OPTIMISATION OF ENERGY ABSORBING LINER FOR EQUESTRIAN HELMETS

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The density of foam used as energy absorbing liner material in safety helmets was optimised in this paper using Finite Element Modelling (FEM). FEM simulations of impact tests from certification standards were carried out to obtain the best performing configurations of helmet liner. For each test condition, two best liner configurations were identified as minimising peak impact accelerations: one was composed of layers of uniform foam and the other of functionally graded foam (FGF). It was found that the observed decreases in the peak accelerations for the best performing helmets in various test conditions are directly related to the contact area, the distribution of internal stresses, and the dissipated plastic energy density (DPED). Application of the methods described in this study could help increase energy absorption for current and future equestrian helmet designs.

KEY WORDS: Functionally graded foam material, helmets, impact.

INTRODUCTION: Epidemiological statistical studies across the world have shown that horse racing is a particularly risky sport (Forero Rueda et al. 2009), particularly when head injury is concerned. EN 1384:1996 is the current European standard to certify equestrian helmets. The new high performing helmet standard EN 14572:2005 is intended for helmets for "high-risk" activities, but it does not supersede EN 1384:1996. No helmet currently available in the market complies with EN 14572:2005. The EN1384:1996 standard specifies an impact speed of 5.4 m.s^{-1}, while the new standard EN 14572:2005 specifies a "high energy" impact velocity (7.7 m.s^{-1}), as well as a "low energy" impact velocity (4.4 m.s^{-1}). This is with the intention of stimulating the construction of helmets that reduce head injury risk for both high and low impact energies. This study aims to suggest a possible solution to manufacturing helmets conforming to standard EN14572:2005 by optimising the liner density.

METHODS: Model description: The current study developed a FE model of an equestrian helmet based on the geometry of commercially available helmets using ABAQUS (ABAQUS 2009). The helmet model consists of an outer shell, foam liner, foam block and ring. The outer shell is modelled as linear elastic material and the ring is modelled as an incompressible rubber elastomer. The foam block between the shell and foam liner is modelled as a hyperelastic elastomeric compressible foam with material constants specified by experimental test data. The expanded polystyrene (EPS) foam liner material is modelled using the crushable foam model with a volumetric hardening rule in conjunction with the linear elastic model (ABAQUS 2007). The stress-strain curve for the polymeric foam is a function of foam density. Constants for the constitutive model used in the current study have been tested and determined in a previous study (Cui et al. 2009). The curve is tri-linear in form, corresponding to elastic, plateau, and densification stages (Figure 1). It is more efficient that the foam liner absorbs energy within the plateau stage as the stress remains nearly constant over a large strain.

The headform is simulated as a rigid body. The helmeted head is impacted against a flat rigid anvil. The impact positions, crown impact (Fig 2(a)) and 45^{o} side impact (Fig 2(b)), are as recommended in both standards. Impact velocities of 5.4 (EN1384:1996), 4.4 and 7.7 m.s^{-1} (EN 14572:2005) are used. ABAQUS/Explicit was used for the finite element helmet dynamic impact tests. The headform is modelled using three dimensional four node elements (R3D4) with a rigid body constraint at the centre of mass where the linear headform accelerations were read. The liner and foam block is modelled as three dimensional eight node linear brick elements with reduced integration and hourglass control (R3D8R). The shell is modelled with four node doubly curved thin shell, reduced integration, hourglass control, finite membrane strain model elements (S4R) with a section thickness of 2mm.

