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Optimisation of energy absorbing liner for equestrian helmets

Part II: Functionally graded foam liner

L. Cui, M. A. Forero Rueda and M. D. Gilchrist*

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 [1], 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.

KEYWORDS

Functionally graded foam material, Safety helmets, Energy absorbing liner; Head impact

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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.

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.

Fig. 1

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.

Fig. 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, 7.7m/s, 5.4m/s and 4.4m/s. The 5.4m/s impact speed corresponds to the test conditions of the EN1384:1996 standard [2], whereas the 7.7m/s and the 4.4m/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].

SIMULATION RESULTS

Peak Accelerations

Peak accelerations for the best performing helmets based on using FGF liners under various impact conditions are listed in Table 3. In each case, the energy absorption of the FGF liner is compared against the performance of a standard uniform foam liner under the same corresponding test conditions. All the best performing FGF liners for each test condition have a higher density foam on the inner layers and lower density on the outer layers, with the exception of one case as indicated in Table 3 by "*". For the 45° side impact position, the best performing liner configuration for the low energy impact reduced the acceleration by 17.3%, while the best configuration for the high energy impact reduced the acceleration by only 0.5%. For the 45° front impact position, the best configuration for the low energy impact reduced the acceleration by 15.3%, while the best configuration for the high energy impact reduced the acceleration by only 1.6%. For the 90° crown impact position, the best configuration for the low energy impact reduced the acceleration by 6.2%; the best configuration for the high energy impact reduced the acceleration by a mere 0.4%. For the 45 ° side impact tests and the 45° front impact tests, most of the FGF liner configurations performed better than the uniform foam liner in the 1384 impact and the low energy impact. The FGF liners which had a wider density range typically improved the performance by a greater amount, providing that the lower density layers were not crushed entirely.

As shown in Table 3, the best performing liner configurations for each impact speed are different. One configuration that performs well under most impact conditions (except for the high energy impact, for which the numerical simulations failed prematurely) is n=4 [35.96, 155.96] $\Delta\rho=120$ (kg/m^3). The peak accelerations for this configuration are shown in Table 4. This configuration improved the performance of the helmet in most of the impact conditions with one single exception.

Contact Areas

Similar to the analysis for the layered foam liner, the contact area between the inner surface of the liner and the headform, and the contact area between the outer surface of the liner and the shell are also analysed for the 45 ^{o} side impact. Fig. 3 compares the evolution of the contact areas for the uniform liner and the FGF liner. The contact areas in the FGF liner in the 1384 impact and the low energy impact are larger than those in the uniform liner (Figs. 3(a), 3(b)), especially at the outer surface where more compliant foam material is located. In the high energy impact, the contact area at the inner surface of the FGF liner is slightly smaller than that of the uniform liner, while the contact area at the outer surface of the FGF liner is slightly larger than that of the uniform liner (Fig. 3(c)). This analysis confirms the relationship that the larger contact areas are consistently related to the lower peak accelerations.

Fig. 3

Distributions of Von Mises Stresses

The distribution of stress and energy absorption through the thickness of the uniform foam liner as well as through the thickness of the FGF liner are analysed below for the condition of the 45 ^{o} side impact. This serves to explore how the FGF configurations improve the energy absorption beyond that provided by the uniform foam liner. The distributions of von Mises stresses at peak acceleration in those in the innermost to outermost layers of the FGF liner and the uniform foam liner are illustrated in Figs. 4(a) to 4(f). When generating these distribution plots, 20 equal intervals of von Mises stresses in the range of [0, 1500] kPa are considered, as shown along the x-axis. The volume fraction of liner materials in the corresponding layer exhibiting stresses in each stress interval is calculated and indicated by “○” or “□ ”. The distribution plots are generated by connecting the “○” or “□ ” volume fractions. To illustrate the mechanics of energy absorption more clearly, only the liner materials that contributed to the plastic energy dissipation are considered for this von Mises stress analysis. These materials are found to be localised around the impact position. To ensure clarity in Fig. 4, only 5 layers out of the total 20 layers through the thickness in the FGF liner are considered in these plots. Similarly, to ensure a direct comparison between the uniform foam liner and the FGF liner, both types of liners were considered to contain 20 layers through thickness in the simulations, i.e., for the same uniform liner, each simulation is performed twice: one contains 3 layers and the other contains 20 layers.

Fig. 4

As shown in Figs. 4(a), 4(c) and 4(e), for the uniform liner, stresses in different layers are comparable, while there are only smaller volumes of liner material reaching these levels in the outer layer than in the inner layer. For the 1384 impact (Fig. 4(b)) and the low energy impact (Fig. 4(d)), the stress levels decrease quickly from the innermost layer to the outermost layer. The majority of stress levels for the Inner 1 layer and the Inner 2 layer are much higher than for the three outer layers, but far fewer amounts of foam liner material contribute to the plastic energy dissipation in the two inner layers than in the three outer layers. For the high energy impact (Fig. 4(f)), the stress levels decrease slightly from the innermost layer to the outermost layer, with similar volumes of foam contributing to the plastic energy dissipation.

