisted in the initial development of the numerical model of the XPS foam. The testing will also assist in developing a testing regime for higher rate testing as detail in Section 6.

Using the software associated with the Instron machine, two different experimental designs were created. The first experimental design was created to measure the loading and unloading response. The response of the foam specimens were measured as they were loaded to 80% compression and then unloaded at the same rate. This loading and unloading process was carried out a total of four times on each specimen in order to assess the resilience of the material upon repeated loadings. This experimental design was carried out at velocities of 8.00, 6.00, 4.00, 2.00, 1.00 and 0.10 mm/s (strain rates of 0.27, 0.2, 0.13, 0.07, 0.03 and 0.003/s).

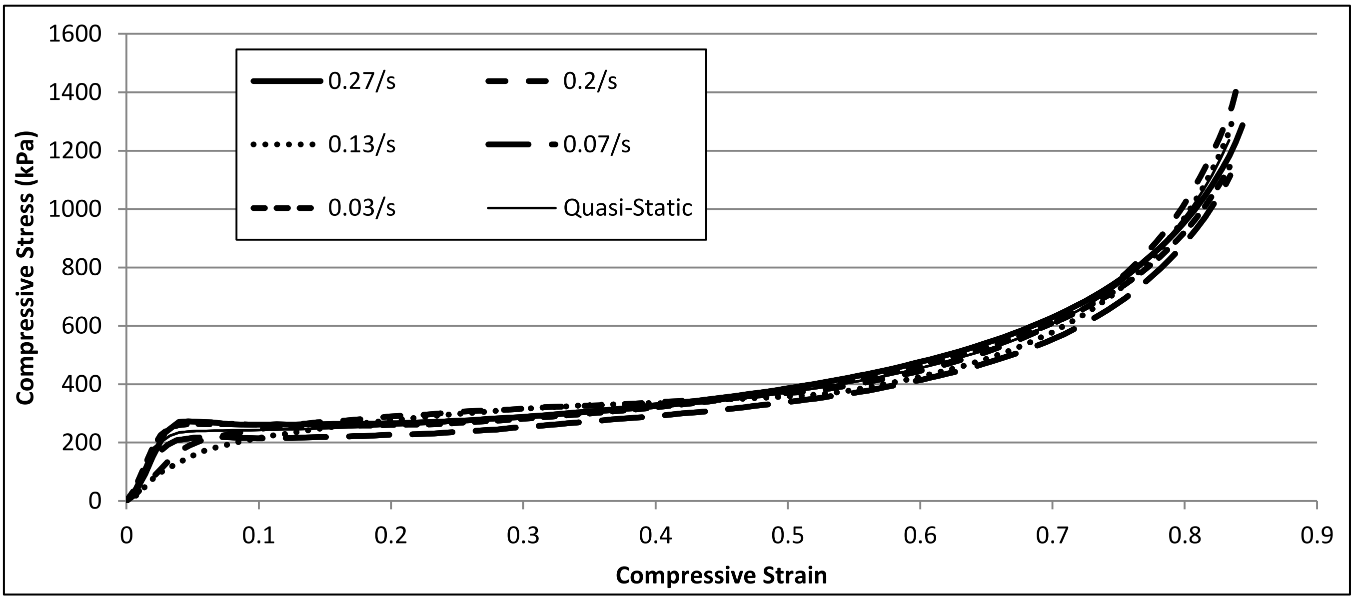

FIGURE 01: Stress versus strain for the compressive loading of XPS 35 foam at a range of strain rates

