JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE 9 (1998) 457–462

Application of laminates to mouthguards: finite element analysis

HO SUNG KIM*, K. MATHIEU
Department of Mechanical Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia

A finite element model comprising a flat-ended indentor and a disc representing a colliding object and mouthguard materials, respectively, has been developed to study stress distribution and impact force in laminates. The disc consists of two layers and its top layer is in contact with the indentor. Two different combinations of layers were employed for the simulation. One had a soft layer placed on top of the rigid layer and the other was vice versa. It was found that the former had no significant difference from a monolayer in stress distribution and impact force. However, the latter was found to have a significant effect on stress distribution, and this effect could be increased by controlling ratios of modulus and volume fractions of the top and bottom layers. It was also found that the magnitude of the impact force increases with increasing effect of stress distribution, but this competition can be reduced to some degree by decreasing the volume fraction ratio of top to bottom layers.

1. Introduction

Mouthguards play an important role in contact sports such as boxing, football, etc., to protect from, or minimize, injuries, including brain concussion [1–3]. The performance of mouthguards is affected by factors such as their geometry and properties. Requirements [4] for the geometry are: (a) to fit the mouth accurately and have sufficient retention not to drop out; (b) not to impinge on the soft tissue; (c) to allow normal breathing and speech; and (d) to afford a high degree of protection. In addition, requirements for the properties are: (a) to be non-toxic; (b) to be sufficiently durable; and (c) to afford a high degree of protection. To achieve a high degree of protection, both geometry and properties should be considered. For the former, the thickness of mouthguards may be increased as long as other requirements are met [5]. For the latter, the compressive elastic modulus may be considered in mouthguard materials (elastomers). There are two types of material which have a modulus of this type. One is monolithic materials and the other laminates. Laminates would afford greater freedom owing to their tailorability when optimization is required.

Mouthguards made of laminates have recently come on to the market and their design has been developed on a rather intuitive basis [5, 6]. The literature on laminates in relation to mouthguards is sparse. In the present work, the effects of modulus and volume fraction on stress distribution and force transmitted in laminates, were studied using a finite element (FE) model for a collision in contact sports.

2. Experimental procedure

In order to obtain input data for FE modelling and to validate the FE model, tests for mechanical properties were conducted.

2.1. Material

The material used for the test was ethylene vinyl acetate (EVA) copolymer supplied by a commercial mouthguard manufacturer. The material was analysed using nuclear magnetic resonance spectra and it was found that it consists of 26% vinyl acetate.

2.2. Test sample preparation

Circular samples were punched out of an EVA sheet, 4 mm thick, using a Shimadzu universal testing machine. To ensure that samples were circular with an edge finish which was square, smooth, straight, parallel and perpendicular to top and bottom surfaces, the edges were subsequently machined on a standard metal cutting lathe with a standard high-speed tool bit and water as a cutting lubricant. Sample dimensions were measured, in accordance with ASTM D3767-84, using vernier callipers with an accuracy of $\pm 5\ \mu m$. The samples were conditioned prior to testing by leaving them wrapped in paper towel in a dry environment at about 23 °C for several days.

* Author to whom all correspondence should be addressed.

2.3. Mechanical testing

Two different types of testing were conducted. One was to obtain material property input to the FE model. The other was to validate the FE model. All samples were tested at a crosshead speed of 5 mm min^{-1}. A grease, Shell Retinex A, was applied to each specimen to minimize friction in its interface with the platens or indentor. The force–displacement curves obtained were modified for the toe region according to ASTM D695-91ANNEX A 1.3.

Fig. 1 shows a typical true stress–strain curve for a diameter of 8 mm under uniformly distributed compressive loading. A value of 18.94 MPa for compressive modulus was obtained from the approximately linear region of the curve and used as a material property input. The true stress, σ_t, and true strain, ε_t, for a circular sample with diameter, d, were calculated on the basis of the constancy of volume yielding

$$\sigma_t = \frac{P}{\left(\pi d_0^2 \frac{h_0}{h}\right) \Big/ 4} \tag{1}$$

and

$$\varepsilon_t = \ln \frac{h}{h_0} \tag{2}$$

where P is the force, h is the thickness and subscript 0 denotes initial.

