The Potential of Biomimetics Design in the Development of Impact Resistant Material

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Abstract

Unique biological solutions from nature provide unlimited ideas in solving human problems. Biomimetics refers to the transfer of solutions originated from nature to the technological application. In this paper, the biomimetics design approach and recent impact resistance of composite developments were reviewed. Interesting biological models such as fish scales and mantis shrimp were studied and the possible biology solutions were extracted and redefined in the engineering term. From the review, the impact resistances of the biological models showed a similar trend of high stiffness materials of exterior and relatively low stiffness materials as interior. To further verifying this statement, materials with stacking sequence of carbon fibre reinforced epoxy (CFRP) as the exterior and polycarbonate material (PC) as the interior were designed based on the principle. Furthermore, the controlled specimen of polycarbonate (PC) was also included in the analysis for comparison purposes. Both types of materials were analysed numerically. The results showed that biomimetically designed composites had higher ballistic limit velocity than the controlled specimens for the same target thickness. It was proven that biomimetically designed impact resistant material could improve the performance of materials.

Keywords. Biomimetics Design; Carbon Fibre Reinforced Epoxy; Ballistic Impact; Ballistic Limit Velocity

1 Introduction

In the past, the impact resistant performance of the polymer matrix composites has been investigated aggressively by numerous researchers during the past. For instance, composite laminates reinforced with different architectures of Ultrahigh Molecular Weight Polyethylene (UHMWPE) were investigated and this concludes that single-ply 3D orthogonal woven fabric composite laminates perform better in impact energy absorption and delamination resistance [1]. A study by Naik and Doshi looks into the impact behaviour of thick composites of E-glass/epoxy and the study found that shear plugging was able to absorb significant amount of energy [2]. Another research, Carrillo et al. compares the ballistic performance of Kevlar aramid fabric/polypropylene composite laminate (CL) with plain-layered aramid fabric (AF) and the result showed that CL performed better than AF in terms of ballistic limit and penetration threshold energy [3]. Other than that, Hosur at al. study the response of stitched/ unstitched woven fabric of carbon fibre reinforced laminates and found that unstitched laminates have higher ballistic limit velocity [4]. In short, the impact resistant properties of polymer matrix composites involve complex interactions between fibre, matrix properties and stacking sequence. The aim of this paper is to demonstrate the biomimetics design approach in the design of the impact resistant composite.

2 Biomimetics Design

Our nature contains unlimited sources of inspiration for us to explore. Each organism evolves itself to an efficient organism to adapt the environment. This evolution passes through numerous generations, tests of extreme environment to ensure their species can be sustained. The term 'Biomimetics' is defined as the transfer of biology inspiration to technological applications [5]. Biomimetics is all about extracting of inspirations or ideas from nature to solve problems that are faced by humans, especially in the engineering, medical and design fields [6].

3 Methodology
3.1 Problem Based Approach

The problem-based approach is defined into six main steps [7]. The approach mainly explains how the information has been transferred from the biological application to the engineering application. The main function of the impact resistant material is to resist the impact generated by high velocity projectile. An ideal impact resistant material shall be strong in terms of stopping projectile and dissipate kinetic energy with minimum weight. During the search of the biological solutions, mantis shrimp and Polypterus Senegalus fish scale were selected as models.

Mantis shrimps are predatory on hard-shelled animals by using their limbs as hammers to strike on it but their hammers are rarely damaged [8]. Apart from that, the Polypterus senegalus, which belongs to the ancient family Polypteridae that still lives today in the bottom of freshwater in Africa [9], are famous with its extra strong fish scale. These selected role models shared a common characteristic of hierarchical/multilayered structures. The Polypterus Senegalus fish scale and mantis shrimp limbs [10-12] show different material properties from the outer layer to the inner layer in which the thickness of outer layer is thicker than the inner and the modulus of outer layer is higher than inner layer. Thus, these characteristics are applied in the conceptual design of the impact resistant material as shown in Figure 1. Moreover, the material was considered as a hybrid composite material for a layer of composite was bonded with a layer of relatively soft materials of thermoplastic.

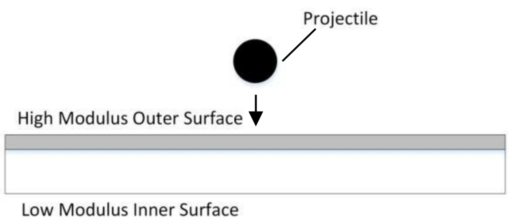

Figure 1. Conceptual design of impact resistant material

3.2 Numerical Analysis

The composite material that was selected as the outer surface contained T700 carbon fibre reinforced epoxy. The outer surface materials were formed of 18 plies of unidirectional fabrics with an arrangement of fibre orientation of $[0/\pm30/\pm60/90]_3$. This T700 CFRP was bonded together with PC sheets with different types of thicknesses such as 2 mm, 3 mm and 4 mm to form a hybrid material of the impact resistant material.

In order to investigate the effect of stacking sequence on the ballistic performance of materials, the second categories of materials were introduced. This was when the position of PC and CFRP layer was reversed. Besides that, the PC targets were introduced as controlled specimens. This study found that the impact resistance of the targets was investigated by putting an impact on a steel ball on the mid span of the target at various impact velocities ranging from 100m/s to 400m/s. The spherical projectile was made of steel 4340 with a diameter of 6 mm and weight of 0.88 g.