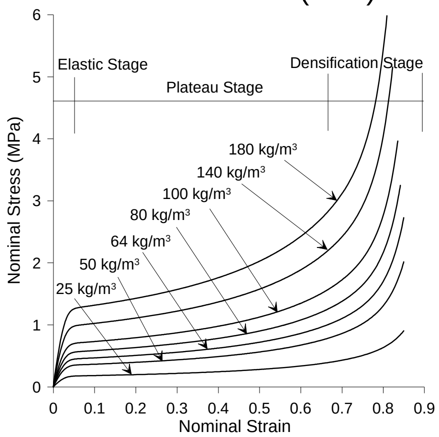

Figure 1: Stress-strain curves for representative densities of EPS foam

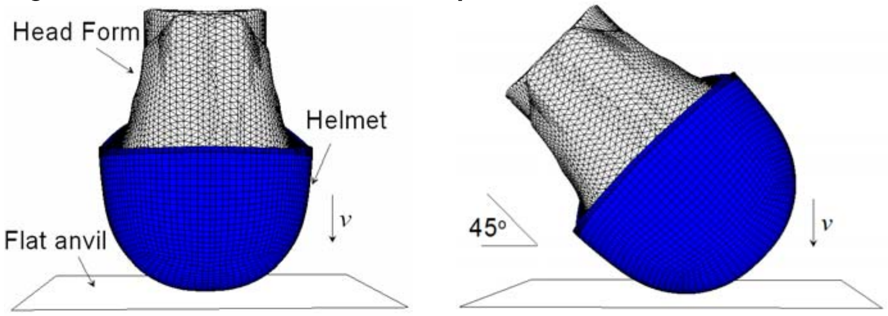

Figure 2: Representative impact configurations (a) 45^{o} side impact; (b) normal crown impact

Simulation parameters: The EPS foam liner material is typically of density 64 kg/m^3. To optimise the liner density, a three equally layered liner and a functionally graded foam (FGF) liner are introduced. The FGF is a type of material, the characteristics of which (e.g. density, strength) vary through the thickness according to various gradient functions. A FGF liner can eliminate issues regarding crack initiation and propagation that discrete interfaces of different foam densities could generate. It is possible to make a liner with different density layers with current manufacturing techniques, while FGF manufacturing methods are still under development. Therefore, both types of liner are considered in this study. Density of each layer is selected from the values of 25, 50, 60, 80, and 100 kg/m^3. The FGF used in the current simulations has its density varied 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 inner and outer surfaces of the liner and *d* is the liner thickness. The FGF liners are set to have the same average density as the corresponding uniform foam liner (64 kg/m^3) to give parallel comparisons. Power index, *n* of 1, 0.25, and 4, and $\Delta\rho$ ($\rho_2 - \rho_1$) of 20, 40, 60, 80, 100, 120, 140, and 160 kg/m^3 are selected for simulations.

RESULTS AND DISCUSSION: The peak accelerations of the best performing helmets with layered foam liners and FGF liners are listed in Table 1 and 2. As there was negligible improvement for three impact positions for the high energy impact, these improvements are still insufficient to make the helmet pass standard EN 14572:2005. However, the best performing helmets of each type substantially improved the energy absorbing performance in the low energy impact and the 1384 impact.

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 analysed for the 45° side impact. Representative comparisons of contact area are shown in Figure 3. Larger contact areas are consistently related to the lower peak accelerations.

Table 1 Peak accelerations of best performing helmets with layered foam liner.

Impact position	Energy	Layered density configuration (kg/m^3)	Acceleration ($g = 9.81\ m/s^2$)	Reduction in Acceleration
45° side	1384	Uniform 64	199.0g	--
		Uniform 50	167.6g	15.8%
	Low	Uniform 64	165.0g	--
		Inner 50-25-25 outer	108.5g	34.2%
	High	Uniform 64	317.5g	--
		Inner 80-64-64 outer	327.4g	-3.1%
Crown	1384	Uniform 64	211.8g	--
		Uniform 50	192.6g	9.1%
	Low	Uniform 64	161.9g	--
		Inner 50-25-25 outer	124.8g	22.9%
	High	Uniform 64	428.2g	--
		Inner 80-64-64 outer	403.6g	5.7%

Table 2 Peak accelerations of best performing helmets with FGF liner (* 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° side	1384	Uniform 64	199.0g	--
		n=4 [40.63, 140.63] $\Delta\rho$=100	186.4g	6.5%
	Low	Uniform 64	165.0g	--
		n=4 [26.61, 186.61] $\Delta\rho$=160	136.5g	17.3%
	High	Uniform 64	317.5g	--
		n=1 [54, 74] $\Delta\rho$=20	315.9g	0.5%
Crown	1384	Uniform 64	211.8g	--
		n=4 [59.33, 79.33] $\Delta\rho$=20*	208.0g	1.8%
	Low	Uniform 64	161.9g	--
		n=4 [26.61, 186.61] $\Delta\rho$=160	151.8g	6.2%
	High	Uniform 64	428.2g	--
		n=4 [59.33, 79.33] $\Delta\rho$=20	426.7g	0.4%

