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Finite Element Analysis of cricket ball impact on Polycarbonate-EVA Sandwich

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Abstract

In cricket, balls are delivered at speeds ranging from 25 to 45 m/s. The force generated upon impact at such high speeds can be detrimental to batsmen's safety. There are several existing equipment that protect batsmen from injury and it is vital to evaluate their effectiveness for use in this sport. Finite Element Methods have come to be an exceptionally reliable tool in the design process of such protective gear as they provide deep insight into the impact phenomenon. With rigorous experimental testing, mathematical models for both the impacting projectile and the protective equipment can be developed and used to simulate the impact scenario under varied circumstances. This paper investigates the strength of a Polycarbonate-foam sandwich against impact by a cricket ball using Finite Element Analysis. The foam sandwiched is Ethylene-Vinyl Acetate, which possesses good impact absorbing characteristics and generally finds application in mouth-guards for sports and recreational activities. The Polycarbonate plate provides tear resistance. The cricket ball was modelled as a viscoelastic material, validated with experimental data available in literature. Additionally, the skin, connective adipose tissue and muscle layers of the human body are also modelled. Simulations with multiple velocities of impact, multiple angles of impact and multiple layer thicknesses of protective system were carried out. Impact force transmitted to the skin and the specific energy absorption of the foam sandwich was determined. The consecutive layers of the protective equipment and the human tissues were modelled together as square plates. The best combination of material thicknesses of the protective material was determined based on the least contact force transmitted to the human skin upon impact.

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Keywords: Cricket Injury;Viscoelastic Materials;Hyperelastic Materials;Ethylene Vinyl Acetate foam

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1. Introduction

In cricket, balls delivered can have speeds as high as 45 m/s. At such velocities, they pose a threat to the safety of batsmen. There have been instances of extreme damage and even death on the cricket field due to the ball hitting critical areas of the batsman's body. In lieu of such events, it is obvious that continuous and thoughtful improvements must be made to the protective equipment utilized by batsmen. Finite element methods have been used by many researchers to aid the process of development of safety equipment and ergonomic sportswear. Subic et al [1] developed an alternate face guard composed of polycarbonate and subjected it to experimental and numerical tests for compliance with existing standards for impact protection. Ethylene-Vinyl Acetate foam (EVA) finds application in midsoles used for running shoes. Verdejo et al [2] performed experimental tests and numerical simulations to measure the pressure distribution at the heelpad-midsole interface. The midsole was composed of EVA foam which reduced the peak impact force of the heelpad through shock absorption. Davey [3] developed a new football shin pad composed of two polycarbonate outer shells sandwiching different polyethylene foams subject to impact by the boot tip. The performance characteristics of the polycarbonate foam sandwich was compared with that of a composite shell and foam sandwich through experimental testing and finite element simulations.

In this work, the authors have analyzed the impact absorbing characteristics of a typical foam sandwich consisting of 3 layers: one layer of EVA foam sandwiched in between two layers of polycarbonate. The choice of polycarbonate as a protective material is attributed to its excellent impact resistant properties and light weight. The aim of this study is to use finite element methods to investigate the performance characteristics of new materials for use as protective gear in cricket.

2. Methods

2.1. Modelling of Human Parts

The human skin, adipose tissue and muscle for the forearm were modelled for this study in order to simulate a more realistic environment. The average skin thickness for the arm was taken as 2.3 mm reported by Lo Presti et al [4]. Bolinder et al [5] reported the thicknesses of the subcutaneous adipose tissues in the proximal, middle and distal sites of the forearm. The middle site of the forearm with an adipose thickness of 5.2 mm is considered in this study. The muscle thickness for the same was taken as 12 mm, which is within the standard deviation limits of that reported by Iivarinen [6]. Liu et al [7] used viscoelastic constitutive models for the skin, tissue and muscle enclosing the heart to evaluate their response upon impact. The same viscoelastic constitutive model was used to model the muscle and skin in the present paper. The equation for the viscoelastic material model is shown below

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \tag{1}$$

Where G_0 and G_∞ are the instantaneous and long term shear moduli respectively with β as the decay constant and t as the time. The model parameters [7] for the skin and muscle are listed in the Table 1. The adipose tissue or the hypodermis is a connective tissue that largely determines the structural response and plays a vital role in absorbing shock due to mechanical load. Hyperelastic material models like the Mooney Rivlin or Ogden 2 parameter is used to describe the mechanical response of the adipose tissue. The Mooney Rivlin model is found to replicate the properties of the adipose tissue to a good accuracy with the RMS error value reported to be less than 0.01267 [8].