Fig. 2 shows an experimental force–displacement curve from a test using the flat-ended cylindrical indentor (shown in Fig. 3) on an EVA specimen under compressive loading.

2.4. Strain rate

Mechanical properties of EVA, like other polymers, are sensitive to strain rate. The strain rate ($d\varepsilon/dt$) at a constant crosshead speed is given by [7]

$$\frac{d\varepsilon}{dt} = \frac{v}{h} \tag{3}$$

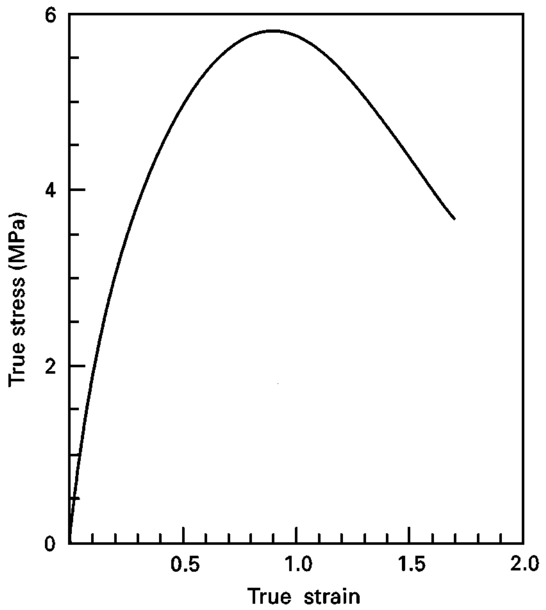


Figure 1 A typical true stress–strain curve under uniformly distributed compressive loading.

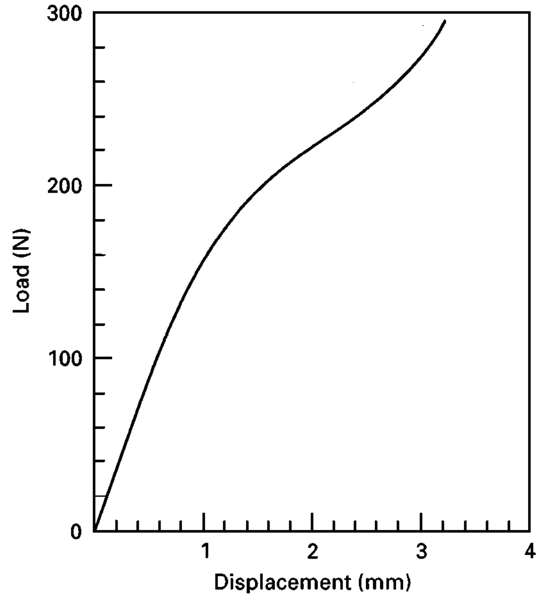


Figure 2 Force–displacement curve obtained from a compressive test using a flat-ended cylindrical indentor with a diameter of 5 mm on a circular specimen with a diameter of 24 mm.

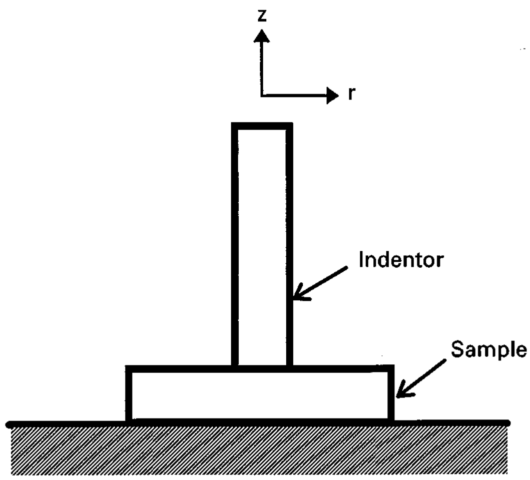


Figure 3 Compression of a cylindrical indentor with a diameter of 5 mm on a disc of mouthguard material with a diameter of 24 mm.