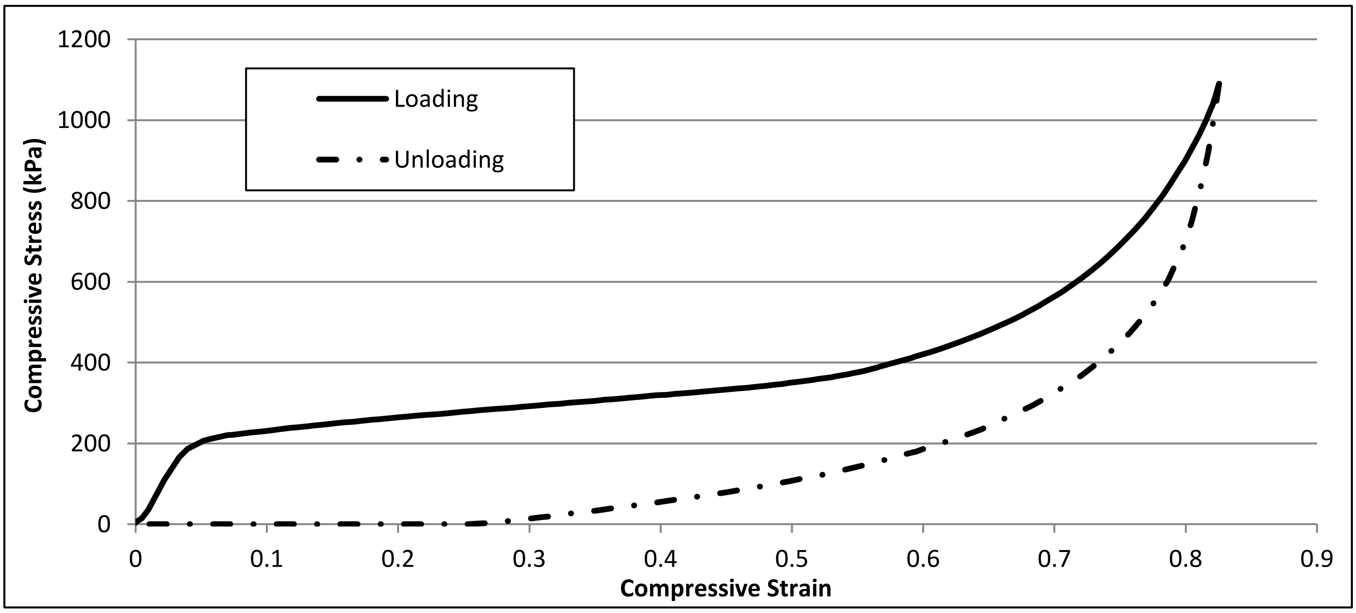

FIGURE 02: The averaged stress versus strain for the compressive loading and unloading of XPS 35 foam