Table 1. Viscoelastic Material Parameters for the Finite Element Model

Material	Density ρ (kg/m3)	Bulk Modulus K (GPa)	Instantaneous Shear Modulus G_0 (kPa)	Long Term Shear Modulus G_∞ (kPa)	Decay Constant β (s^{-1})
Skin	1200	2.9	200	195	0.1
Muscle	1120	1.03	200	195	0.1
Cricket Ball	851	0.134	43400	11500	10500

$$U = C_{10}\left(\overline{I_1} - 3\right) + C_{01}\left(\overline{I_2} - 3\right) + \frac{1}{D_1}\left(J_{el} - 1\right)^2 \tag{2}$$

Where U is the strain energy per unit volume and J_{el} is the elastic volume ratio. I_1 and I_2 are the first and second deviatoric strain invariants. The material parameters C_{10} and C_{01} are shown in Table 2 [8].

2.2. Modelling of Cricket ball and Polycarbonate Foam Sandwich

The cricket ball is a solid sphere of diameter 72mm [9] and mass of approximately 166g. The viscoelastic material model shown in Equation 1 was also used to describe the ball behaviour. Smith et al [10] determined the viscoelastic material parameters for the cricket ball and experimentally validated them at strain rates corresponding to the sport. The viscoelastic material properties used to describe the ball are shown in Table 1. The total thickness of the Polycarbonate foam sandwich was taken to be 15 mm. A N =2 Ogden Hyperfoam material is used to model the EVA foam shown in Equation 3. The material properties of the foam are shown in Table 2

$$U = \frac{2\mu}{\alpha^2}\left[\left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right) + \frac{1}{\beta_i}\left(J^{\alpha_i\beta_i} - 1\right)\right] \tag{3}$$

Where U is the Ogden strain energy function and λ_i are the principal extension ratios. The parameter J is measure of relative volume. α_i and β_i are the power indices. μ_i are shear modulus coefficients.

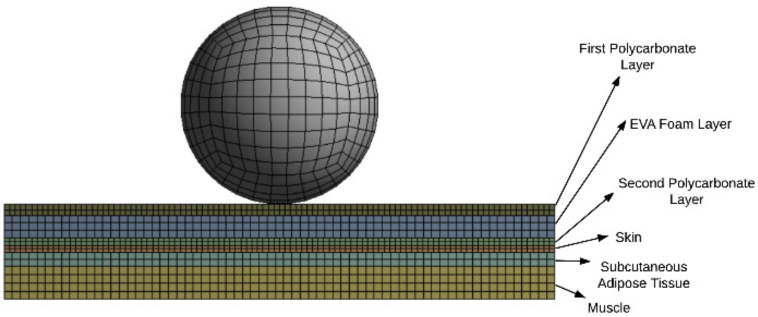

Fig. 1. FE Model of the Ball, Polycarbonate Foam Sandwich and Human Tissues

Table 2. Material Parameters of Human Adipose Tissue and EVA Foam

Material	Material Model	Density (kg/m3)	Poisson's Ratio (υ1)	Poisson's ratio (υ2)	C10 (kPa)	C01 (kPa)	µ1 (kPa)	α1	µ2 (kPa)	α2
Adipose Tissue	Mooney Rivlin 2 parameter	1100	0.492	—	17.6	9.9	—	—	—	—
EVA Foam	Ogden Hyperfoam	170	0	0.4	—	—	1000	10	50	-4

2.3. Finite Element Analysis of the Impact

In the interest of testing the suitability of the model in the scenario of high speed impact, preliminary simulations were conducted as per the experimental set up of Pang et al [11]. The model showed good match between experimental and simulation results at high speeds. The Coefficient of Restitution (COR), which in this case is the ratio of the rebound velocity to the inbound velocity, was used as a parameter for comparison.

$$COR = \frac{V_0 sin\theta_0}{V_i sin\theta_i} \tag{4}$$

Where V_0 and V_i are the rebound and inbound velocities respectively. θ_0 is the rebound angle in the same plane of impact as the inbound angle θ_i. The values of COR determined from the simulations were found to be within permissible standard deviation limits of the experimental results. It was necessary that the simulation predicted the contact force accurately. Hence, simulations based on the work of Cheng et al [9] were also conducted and the contact forces obtained were compared. There was a close match between the two results.

