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Optimisation of energy absorbing liner for equestrian helmets. Part II: Functionally graded foam liner

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ABSTRACT

The energy absorbing liner of safety helmets was optimised using finite element modelling. In this present paper, a functionally graded foam (FGF) liner was modelled, while keeping the average liner density the same as in a corresponding reference single uniform density liner model. Use of a functionally graded foam liner would eliminate issues regarding delamination and crack propagation between interfaces of different density layers which could arise in liners with discrete density variations. As in our companion Part I paper [Forero Rueda MA, Cui L, Gilchrist MD. Optimisation of energy absorbing liner for equestrian helmets. Part I: Layered foam liner. Mater Des [submitted for publication]], a best performing FGF liner configuration was identified for a variety of different test conditions. Similar results were found and these compare favourably against the energy absorption of uniform density foam liners. Reduction in peak accelerations is dependant of contact area, the distribution of stress along the thickness of the liner, and the dissipated plastic energy density (DPED). This suggests that it should be possible to use FGF liners instead of discrete foam layers to reduce peak linear acceleration and thereby to maximise the energy absorbing efficiency of the available space within a helmet.

1. Introduction

A companion Part I paper to this present Part II paper [1] has developed a generic finite element (FE) model of an equestrian racing helmet to optimise the helmet liner configuration for energy absorption performance. This study was motivated by the new high performance helmet standard EN 14572:2005 [2], which is a complement to the current European certification standard for equestrian helmets (EN 1384:1996 [3]) and is intended for “high-risk” activities. A particular challenge in manufacturing helmets to pass this standard is the requirement for a helmet to simultaneously protect against both high and low energy impacts. At present no commercially available helmet conforms to this standard. Our previous paper [1] has proposed an approach to this challenge to manufacture helmets conforming to standard EN14572:2005 by using a layered foam liner. Such a layered foam liner would consist of discrete layers of uniform foams, each having different densities, and thus energy absorbing characteristics. These could be used easily in current manufacturing processes to replace single uniform foam energy absorbing liners. However, a possible problem with using such layered materials, especially in the event of poor quality control during manufacturing, is the concentration of localised stresses at discrete layer interfaces: these localised stresses could lead to delamination [4–6] and subsequent crack propagation. This present paper introduces the concept of a functionally graded foam (FGF) liner which would avoid the discreteness in material properties and thus prevent such potential failures of layered liners whilst retaining their improvements in energy absorbing performance.

A FGF is a material, the characteristics of which (e.g., density, stiffness, yield stress) vary through the thickness according to various gradient functions. Functionally graded materials are ideally suited for use in energy absorbing structures [7,8]. A functionally graded material model was developed in a previous study [9] in order to evaluate the energy absorption capacity of alternative cushioning structure designs. Alternative designs for helmets using FGF liners were virtually tested in the current study using this constitutive model to measure their energy absorption performance and thereby to optimise and obtain the best performing configurations of gradients.

The computational model and simulation parameters are described first in the following section. The best performing helmet FGF liner configurations for each impact position and each impact velocity are obtained from the optimisation study. Then, the best performing configuration for one impact position, 45° side impact, are considered in detail. The peak acceleration, the contact areas at the inner and outer surfaces of liners, the von Mises stress and the dissipated plastic energy density in various layers are analysed in detail. Finally, the relationship between peak acceleration, contact area, stresses, and plastic energy is illustrated.

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2. Fe model and simulation parameters

The FE models have been described in detail in our companion paper [1] and consequently, will only be outlined here. The helmet model consists of an outer shell, a foam liner, a foam block and a ring, as shown in Fig. 1. The headform is simulated as a rigid body, while the outer shell of the helmet is modelled as a linear elastic material, and the ring as a rubber elastomer. The foam block joining the shell and foam liner is modelled as a hyperelastic elastomeric compressible foam. The foam liner, made from expanded polystyrene (EPS) [10,11], is modelled using a crushable foam model with a volumetric hardening rule combined with the linear elastic model. ABAQUS/Explicit [12] was used with a central-difference time integration rule for all the dynamic impact tests. The headform elements were modelled using three-dimensional four node elements (R3D4), while the foam liner and the foam block were both modelled with three-dimensional eight node linear brick elements with reduced integration and hourglass control (R3D8R). The outer shell was modelled using four node thin shell elements (S4R). The only difference in the FE model of this present paper and our previous paper [1], which concentrated on using a layered foam liner instead of a FGF liner, is the mesh density of the foam liner. In this present paper, the foam liner is meshed using 20 elements through its thickness and each layer of elements is assigned a material property to obtain a quasi-smooth variation from one surface to another.