where v is the crosshead speed (or indentor speed) and h is the instantaneous thickness of the sample. To ensure that strain-rate effect is minimized, true strain rate is plotted in Fig. 4 as a function of platen displacement in accordance with Equation 3 for a crosshead speed of 5 mm min^{-1} and a sample with a thickness of 4 mm. It is seen that, in the initial stages of displacement, the strain rate is approximately constant. Also note that the value of 18.94 MPa, taken as a compressive modulus for input to the FE model, corresponds to a platen displacement of 0.35 in Fig. 4.

3. Finite element modelling

An axisymmetric FE model was developed using STRAND 6 software [8] to simulate a system shown in Fig. 3 comprising a disc and a rigid cylindrical indentor pressing on the disc centre. Fig. 5 shows a two-dimensional, radial cross-section of the model.

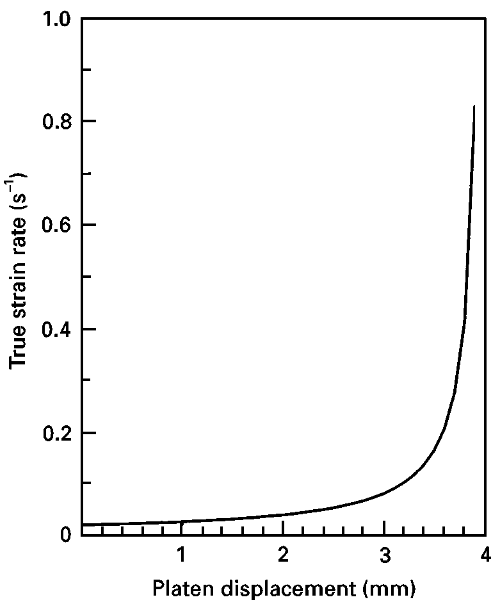


Figure 4 A plot of strain rate as a function of platen displacement for a crosshead speed of 5 mm min^{-1} and a sample with a thickness of 4 mm under uniform stress.

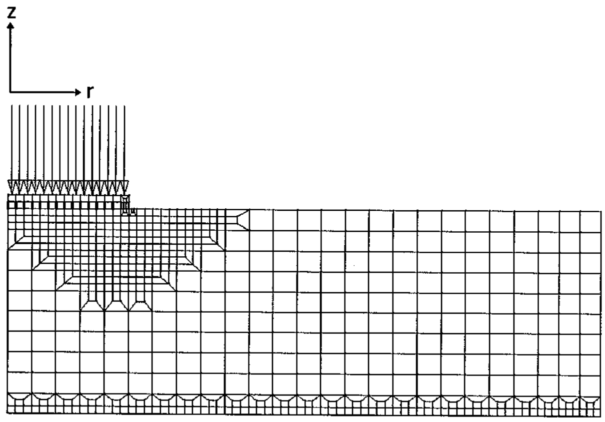


Figure 5 FE model developed to simulate a system comprising a disc and a rigid cylindrical indentor pressing on the disc centre shown in Fig. 3. The gap elements interfaced with other elements are shown as bold lines connecting the row of elements for the indentor at the top to concurrent nodes on the upper surface of the disc.

The mesh for the disc and the indentor was constructed using Quad 4 (four node linear quadrilateral) elements. The "compression only beam elements" are also used as gap elements between indentor and the disc, as shown in bold lines connecting the row of elements for the indentor at the top to the concurrent nodes on the disc upper surface. Nodes along the lower disc surface were restrained in the direction of z and unrestrained in the direction of r allowing the lower surface of disc to be frictionless.

For simulation of a collision, strain energy stored due to the compression of the indentor on the model was used to represent the collision energy, assuming that all of the kinetic energy of the striking body (indentor) is transferred to the disc [9].