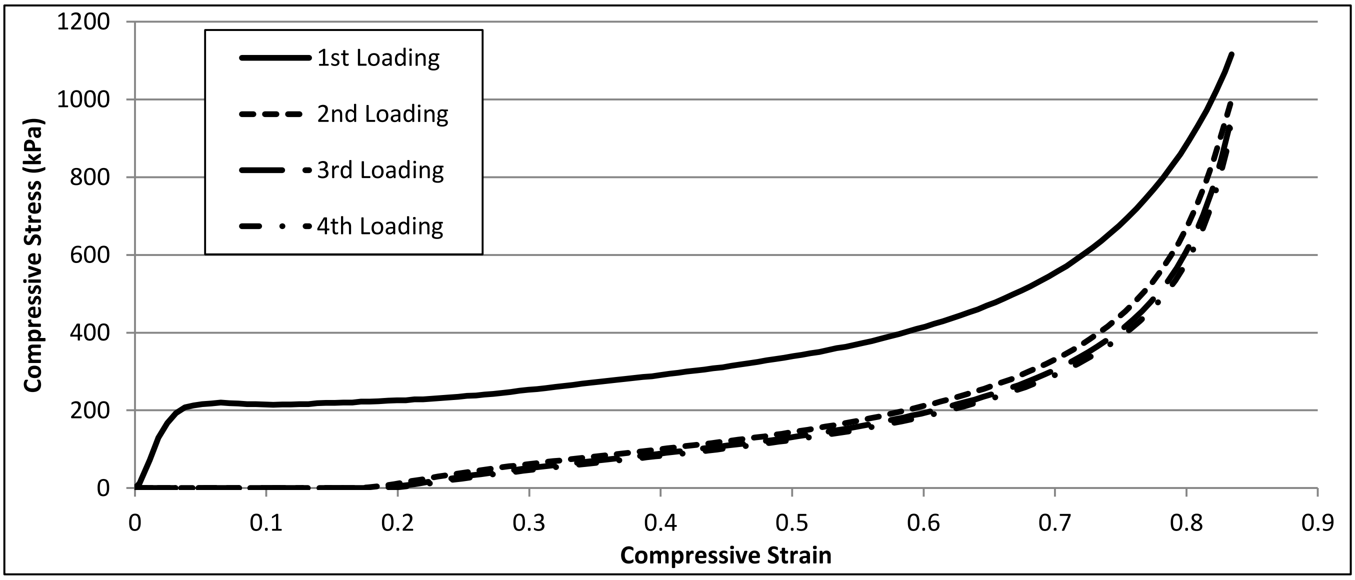

FIGURE 03: The averaged stress response of the XPS35 foam for four sequential loadings

Force and deflection were measured and recorded using the Instron 5567 and the associated software, which was later used to calculate the principal stress and principle strain values for analysis and input into the numerical material model.

3.2 **Material sample preparation**

The XPS foam used in the experiments had a density of 35 kg/m^3 and is known commercially as Foamular 250. The samples obtained originally had been sun damaged, therefore in the preparation of the specimens it was important to remove any portions that had been damaged. The specimens were cut to size using a wire cutter to 30x30x30 mm. Each specimen was visually checked for imperfections, including cracking, large variances in cell size and sun damage.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 **Low strain rate testing**

The experiments produced stress-strain curves from all of the compression strain rates that were tested. There was little variation between the strain rates, as can be seen in . shows the foam displaying the three separate stages of response of initial elastic, densification plateau and solidification phase. The densification plateau of the XPS foam can be seen to increase with strain due to the closed cell nature of the foam.

Energy absorption of the foam was relatively constant over the range of examined strain rates, with the average specific energy absorption (SEA) of the XPS 35 foam measured to be 8.90 kJ/kg and a maximum variation of 9%. Due to the buckling and plastic deformation of the internal structure of the foam, energy absorption dropped off considerably after the initial loading (**Error! Reference source not found.**). The SEAs of subsequent compressions were to reduced averages of 4.14, 3.74 and 3.57 kJ/kg. Analysis of the first unloading phase revealed an average of 66% of the initial absorbed energy would be elastically released, with 3.01 kJ/kg being plastically retained. Residual plastic strain in the post compression foam was averaged at 25% regardless of the number of compressions.

There were issues concerning the repeatability of the results which were caused by inconsistencies in the foam‘s structure. Sections of the foam which were denser (i.e. had a smaller cell size) had a longer initial deformation phase, which lead to uneven deformation of the foam. These results were easily identifiable and were filtered out from the data set. Larger dimensions for the specimens would help to minimise the effect of the denser regions, however it would adversely result in a smaller range of available strain rates.

5 MATERIAL MODEL DEVELOPMENT

5.1 **Numerical simulation development**

A functioning numerical material model of the XPS 35 foam was created for use in the explicit finite element code LS-DYNA. The material model was required to simulate certain important characteristics of the XPS foam, including the three phases of the loading, the hysterical unloading behaviour and the strain rate dependence at impact rates. To achieve these functional requirements the Fu-Chang material formulation (MAT_83) was chosen as the material formulation to develop the model.

Using this material formulation, the model can be produced in two separate ways; specification of the twelve separate material parameters which dictate to loading and unloading behaviour as per Section 2.3, or supply the stress strain curves for the relevant strain rates and a quasi-static unloading curve, from which the material parameters will be calculated by LS-DYNA (Hallquist, 2006). The later method was selected and the data was entered into the material model with consideration given to the need for a closed-loop between the loading and unloading curves. Hysteresis effects were calculated based on the stress-strain data to give the most accurate behaviour, though this led to a minor increase in computational cost of the model. As there was negligible variability in the loading responses of the different strain rates (Fig. 01), the averaged response (Fig. 02) was used as to construct the material model. This approach reduces the computational time associated with the elemental behaviour considerable, though no strain rate affects will be implemented in this material model. From the stress response plot, the solver internally calculated the twelve material constants as per (2), (3), (4), (5), (6) and (7), which were used to determine the response of the foam.