4. Result and Discussion
4.1 Validation

Numerous simulations were done with similar numerical settings in this work and were compared with the existing results from B. Wang [13]. Both results from this work were matched with the result from [13] but this only concluded that the numerical setting of this simulation could be considered acceptable only with certain accuracy. Thus, further experimental works shall be conducted in the future to further validate the results from the numerical simulation analysis.

4.2 Ballistic limit velocity

In general, there were two possible results happened on the projectile when impacted on target either it perforated the target with a velocity or it stopped and went through a rebound with a residual velocity. These situations can be seen in Figure 2, in which the projectile hit the 5.5 mm PC target with having the impacted velocity of 327 m/s rebounded. The velocity of the projectile started with 327 m/s reduced to almost zero at 105 μs then increase again. This happened due to the elastic recovery of the targets where the PC materials acted like a spring to store the energy from the projectile initially and then transferred back to the projectile. The minimum residual velocity of the projectile was not achieved to the exact zero velocity due to the automatic time step control of the simulation programme. The problem could be solved by adjusting small steps. Since only the residual velocity of the projectile is concerned, the control of time steps remains into default setting. On the other hand, the example of the projectile perforating the target could be observed at impact velocity of 328 m/s. Furthermore, the velocity of the projectile started with 328 m/s reduced and then it maintained a certain velocity. This indicates that the projectile perforated the target and travelled with a velocity. Thus, we can conclude that the 5.5 mm thickness of PC has a ballistic limit velocity of 327 m/s where it has a ballistic limit velocity of other targets, shown in Figure 3.

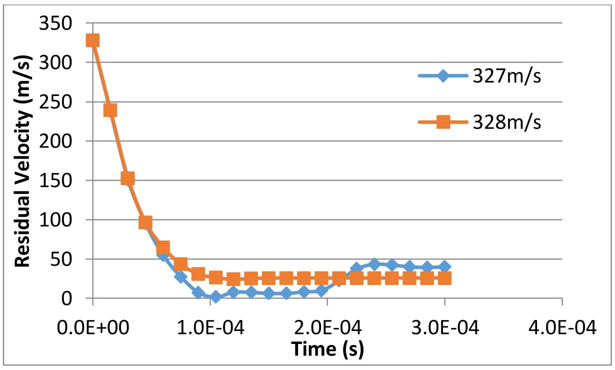

Figure 2. Graph of residual velocity versus time of PC target. Target thickness = 5.5 mm

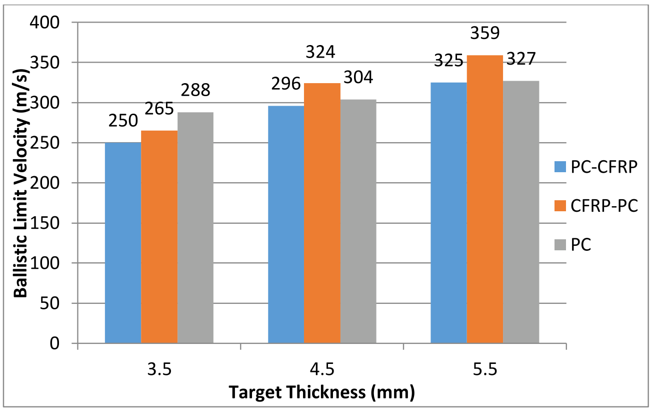

Figure 3. Ballistic limit velocity of various targets

As a whole, the increase of the target thickness leads to the increase of the ballistic limit velocity. The PC target also shows a superior ballistic performance as opposed to PC-CFRP and CFRP-PC at thin thickness but this is not applicable for a higher level of thickness. This phenomenon takes place due to the different impact responses between thin and thick PC plates [14]. Considering the projectile impacting the thin PC plate, stretching deformation (dishing) and yielding on circular region of the plate surrounding the sphere projectile were shown. As for the thin PC, dishing is a dominant kinetic energy absorption mechanism, where a large amount of energy can dissipate. As the thickness of the plate increases, the degree of dishing reduces. Hence, the total amount of dissipated kinetic energy reduces. As a result, a small zone of yielding and bulging occurs on the back face of the target. This evident that the high degree of dishing can dissipate more kinetic energy yet increases the ballistic limit velocity.

By comparing the stacking sequences, CFRP-PC always has higher ballistic limit velocity than PC-CFRP. Different stacking sequences results in different deformation on the target. The high modulus CFRP shows hard and brittle properties and PC depicts a ductile property. In terms of energy absorption mechanism, CFRP tends to absorb kinetic energy from the projectile by fibre breakage or matrix cracking. For instance, the PC material, elastic and plastic deformations are the main energy absorption mechanisms. By placing CFRP as the outer surface and PC as the inner surface, these materials do not influence each other during the energy absorption. But with the reversed stacking sequence, the high modulus material of CFRP has restricted the degree of dishing of the PC thereby reduced the total energy absorption.

5 Conclusion

Two biological models were selected in the development of the impact resistance of materials. The inspirations from fish scale and mantis shrimps have successfully been transferred into the engineering application by using the biomimetics approach. The analyses of the impact resistance of materials have been demonstrated through numerical analysis. The material with the configuration that was inspired from nature suggests a better performance in terms of impact resistance. However, more experimental or empirical studies are required to further investigate the results that are generated by numerical analysis in this work.

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