Relatively high compressive moduli, 10^{12} and 10^{8} MPa are assigned to indentor and gap elements, respectively. The gap elements were also assigned a shear modulus of zero to remove any resistance, effectively simulating a frictionless contact in the interface. Poisson's ratio for the disc was assigned 0.4 [10]. It was noted that the radius of the interface between gap elements and the upper surface of the disc changes under loading. The change was -3 μm at a force of 19.6 N for a monolayer with a compressive modulus of 18.94 MPa, which is considered to be negligibly small to affect any results for the purpose of this work.

Strain-energy values from tests (Fig. 2) and the model were compared for validation. Strain energy at a force of 19.6 N was found to be an average of 1.080×10^{-3} J for tests and calculated to be 1.063×10^{-3} J for the model. This provides an accuracy of 2%.

Assignment of compressive moduli to laminates comprising two layers was conducted according to the rule of mixtures for modulus [11]

$$\frac{1}{E_e} = \frac{v_1}{E_1} + \frac{v_2}{E_2} \tag{4}$$

where E_e is the compressive modulus in the transverse direction for a laminate, $(E_1, E_2)\,\gamma$ are the compressive moduli for layers 1 and 2, respectively, and (v_1, v_2) are the volume fractions of layers 1 and 2, respectively.

4. Results and discussion
4.1. 50/50 volume fraction

Two sets of results for stress distribution for laminates with a volume fraction ratio of 50/50 were obtained. One is based on the model comprising two layers in which the upper layer (to be in contact with indentor) is soft and the lower layer is relatively rigid, or both are equal in modulus, and the other is vice versa. The compressive composite modulus in the transverse direction, E_e, was kept equal to that of the monolayer (18.94 MPa) for the purpose of comparison, but the modulus ratio of rigid to soft layers was varied up to 10 560 according to Equation 4. (Modulus ratio will be referred to, below, as modulus ratio of rigid to soft layers.) The strain energy, 1.063×10^{-3} J, was also kept constant. The moduli for the layers are listed in Table I. Some high values of modulus are comparable with those of fibre-reinforced polymers [12].

Compressive stress in the axial direction, (σ_z), of the lower surface of disc laminates with soft and rigid upper and lower layers, respectively is plotted as a function of radial distance from the centre of the disc

TABLE I Compressive moduli of rigid and soft layers for a constant composite modulus, E_e, of 18.94 MPa. Volume fraction ratio of top to bottom layers is 50/50

Modulus ratio of rigid to soft layers	Modulus of rigid layer (MPa)	Modulus of soft layer (MPa)
1	18.94	18.94
10	10^2	10.46
105	10^3	9.56
1 055	10^4	9.48
10 560	10^5	9.47

in Fig. 6. (Laminates with soft and rigid upper and lower layers, respectively, will be referred to, below, as laminates SR, and RS for vice versa.) There is a small change in the stress distribution with varying modulus ratio, although the maximum compressive stress slightly increases with increasing modulus ratio. In contrast, a significant stress distribution effect is found in laminates RS, as shown in Fig. 7. As the modulus ratio increases, the maximum compressive stress decreases, resulting in a greater stress-distribution effect.

The stress-distribution effect is one of the factors affecting the performance of mouthguards. Another factor is the force transmitted through the mouthguard materials. The force transmitted for the stress distribution shown in Figs 6 and 7 is shown in Fig. 8. It is seen that the force for laminates SR rapidly tends to be independent of modulus ratio. In contrast, the force for laminates RS rapidly increases with increasing modulus ratio. For instance, at a modulus ratio of 10 560, the force transmitted is 3.7 times that of monolayer. Thus, the reduction in stress concentration is in conflict with the decrease in force transmitted.