A simulation was established in the pre-processor LS-PrePost based on the experimental process as previously detailed. The foam specimen model, which consisted of 125 solid elements (Fig. 04), was constructed and meshed using MSC Patran® (MSC Software Corporation, 2008) then exported in LS-DYNA keyword format for use in LS-PrePost (LSTC, 2010b). A single point co-rotational element formulation was used in conjunction with stiffness controlled hourglass control for the foam elements. One static rigidwall was used to simulate the fixed bottom platen of the Instron 5567, with a moving rigidwall was using to simulate the compression platen. The moving rigidwall‘s motion was defined by a displacement curve which was based on the experimental strain rates, with the transition from loading to unloading smoothed in order to ensure numerically stability. Simulations were created for each of the strain rates used in the experiments.

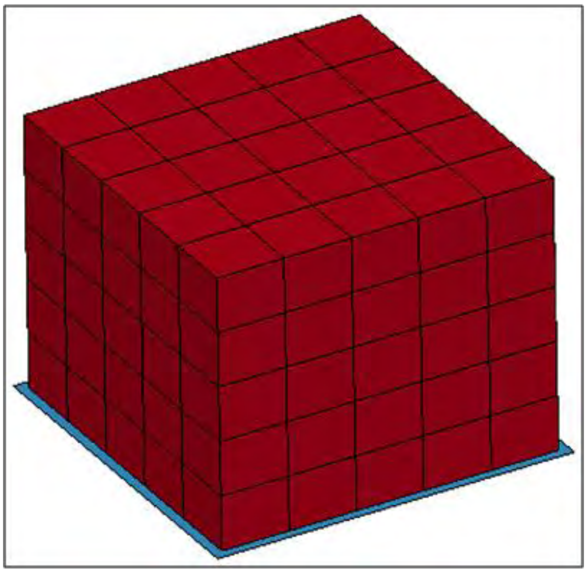

FIGURE 04: Numerical simulation of experimental process viewed in LS-PrePost at 25% strain

5.2 **Simulation discussion**

The simulation took 120 minutes to calculate on a single 1.6 GHz CPU with 4 GB for memory for a strain rate of 0.27/s. This relatively long solve time was a product of the small geometric size of the mesh and the long simulation time. Further studies where performed with a range of mesh sizes. A finer mesh resolution resulted in good correlation to testing data along with a greatly increasing computational cost. Correlation was achievable with a coarser mesh was achievable; however it required a much more aggressive hourglass formulation. The stress and strain results of the simulation correlated directly with those of the experimental procedure. The material model was able to accurately simulate the