The distribution of stress and plastic energy absorption through the thickness of different types of foam liner for the 45° side impact are shown in Figure 4 to explore how the non-uniform foam liners improve the energy absorption. By comparing Figure 4 and the plateau stresses in Figure 1, a relationship between the energy absorption, the stress level and the peak acceleration is found. For the uniform liner in the low energy impact, the majority of the form absorbs the energy at the early plateau stage; the energy absorbed is lower than the layered liner and is proportional to the volume of material plastically deformed. For the layered foam liner, the outer layer and the middle layer of the liner reaches the middle and late plateau stage so the plastic energy absorbed by them reaches high values; the inner layer reaches the initial plateau stage so the energy absorbed only reaches a lower value. Therefore, the layered foam liner in the low energy impact substantially improves the energy absorption efficiency and reduces the peak acceleration imparted to the head. The comparison for the high energy impact shows that both the uniform and layered liners absorb energy at initial plateau stage. The layered liner neither improved the energy absorption efficiency nor reduced the peak acceleration. Similar findings are obtained for the FGF liner.

CONCLUSION: The observed decreases in the peak accelerations for the best performing helmets in various test conditions are found to be related to the increase of contact area between the liner and either the inner headform or the outer shell. The peak acceleration is reduced if the foam liner absorbs the energy in the late plateau stage or if a larger part of the liner contributes to energy absorption; the peak acceleration is reduced when the DPED in the foam liner is increased. This study suggests a possible approach to manufacturing helmets that would conform to EN14572:2005 while keeping overall size and weight. Future helmets that comply with EN14572:2005 could help attenuate injury risk for a wider range of impact energies.

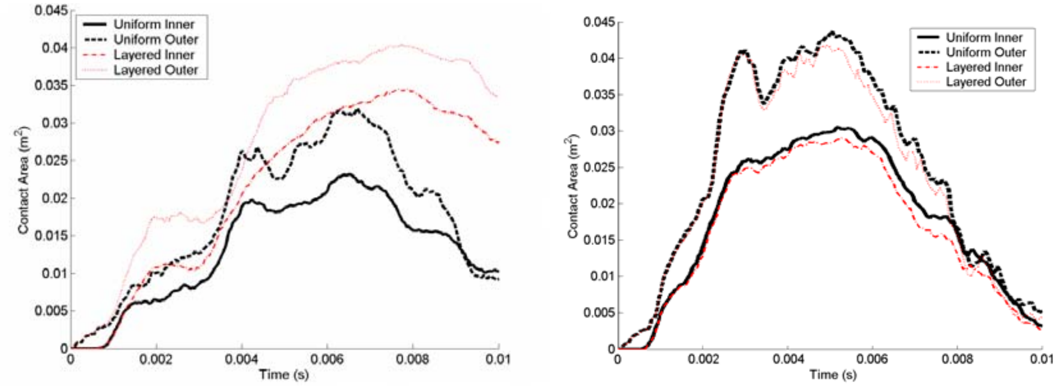

Figure 3: Evolution of contact areas at the inner and outer surfaces of helmet liner using either a uniform liner or a layered liner: (a) Low energy impact; (b) High energy impact

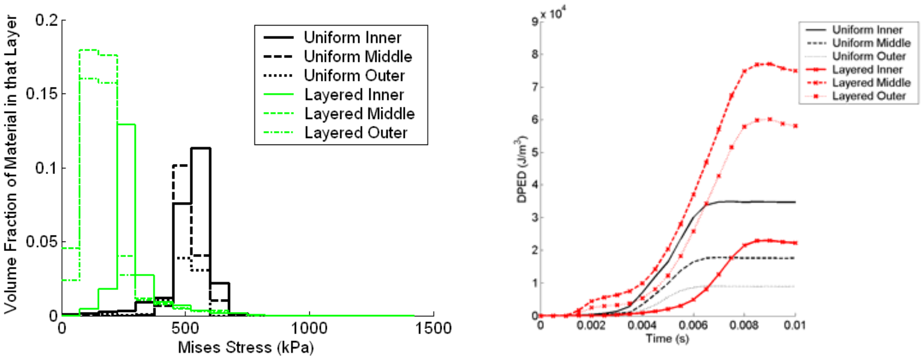

Figure 4: (a) Distributions of von Mises stress at peak acceleration in three layers for helmet liner of uniform density and of layered density at low energy impact; (b) Evolution of average DPED in three layers for helmets of uniform density foam and of layered density foam at low energy impact

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Acknowledgement

This study has been funded by Enterprise Ireland (PC/2005/071), Science Foundation Ireland (08/RFP/ENM/1169), and the Turf Club of Ireland.