4.2. Volume fraction effect

In addition to volume fraction ratio, 50/50, other volume fraction ratios, 30/70 and 10/90 are considered for calculations of stress distributions of laminates RS as shown in Fig. 9. As the volume fraction ratio (of rigid to soft layers) decreases and modulus ratio increases, the maximum compressive stress increases, resulting in increased stress concentration at the centre of the disc lower surface. However, force significantly decreases with decreasing volume fraction ratio as shown in Fig. 10. The maximum compressive stress

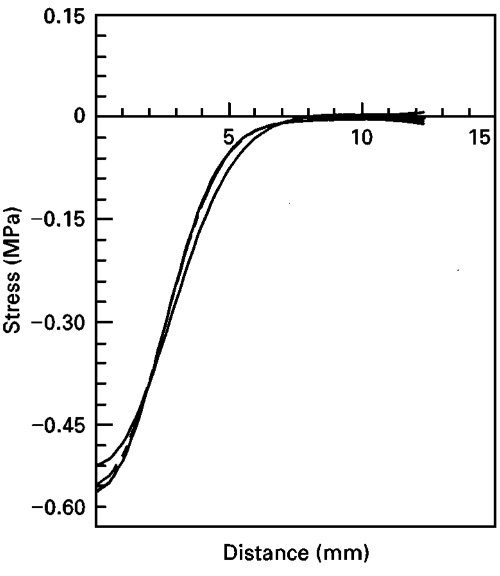


Figure 6 Compressive stress in the axial direction, σ_z, of lower surface of disc laminates with soft and rigid top and bottom layers, respectively, is plotted as a function of radial distance from the centre of the disc. Modulus ratios of rigid to soft layers are (——) 1 (monolayer), (–·–) 9.56, (–· ·–) 105, (- - -) 1055 and (– – –) 10 560. (Overlaps between curves for high modulus ratios have reduced visibility of curves.) Modulus and strain energy were kept constant for all laminates as well as the monolayer at 18.94 MPa and 1.06×10^{-3} J, respectively.

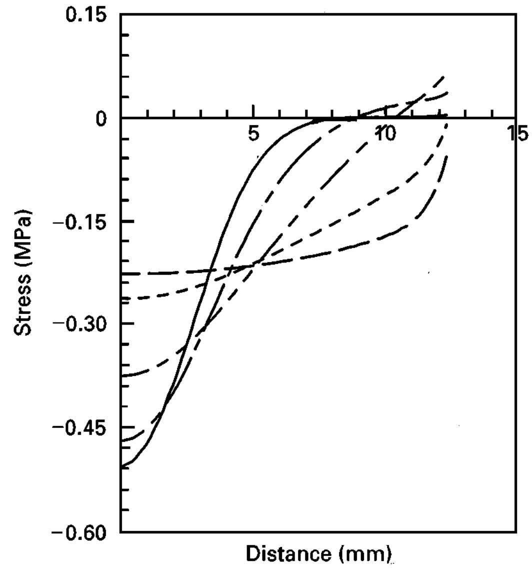


Figure 7 Compressive stress in the axial direction, σ_z, of the lower surface of disc laminates with rigid and soft upper and lower layers, respectively, plotted as a function of radial distance from the centre of the disc. Modulus ratios of rigid to soft layers are (——) 1 (monolayer), (–·–) 9.56, (–· ·–) 105, (- - -) 1055 and (– – –) 10 560. Modulus and strain energy were kept constant for all laminates as well as the monolayer at 18.94 MPa and 1.06×10^{-3} J, respectively.

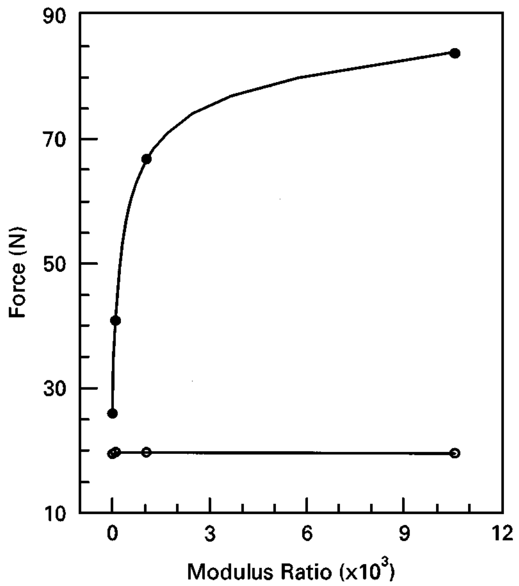
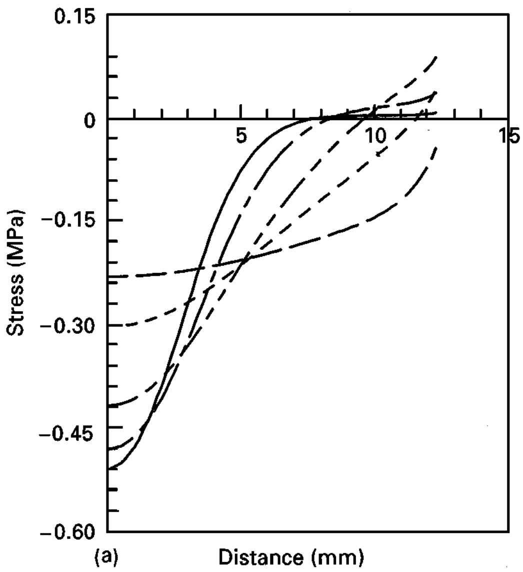