After initial validations to ensure the soundness of the cricket ball model, 3 sets of finite element simulations of the cricket ball impacting the protective equipment and human tissue were conducted. The explicit dynamics solver of the commercially available software package ANSYS 14.5 was used for this purpose. The end time of the simulation was set to 4 milliseconds after impact.

Three separate sets of simulations were conducted as follows:

- Varying thicknesses
  Considering a constant total thickness of 15 mm, the thicknesses of the individual layers of the protective sandwich were varied in order to find the best possible combination, for a given velocity, that resulted in the least force transmitted to the human tissues. This configuration was used for the next sets of simulations. The minimum thickness of EVA foam was fixed at 5mm. The impact was normal to the target plates and at 45 m/s
- Varying velocities.
  Simulations of velocities ranging from 25 to 45 m/s under normal impact were conducted for the best configuration of the protective sandwich. The contact force endured by the skin layer was again measured.
- Varying angles of impact.
  To study the effect of impact at oblique angles, simulations were conducted for the best combination of the protective gear at 45 m/s.

3. Results

3.1. Varying Thicknesses

Impact Simulations on the Polycarbonate EVA sandwich indicate that it shows good resistance to impact even for speeds up to 45 m/s (162 km/h). For a given velocity, the values of COR remained fairly constant to two decimal places. The maximum stress transferred to the skin, tissues and muscle was significantly lesser than their ultimate tensile and yield stresses. In general, the increase in foam thickness brought about a reduction in the contact force transmitted to the skin. Figure 2(a) shows the contact force transmitted for each model number that corresponds to different configurations of protective equipment layer thicknesses at an impact velocity of 45 m/s.

Among the combinations of materials considered, Model 9 was found to be most effective with the least transmitted contact force to the skin equal to 3538.98N. The corresponding thicknesses of the first polycarbonate, middle EVA foam and second polycarbonate layer were 4mm, 8mm and 3 mm respectively. The maximum stress induced on the skin was 0.46453 MPa which was considerably lower than its Ultimate Tensile strength [12]. The 4mm thick polycarbonate layer provided some initial rigidity and impact strength to the foam sandwich composite. The relatively thick EVA foam (8mm) was ideal for absorbing and damping the shockwave formed upon impact by the ball and thereby reducing the peak impact force transmitted through the body. The maximum energy absorbed by the sandwich

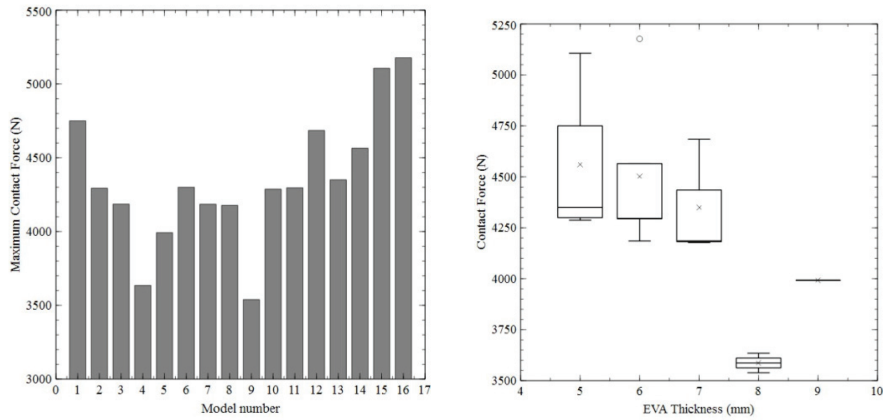

Fig. 2. (a) Contact force transmitted v/s the corresponding model number describing material thicknesses; (b) Box plot of Maximum transmitted contact force plotted against the EVA foam thickness.