The comparison between Fig. 4 and Table 1 illustrates a similar relationship as observed from the study of a layered foam liner. For the FGF liner in the 1384 impact, most of the liner reaches the early and middle plateau stage. However, the volumes of liner material contributing to plastic energy dissipation in the inner layers are much smaller than those in the outer layers. For the FGF liner in the low energy impact, the inner layers reach the initial and early plateau stage, while the outer layers reach the middle and late plateau stage. The quantity of liner material contributing to plastic energy dissipation in the inner layers is also much smaller than those in the outer layers. For the FGF liner in the high energy impact, most of the liner reaches the initial and early plateau stage. Similar quantities of material contribute to plastic energy dissipation in the various layers. Based on the comparison of stress levels, it can be seen that the efficiency of energy absorption for the FGF liner is improved in the 1384 impact and in the low energy impact, while it remains similar to the uniform foam liner in the high energy impact. This agrees with the findings of peak accelerations.

Dissipated Plastic Energy Density (DPED)

The comparison of the DPED (the quantity of dissipated plastic energy normalised by the corresponding volume of material) between the FGF liner and the uniform foam liner is illustrated in Fig. 5. For all the test conditions, the DPED for all the uniform foam liners decreases from the innermost layer to the outermost layer. This is because the amount of material contributing to plastic energy dissipation decreases from the innermost layer to the outermost layer, as described above.

Fig. 5

In the 1384 impact and the low energy impact for the FGF liner, the different density layers reached their respective plateau stages; however, the respective volumes of foam contributing to plastic energy dissipation is low in the inner layers (Figs. 4(b) and 4(d)). Therefore, the energy density increases from the innermost layer to the outermost layer (Fig. 5), and the energy density for the whole FGF liner is higher than that for the uniform liner. In the high energy impact, the energy density remains similar throughout the liners (Fig. 5) as a combined result of the stress level and the volumes of foam contributing to plastic energy dissipation (Fig. 4(f)). The DPED for the whole FGF liner is similar to that for the uniform liner in the high energy impact. All these findings agree with the comparison of peak accelerations.

DISCUSSION AND CONCLUSIONS

The FE helmet model of our companion Part I paper [1] was modified to allow a FGF energy absorbing liner to be modelled instead of a layered liner. The impact performance of various designs of a graded liner was compared against uniform foam liners of identical weight in order to optimise the best FGF liner configuration. Similar results to those using a layered foam liner were found from the present simulations for the FGF liner, namely:

- Peak acceleration is reduced with increased contact area.

- Peak acceleration is reduced by using the energy absorption capabilities of the liner more efficiently by optimising the balance between absorbed energy and contact force. This is achieved when the foam is in the late plateau stage.
- When analysing the dissipated plastic energy density (DPED), it is seen that it is directly related to reductions in peak acceleration.
- The use of a higher inner liner density and a lower outer liner density can improve efficiency of material usage while strengthening the inner liner section.

A FGF liner can avoid issues regarding crack initiation and propagation that could be associated with discrete interfaces arising from the use of different foam densities in a liner instead of a single uniform foam liner. Cracks in the helmet liner are likely to adversely affect helmet performance and compromise the integrity of a helmet and therefore its energy absorbing capabilities in the event of an impact or crushing. FGF liner manufacturing methods are still in the concept phase even for flat specimens; therefore, considerable work is still required in order to be able to manufacture curved FGF materials which could be applied to helmet liners.

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LIST OF FIGURES

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

Table 3

Best performing helmets with FGF liner (* where higher density outside and lower density inside)

Impact position	Energy	FGF density configuration (kg/m^3)	Acceleration (g = 9.81 m/s^2)	Reduction in Acceleration
45^{o} side	1384	Uniform 64	199.0g	--
		n=4 [40.63, 140.63] Δρ=100	186.4g	6.5%
	Low	Uniform 64	165.0g	--
		n=4 [26.61, 186.61] Δρ=160	136.5g	17.3%
	High	Uniform 64	317.5g	--
		n=1 [54, 74] Δρ=20	315.9g	0.5%
45^{o} front	1384	Uniform 64	198.3g	--
		n=4 [49.98, 109.98] Δρ=60	190.4g	4.0%
	Low	Uniform 64	159.0g	--
		n=4 [26.61, 186.61] Δρ=160	134.6g	15.3%
	High	Uniform 64	320.8g	--
		n=1 [54, 74] Δρ=20	315.7g	1.6%
Crown	1384	Uniform 64	211.8g	--
		n=4 [59.33, 79.33] Δρ=20*	208.0g	1.8%
	Low	Uniform 64	161.9g	--
		n=4 [26.61, 186.61] Δρ=160	151.8g	6.2%
	High	Uniform 64	428.2g	--
		n=4 [59.33, 79.33] Δρ=20	426.7g	0.4%

Table 4

Single best liner configuration of FGF liner for most impact conditions

Impact position	Energy	FGF density configuration (kg/m^3)	Acceleration (g = 9.81 m/s^2)	Reduction in Acceleration
45^o side	1384	Uniform 64	199.0g	--
		n=4 [35.96, 155.96] Δρ=120	189.7g	4.7%
	Low	Uniform 64	165.0g	--
		n=4 [35.96, 155.96] Δρ=120	141.3g	14.4%
45^o front	1384	Uniform 64	198.3g	--
		n=4 [35.96, 155.96] Δρ=120	195.0g	1.7%
	Low	Uniform 64	159.0g	--
		n=4 [35.96, 155.96] Δρ=120	136.6g	14.1%
Crown	1384	Uniform 64	211.8g	--
		n=4 [35.96, 155.96] Δρ=120	224.7g	-6.1%
	Low	Uniform 64	161.9g	--
		n=4 [35.96, 155.96] Δρ=120	154.3g	4.7%