Figure 8 Force transmitted versus modulus ratio (of rigid to soft) for (●) laminates RS, and (○) laminates SR. Transverse modulus and strain energy for all laminates are 18.94 MPa and 1.06×10^{-3} J, respectively. Volume fraction ratio of top to bottom layers is 50/50.

at a modulus ratio of 10 560 increases by 20% when the volume fraction ratio varies from 50/50 to 10/90. Concurrently, the impact force at the same ratios of modulus and volume fraction reduces by 48%. (See Tables II and III.) Accordingly, although the reduction in stress concentration is still in conflict with the decrease in force transmitted, the gain in impact force reduction is higher than the loss in stress distribution effect when the volume fraction ratio is taken into account.

Fig. 11 shows variations of stress distribution for laminates SR with volume fraction ratios, 30/70 and



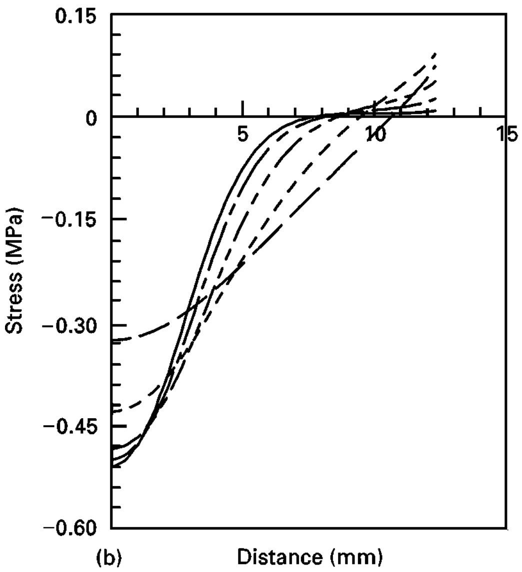


Figure 9 Compressive stress in the axial direction, σ_z, of the lower surface of disc laminates with rigid and soft upper and lower layers, respectively, plotted as a function of radial distance from the centre of the disc. Volume fraction ratios (of top and bottom layers) are: (a) 30/70, and (b) 10/90. Modulus ratios of rigid to soft layers are (——) 1 (monolayer), (–··–) 9.56, (–···–) 105, (- - -) 1055 and (– – –) 10 560. Modulus and strain energy were kept constant for all laminates as well as the monolayer at 18.94 MPa and 1.06×10^{-3} J, respectively.

