NOVEL ENERGY ABSORBING MATERIALS WITH APPLICATIONS IN HELMETED HEAD PROTECTION.

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A finite element, functionally graded foam model (FGFM) is proposed, which is shown to provide more effective energy absorption management, compared to homogenous foams, under low energy impact conditions. The FGFM is modelled by discretising a virtual foam into a large number of element layers through the foam thickness. Each layer is described by a unique constitutive cellular response, which is derived from the initial foam density, ρ, unique to that layer. Large strain unixial compressive tests at a strain rate of 0.001 s^{-1} are performed on expanded polystyrene (EPS), and their $\sigma-\varepsilon$ response is used as input to a modified constitutive model from the literature. It is found that under low energy impacts an FGFM can outperform a uniform foam of equivalent density terms of reducing peak accelerations, while performing almost as effectively as uniform foams under high energy conditions. These novel materials, properly manufactured, could find use as next generation helmet liners in answer to recent, more rigorous equestrian helmet standards, e.g. BS EN 14572:2005.

KEY WORDS: constitutive model, functionally graded foam, energy absorption.

INTRODUCTION: Cellular foams are widely used in energy absorbing applications where it is important to minimise the peak acceleration of the impacting body (Hilyard & Djiauw, 1971), e.g packaging of fragile goods, helmets and head protection systems (Doorly & Gilchrist, 2006) and body garments. This is due to their low solid volume fraction and complex microstructure, which allows large degrees of plastic crushing to occur at a fairly constant plateau stress value.

The ability of a uniform foam in reducing the peak acceleration of an impacting body is dependant on both volume and density. It is shown in this study that by varying the density spatially throughout the volume of a foam, it is possible to dramatically reduce peak accelerations without the need to increase its volume. This technique could have reaching implications in helmet manufacture, whereby such foams could provide additional head protection without sacrificing helmet aesthetics in the form of increasing the liner thickness.

METHODS: Data Collection: The ABAQUS crushable foam model (ABAQUS, 2007), in conjunction with an existing model from the literature (Schraad & Harlow, 2006) was used to describe the $\sigma-\varepsilon$ behaviour of each element layer through a virtual foam's thickness. In order to calibrate the Schraad & Harlow model for any given ρ, large strain uniaxial compression tests on expanded polystyrene (EPS) specimens of density 15, 20, 25, 50 and 64 $kg.m^{-3}$ were performed. Using data from these results, the model could be calibrated to generate a complete $\sigma - \varepsilon$ curve from an arbitrary ρ, value as an input argument. Table 1 shows the material gradients and density ranges used in the simulations for a density difference of $\Delta\rho$ = 40 $kg.m^{-3}$. For all simulations the material gradients decreased monotonically from the striker to the anvil face as preliminary results showed this to be the more favourable gradient orientation for reducing peak accelerations. A single striker impact velocity of 5.4 $m.s^{-1}$, for striker masses of 1, 2, 4, 6, 8, 10, 12 and 14 kg, was used in all simulations and rate independent plasticity was assumed in order to quantify the influence of the material gradients alone. Figure 1 shows the model geometry used during the simulations. The foam relative density is the controlling parameter in describing the shape of each $\sigma-\varepsilon$ curve. By varying this parameter in an incremental manner, it is possible to generate multiple $\sigma-\varepsilon$ curves and calibrate the ABAQUS crushable foam model for a range of foam densities. Each calibrated crushable foam model for a given density may then be assigned to a given element layer through the specimen thickness, creating a quasi-graded cellular constitutive response. This methodology has previously been used by Cui et al, 2009a and Kiernan et al, 2009b for investigating the dynamic behaviour of FGFMs.

Table 1. Material gradients with density ranges used in striker impact simulations.

Gradients	Density Range (kg.m^{-3}) $\Delta\rho$ = 40 kg.m^{-3}				
Uniform	44	54	64	84	104
Logarithmic	74.4 – 34.4	84.4 – 44.4	94.4 – 54.4	114.4 – 74.4	134.4 – 94.4
Square Root	70.6 – 30.6	80.6 – 40.6	90.6 – 50.6	110.6 – 70.6	130.6 – 90.6
Linear	64.0 – 24.0	74.0 – 34.0	84.0 – 44.0	104.0 – 64.0	124.0 – 84.0
Quadratic	57.5 – 17.5	67.5 – 27.5	77.5 – 37.5	97.5 – 57.5	117.5 – 77.5
Cubic	54.2 – 14.2	64.2 – 24.2	74.2 – 34.2	94.2 – 54.2	114.2 – 74.2