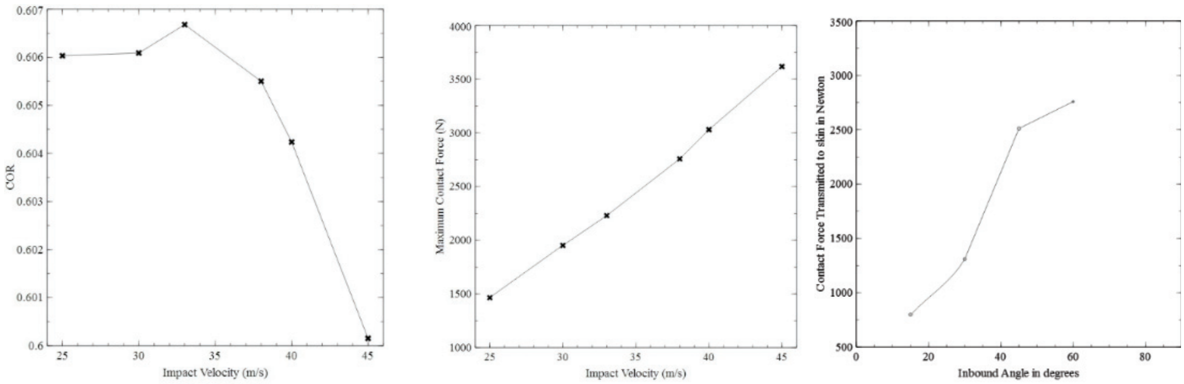

Fig. 3. (a) Variation of COR with impact velocity; (b) Variation of contact force with impact velocity; (c) Contact force variation with inbound angle of impact at a velocity of 45 m/s.

at the point of contact with the ball was found to be 7.2J/kg. Although, other combinations of material thicknesses yielded higher values of absorption energy per unit mass, the contact force transmitted to the skin was comparatively high which, combined with the higher mass, was not considered optimal for use as protective equipment.

3.2. Varying Velocities

Impact simulations were conducted at 25m/s, 30m/s, 33m/s, 38m/s, 40m/s and 45 m/s on the most effective combination of polycarbonate and foam thicknesses. Figure 3 (a) represents the variation of COR with the impact velocity for the ideal Polycarbonate foam sandwich. The value of COR is fairly constant up to two decimal places. In general, the ideal polycarbonate EVA protective equipment behaves largely in an elastic manner for all speeds characteristic to the game. The contact force is plotted against impact velocity in Figure 3 (b).

3.3. Varying angles of impact

Impact simulations were also carried out at different angles of impact with respect to the Y axis. The magnitude of impact velocity considered in these simulations is 45 m/s. The simulations were performed on the best configuration of polycarbonate-foam thicknesses. Figure 3(c) shows the variation of COR and Contact force with the inbound angle. It is seen that as the inbound angle increases, the contact force transmitted to the skin increases. This behaviour is expected as the increase in the normal component of velocity results in a higher momentum transfer to the protective equipment resulting in a higher contact force.

4. Discussion

Simulations of the 3D finite element model of a cricket ball impacting a protected human forearm were carried out. The protective equipment fared well for even the highest velocities encountered in the sport. Optimization of layer thicknesses to obtain minimum transfer of force to the human skin found that the combination of 4-8-3 mm produced the best results. It was initially expected that 3-9-3 would be the best combination for absorbing impact. The reason for the departure is unknown as it was difficult to establish a correlation between the contact force and material thicknesses of the individual layers of protective equipment in the scenario presented. Analyzing the effect of EVA foam on the impact force, it was observed that in general, increase in the thickness of EVA led to a decrease in contact force transmitted to the human body. As the impact velocity was increased, a very slight but definite decrease in the COR of the system was measured. Higher velocities created a slightly more plastic response in the system. Nevertheless, the decrease in COR is noticeable only in the third decimal place and practically the COR may be considered constant. Increase in the impact velocity caused the contact force at the skin to increase linearly. As COR is almost constant over the range of velocities, a linear relation between the velocity and force is unsurprising. With further analysis, it is possible to optimize the protective gear further in order to decide the weight and form factor that can provide maximum comfort to the wearer whilst ensuring effective protection. The use of numerical parameters for injury assessment of human tissues can be instrumental in developing more efficient protective equipment in the future by investigating new materials that can help mitigate fatal injuries in cricket. Further research is aimed at studying the performance characteristics of other impact absorbing foams and complete geometric design and testing of the protective equipment in order to conform to existing standards.

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