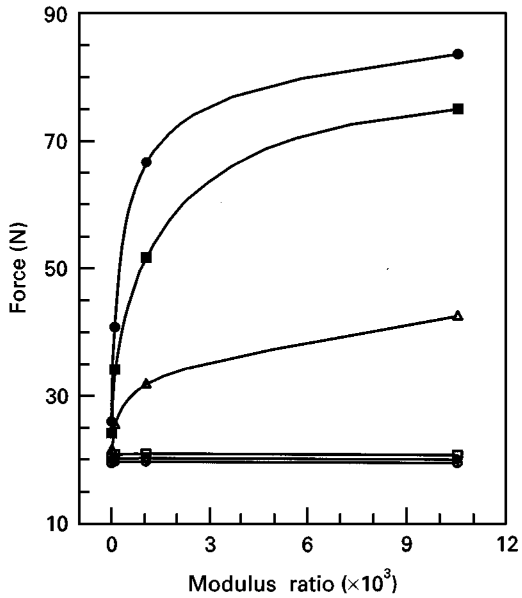


Figure 10 Force transmitted versus modulus ratio (of rigid to soft) for laminates RS and laminates SR with volume fraction ratios 30/70 ((■) RS, (□) SR) and 10/90 ((△) RS, (▽) SR) are superimposed on those in Fig. 8 for laminates 50/50 ((●) RS, (○) SR). Modulus and strain energy were kept constant for all laminates at 18.94 MPa and 1.06×10^{-3} J, respectively.

TABLE II Compressive moduli of rigid and soft layers for a constant composite modulus, E_c, of 18.94 MPa. Volume fraction ratio of top to bottom layers is 30/70

Modulus ratio of rigid to soft layers	Modulus of rigid layer (MPa)	Modulus of soft layer (MPa)
1	18.94	18.94
10	132	13.85
105	1 392	13.31
1 055	13 992	13.26
10 560	139 996	13.26

TABLE III Compressive moduli of rigid and soft layers for a constant composite modulus, E_c, of 18.94 MPa. Volume fraction ratio of top to bottom layers is 10/90

Modulus ratio of rigid to soft layers	Modulus of rigid layer (MPa)	Modulus of soft layer (MPa)
1	18.94	18.94
10	165	17.24
105	1 785	17.06
1 055	17 985	17.05
10 560	179 981	17.05

10/90. In these combinations of layers, no significant difference from the monolayer in both stress distribution and impact force, is seen.

4.3. Application to mouthguards

A mouthguard covers teeth and gingiva (gum). Some parts of the mouth would require a greater effect of stress distribution than others, while other parts only require a reduction in impact force. For example, a stress concentration on teeth should be avoided because they are brittle and hard materials which tend to possess low resistance to stress concentration. Occlusal surfaces may not require a stress-distribution effect by the laminates, because they are relatively uniform in force distribution and therefore there would be little chance of a stress concentration occurring due to the small contact area. Gingiva protection would be another area for consideration in a further study. For the materials, most low moduli can readily be obtained by using polymers, but some high moduli in laminates could be achieved by the use of reinforcing fibres.

In general, the set of parameters involved in a collision in sports, includes collision energy, contact area and materials properties. It is noted that the present work is limited to the last aspect in relation to