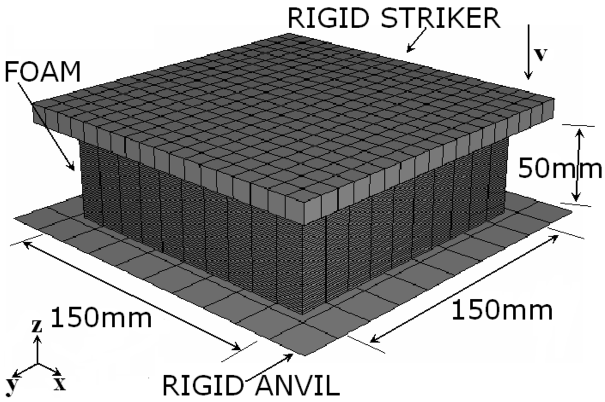
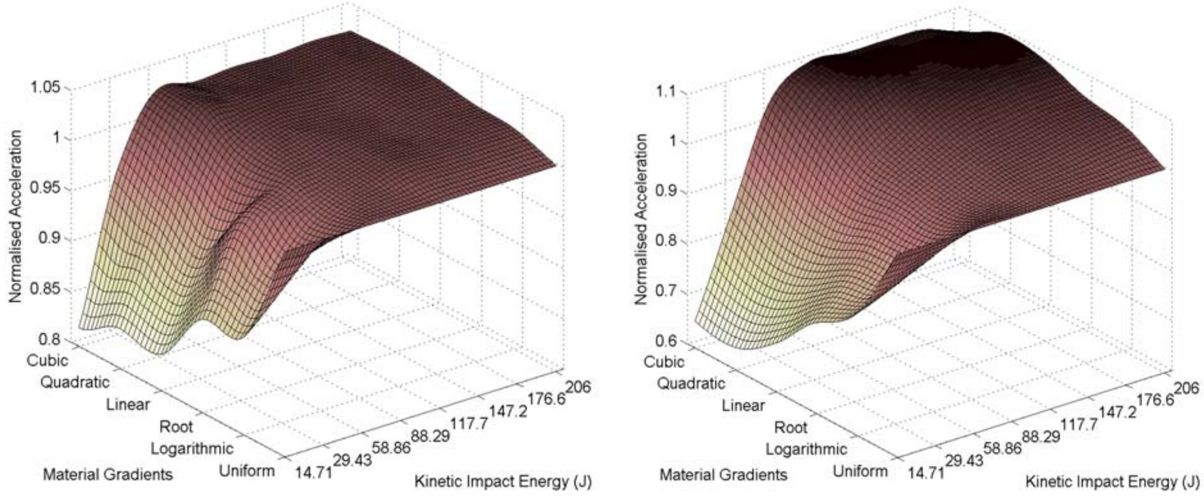


Figure 1. Modelling of the FGFM is achieved by approximating a specimen with a continuous variation in material properties as fifty discrete, finely meshed element layers though the thickness, with a unique $\sigma - \varepsilon$ curve associated with each layer along the z-direction.

RESULTS: By plotting the peak acceleration (normalised against the peak acceleration of the equivalent uniform foam) of each simulation against input parameters such as material gradient and kinetic impact energy, it can be easily seen in Figure 2 under what conditions a FGFM is most advantageous in reducing the peak acceleration of an impact. The average density of all gradients shown here is 54 kg.m^{-3}, with a density difference of 20 kg.m^{-3} and 40 kg.m^{-3} in Figure 2(a) and 2(b) respectively. It is clear that increasing this density range has a considerable influence on peak acceleration values in the low energy region while only a slight influence at higher energies.

DISCUSSION: The surface plots of Figure 2 are indicative of an FGFMs impact response for the different average densities examined. For low kinetic energy impacts, a graded foam performs more effectively than an equivalent uniform foam and the convex gradients (e.g. quadratic) perform better than the concave gradients (e.g. square root). However, as the impacting mass (and therefore KE) is increased to 14 kg, an opposite trend is observed. The marked improvement of the FGFM over the uniform foam in reducing the peak acceleration of the lower energy impacts can be explained as follows.