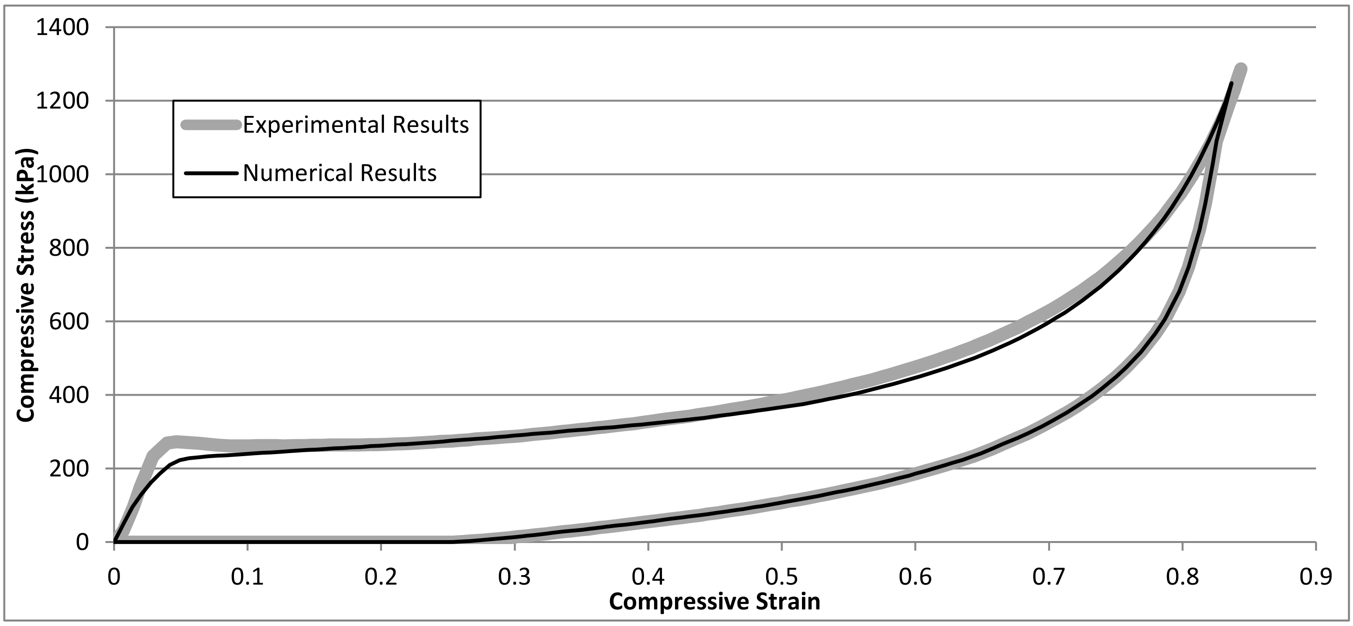

FIGURE 05: Stress strain response of the numerical simulation compared to the response of the experimental tests at 0.27/s

material response as shown in Fig. 05. Some numerical errors were observed in the transition between the loading and unloading, which was cause by a combination of the stiff contact between the foam and the rigidwall, and elemental effects of the transition. This disparity is considered minor as it has an extremely minor effect on the behaviour and does not detract from the numerical stability of the model. A number of strain rates were simulated, with all rates resulting in a stable stress response as it was designed to.

During the development of the numerical simulation, a number of parameters were determined to have an important influence on the behaviour of the model. The choice of element formulation was important, as using fully integrated or semi-reduced elements resulted in an overly stiff response causing numerical instabilities. To remedy this, a single point element formulation was used, which necessitated the use of hourglass control for these elements. A stiffness based hourglass control was found to work best for low velocity impacts and was used successfully in these simulations.

6 FUTURE WORK

Based on the data produced by the experimental process and limitations discussed, a new experimental design process is being constructed. This experimental design will test the XPS foam at higher rates using a tensile testing machine (MTS 810) with a capacity for higher velocities. Material specimen size will also be increased in order to limit the effect of material variations and discontinuities of the foam. The results of these tests will allow the behaviour of the XPS foam to be determined at strain rates up to 4/s, which are expected for its application in a road safety barrier. These experiments will also be performed on a range of densities of XPS foam, which will assist in creating the optimal design of road safety barrier.

Work is continuing using the numerical material model developed and it will be used in future studies in the development process of the road safety barrier. New data from aforementioned experiments will be added to the material model to ensure it will produce the most accurate results at the expected impact strain rates.

7 CONCLUSION

An experimental testing process has been carried out to assess the behaviour of extruded polystyrene foam at low strains rates. The results of the experimental process showed that the response of the foam remains effectively constant across the static of strain rates tested. The loading response of the foam showed the three distinct phases that are sought after in impact attenuating devices. The unloading response showed that a significant portion of the initial energy absorbed was elastically released and that the material had a significant permanent amount of plastic deformation.

The data from the experimental process was used to create a material model of the foam using the Fu-Chang formulation for use in the explicit finite element solver LS-DYNA. A simulation of the experimental process was created in order to ensure the accuracy of the material model. A number of elemental and material parameters needed to be correctly and accurately defined in order to obtain an accurate response. The results of the numerical simulation showed that the XPS foam material model is capable of accurately simulating the response of the material and it will be used to assess the potential of using the polymeric foam as part of a new design of portable road safety barrier.

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