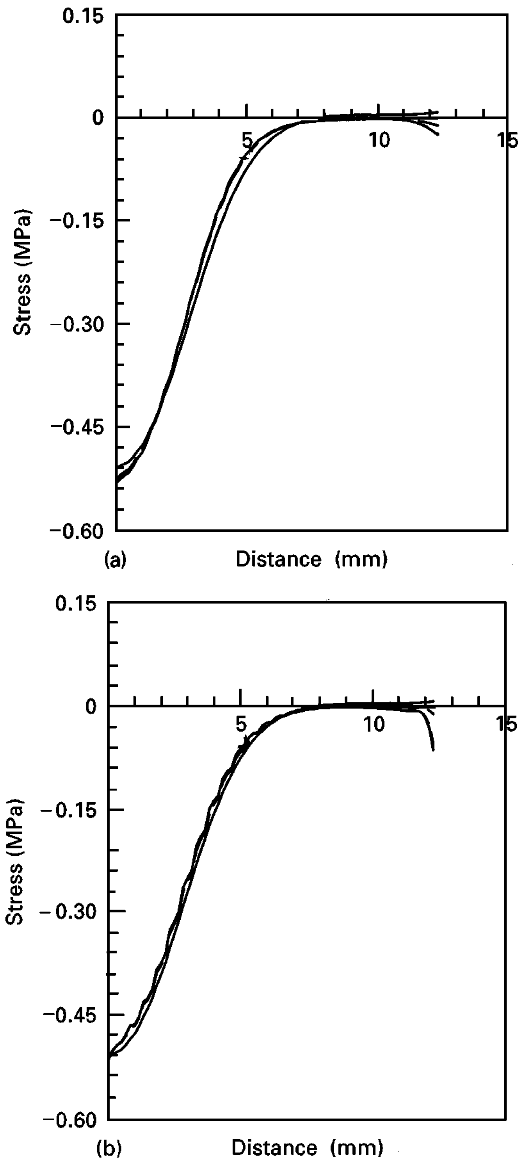


Figure 11 Compressive stress in the axial direction, σ_z, of the lower surface of disc laminates with soft and rigid upper and lower layers, respectively, is plotted as a function of radial distance from the centre of the disc. Volume fraction ratios (of upper and lower layers) are: (a) 30/70, and (b) 10/90. Modulus ratios of rigid to soft layers are (——) 1 (monolayer), (–·–) 9.56, (–· ·–) 105, (- - -) 1055 and (– – –) 10 560. (Overlaps between curves for high modulus ratios has reduced visibility of the curves.) Modulus and strain energy were kept constant for all laminates as well as the monolayer at 18.94 MPa and 1.06×10^{-3} J, respectively.

compressive modulus and laminates. Also, it is only qualitative in application, because the model is not the same shape as a mouthguard. However, it is intended to provide an insight into controlling parameters for protection, such as volume fraction ratio and modulus ratio.

5. Conclusion

The stress distribution and impact force transmitted through laminates comprised of two layers have been studied using a finite element model, in respect of their application to mouthguards. Two parameters were considered, i.e. modulus ratio (> 1) of rigid to soft layers, and volume fraction ratio (< 1) of top to bottom layers. It was found for the laminates RS that (a) the stress-distribution effect can be enhanced by increasing both ratios of the modulus and the volume fraction, and (b) the magnitude of impact force decreases on decreasing both ratios of the modulus and the volume fraction. As such, there is competition between the effect of stress distribution and the reduction in impact force. However, the competition has been found to be reduced, to some degree, by decreasing volume fraction ratio of rigid to soft layers. In contrast, in laminates SR, neither modulus ratio nor volume fraction ratio significantly affected stress distribution and impact force.

Acknowledgement

The authors thank Mr Sase Stojcevski for providing the NMR result for EVA.

References

1. W. C. GODWIN, *J. Am. Dent. Assoc.* **77** (1968) 1316.
2. M. DUDA, *Physician Sports Med.* **15** (1987) 179.
3. D. M. LANCASTER, *Pediat. Dent.* **15** (1993) 398.
4. C. H. TURNER, *Br. Dent. J.* **143** (1977) 82.
5. J. B. PARK, K. L. SHAULL, B. OVERTON and K. J. DONLY, *J. Prosthet. Dent.* **72** (1994) 373.
6. A. JOHNSON, Signature Mouthguards Pty Ltd., private communication (1996).
7. G. E. DIETER, in "Mechanical Metallurgy" (McGraw-Hill, Kogakusha, 1976) p. 350.
8. STRAND 6 Finite Element Analysis System, Reference Manual and User Guide (G + D Computing Pty Ltd, Sydney, 1993).
9. F. P. BEER and E. R. JOHNSTON Jr., in "Mechanics of Materials" (McGraw-Hill, Toronto, 1985) p. 492.
10. A. W. BIRLEY, B. HAWORTH and J. BATCHELOR, in "Physics of Plastics" (Hanser, Munich, Vienna, New York, Barcelona, 1992) p. 255.
11. R. J. CRAWFORD, in "Plastics in Engineering" (Pergamon Press, Oxford, New York, Beijing, Frankfurt, San Paulo, Sydney, Tokyo, Toronto, 1987) p. 90.
12. M. F. ASHBY, in "Materials Selection in Mechanical Design" (Pergamon Press, Oxford, New York, Seoul, Tokyo, 1992) p. 73.

Received 19 May
and accepted 16 September 1997