A homogenous foam is most efficient at absorbing impact energy when it works within the plateau strain region, up to densification, as it is here where it absorbs most energy under large plastic strains with little corresponding increase in stress.



(a) $\Delta\rho = 20$ kg.m^{-3} (b) $\Delta\rho = 40$ kg.m^{-3}

Figure 2. Surface plots of normalised (against uniform foams) peak accelerations of five material gradients across a range of striker impact energies. Significant reduction of peak acceleration is seen in the low energy regions of the plot.

From simulation it was found that for a uniform foam of 44 kg.m^{-3}, the stress imparted at the time of peak acceleration was 198 kPa for a striker energy of 206J and was 581 kPa for a striker energy of 14.71J. From the experimental $\sigma - \varepsilon$ compression tests it can be deduced that 44 kg.m^{-3} EPS foam will yield at about 310 kPa and thus will not yield when struck with a striker of 1 kg at 5.4 m.s^{-1} (14.71J), but rather will behave elastically with very little deformation, resulting in high peak accelerations. However, when struck with a striker of 14 kg at 5.4 m.s^{-1} it will absorb the corresponding kinetic energy within the plateau stress region up to 0.6 strain. The FGFMs perform distinctly better than the uniform foam when absorbing the lower energies due to their spatially varying yield surface, a direct result of the density gradient. From Table 1, for example, the density of a cubically varying foam with an average density of 44 kg.m^{-3} will vary from 54.2 kg.m^{-3} to 14.2 kg.m^{-3}. At 14.2 kg.m^{-3}, local plastic deformation was found from simulations to initiate at about 100 kPa, deforming to almost 0.7 strain, and approximately 20% by volume (14.2 - 28 kg.m^{-3}) of the graded foam will yield plastically at a stress of 198 kPa. This is in stark contrast to the equivalent uniform foam, which exhibits no yielding at this stress level. As the kinetic energy of the striker is increased the advantage gained by a varying yield surface diminishes rapidly. Low yielding regions of the FGFM are no longer effective and local deformation beyond their densification strains occurs while mitigating only a small fraction of the total energy.

Results show that a uniform 44 kg.m^{-3} foam experiences 0.54 strain at the incident surface and 0.52 strain at the distal surface when impacted by a 14 kg striker at 5.4 m.s^{-1}. In contrast, the cubically varying FGFM deforms locally to only 0.2 strain at the incident surface and yet there is 0.98 strain at the distal face. Intuitively, and from previous work (Avalle et al. 2001), it is more advantageous for a foam's entire volume to deform up to, but not beyond, its densification strain if it is to act most effectively as a cushioning structure.

CONCLUSION. A functionally graded polymeric foam model was proposed and its energy absorbing ability has been analysed using the finite element method. The influence of material distribution, controlled by various explicit gradient functions, was studied. The main findings can be summarised as:

It is shown that a functionally graded foam can exhibit superior energy absorption over equivalent uniform foams under low energy impacts, and that convex gradients perform better than concave gradients. This advantage is negated when the impact energy becomes significantly high such that low-density regions of the graded foam become ineffective at bearing the higher load and they densify after absorbing only a small fraction of the total energy. What constitutes a 'high energy impact' is somewhat difficult to define but will depend on the average density of the foam, matrix composition, and the density gradient.
For a specified density range the energy absorption performance of a functionally graded foam under low energy impacts can be improved if the density range is increased. For higher energy impacts, increasing the density range can reduce the performance of the graded foams due to a higher volume fraction deforming beyond the densification strain. Functionally graded foams are capable of reducing the duration of the high acceleration during an impact event. This property could have wide implications in the head protection industry as many head injury criteria rely on acceleration durations as indicators of the likelihood for a person suffering significant head trauma. In this respect, protective headgear, e.g., safety helmets, employing functionally graded foams as the liner constituent may be advantageous to the wearer in reducing the risk of brain injury after a fall.
Traditionally, many helmet certification standards require a helmet to keep the acceleration of a headform dropped from a single drop height below some certain target level – achieving this is quite simple. However, recent helmet standards demand that helmets be effective at multiple drop heights, thus simulating both high and low energy impacts. This can be more difficult to achieve with current helmet liner technologies. Functionally graded foams have been shown to exhibit significant advantages under low energy impact conditions while still performing nearly as well as their uniform counterpart under high energy conditions. These foams, carefully manufactured, may be one possible answer to the more stringent requirements of emerging helmet standards such as BS EN 14572:2005.

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