The constitutive models and mechanical properties of the component materials have already been described fully [1]. The stiffnesses, densities and Poisson's ratios of all materials other than the energy absorbing foam liner are the same as in our companion paper [1]. The FGF used in the current simulations has its density increased or decreased through the thickness according to a power-law gradient function as

$$\rho(y) = \rho_1 + (\rho_2 - \rho_1)\left(\frac{y}{d}\right)^n$$

where ρ_1 and ρ_2 are the densities at the exterior surfaces of one foam specimen and d is the depth of the foam block in the thickness direction. The stress–strain curve for each density follows the relationship as described in previously by Cui et al. [9]. Typical curves are shown in Fig. 2, and yield and plateau stresses for foams of typical densities are listed in Table 1. In order to make parallel comparisons between the foam of uniform density and the FGF, all the FGF liners are targeted to have the same average density as the corresponding uniform foam liner. Parameters of the gradient functions and density ranges used in the simulations are listed in Table 2.

Simulations using the FGF liner were carried out for three impact velocities which correspond to those in the certification test standards [2,3], namely, 7.7 m/s, 5.4 m/s and 4.4 m/s. The 5.4 m/s impact speed corresponds to the test conditions of the EN1384:1996 standard [2], whereas the 7.7 m/s and the 4.4 m/s correspond to the high energy and low energy impact conditions of the EN14572:2005 standard [3]. In the results of the following section, these test conditions are referred to as the "1384 impact", the "high energy" impact and the "low energy" impact, respectively. Three impact positions against a flat anvil, which also correspond to those in the same test standards, were considered, namely 45° side impact, 45° front impact and normal crown impact. These impact positions and impact velocities are the same as have been investigated using a layered foam liner in our earlier work [1].

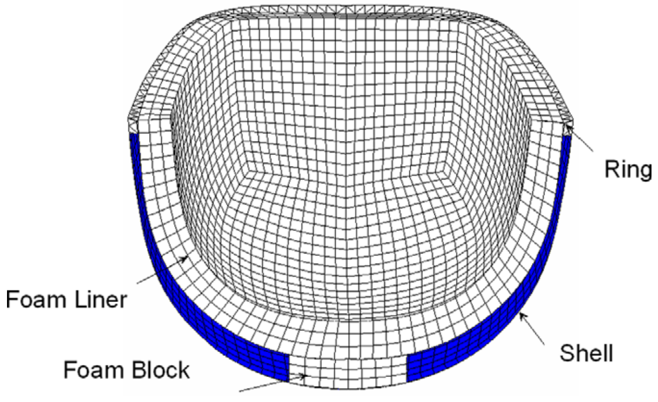

Fig. 1. Components of helmet finite element model.

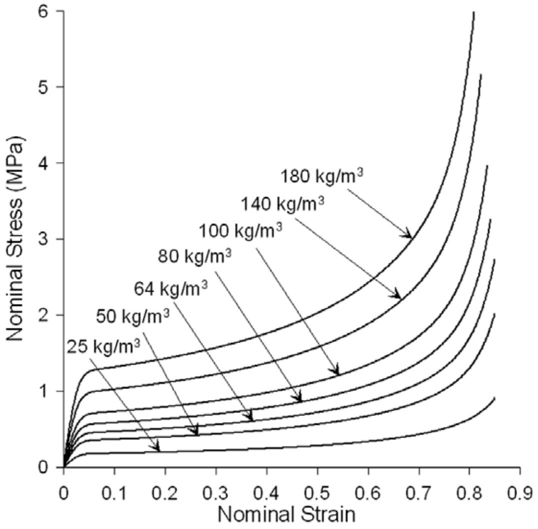

Fig. 2. Stress–strain curves for representative densities of EPS foam.

Table 1
Yield and plateau stresses for foams of different densities, as obtained from the constitutive model [7].

Density (kg/m^3)	Yield stress (kPa)	Plateau stress (kPa)
25	180	180–380
50	350	350–760
64	450	450–970
80	580	580–1200
100	720	720–1510
140	1000	1000–2120
180	1250	1250–2720

Table 2
Parameters for the FGF used in the simulations.

Gradient function	Power index	Density range $\Delta\rho$ (kg/m^3)
Uniform foam	–	64
Linear	$n = 1$	[54, 74] $\Delta\rho = 20$
		[44, 84] $\Delta\rho = 40$
		[34, 94] $\Delta\rho = 60$
		[24, 104] $\Delta\rho = 80$
Non-linear	$n = 0.25$	[48.97, 68.97] $\Delta\rho = 20$
		[33.93, 73.93] $\Delta\rho = 40$
		[18.90, 78.90] $\Delta\rho = 60$
	$n = 4$	[59.33, 79.33] $\Delta\rho = 20$
		[54.65, 94.65] $\Delta\rho = 40$
		[49.98, 109.98] $\Delta\rho = 60$
		[45.30, 125.30] $\Delta\rho = 80$
		[40.63, 140.63] $\Delta\rho = 100$
		[35.96, 155.96] $\Delta\rho = 120$
		[31.28, 171.28] $\Delta\rho = 140$
		[26.61, 186.61] $\Delta\rho = 160$