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Impact behaviour and design optimization of a ductile scale-cellular composite structure for protection against localized impact

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ABSTRACT

A good protective structure must be effective in dissipating impact energy as well as minimizing stresses transferred to a protected object. A novel composite protective structure which combines an assembly of ductile scales as an outer layer for energy dissipation and a cellular material with foam-like properties as an inner layer for stress minimization was examined in this study, focusing on its mechanical behaviour and design optimization. Finite element simulations were adopted to investigate the mechanical behaviour and impact performance of specimens with different geometrical and material properties of the assembly of scales and cellular layer. Results from the numerical analyses indicate that the mechanical behaviour and impact performance of the composite structure are governed by the overall stiffness of the assembly of scales relative to the underlying layer. The desired impact performance could be achieved when the assembly of scales are neither too weak such that they collapse easily when subject to impact, nor too stiff such that they tend to puncture into the underlying layer. When the stiffness of the assembly of scales is optimum, the scales are effective in dissipating a significant proportion of the impact energy as they deform. This results in reduced compression on the underlying cellular layer and low peak stress transferred by the composite structure. The following key outcomes were established in this study in order to achieve this desired impact performance: (a) recommended bounds for the Young's modulus and yield strength of the scales relative to those of the underlying layer; (b) a geometric stiffness parameter to account for the combined effects of aspect ratio, curvature, degree of overlapping, and size of the scales on the impact performance of the composite system, and the optimum range for this parameter; and (c) recommended bounds for the volume of the scales relative to that of the underlying layer. These findings can be used to develop an approach to determine the optimum design configurations of the composite structure for various applications.

1. Introduction

Damage resulting from impact loading commonly occurs because of natural reasons and man-made threats. Examples of impact loading include hailstorms, trains crashing into buffer stops, and barge collisions on bridge piers. Such incidents could lead to structural failure and loss of human lives even though the impact velocity may be relatively low. During an impact event, an impactor may transfer a large amount of energy and high stresses to an object which may cause damage on the object when the stresses transferred are higher than their allowable limits. Thus, a good protective structure must be effective in dissipating impact energy as well as minimizing stresses transferred to a protected object.

In the search for effective protective structures against impact loading, nature can serve as a good source of inspiration (Barthelat, 2007). For example, scale structures, which consists of overlapping hard plates that are underlain by a relatively soft layer, have been reported to have good protective qualities. Such structures are commonly found on the body of fish and reptiles. These structures have good penetration resistance due to the strain stiffening response of the scale assembly that helps to prevent localized injury during predator attack (Song, 2011; Yang et al., 2012). Using an analytical approach, Vernerey and Barthelat (2010) found that scale density (i.e. the average number of overlapping scales per unit span of the scale structure) and attachment-scale stiffness ratio (i.e. stiffness of joints between the scales and the underlying skin relative to bending resistance of the scales) affect the deformation response of the structure. It was found that higher scale density and lower scale-attachment stiffness ratio result in improved penetration resistance. In another study, Browning (2012)

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examined the performance of macroscale prototypes made of acrylonitrile butadiene styrene (ABS) scales that were embedded within a silicon rubber layer. Through simulations and experimental tests on the prototypes, they looked at the effects of various structural parameters including angle, degree of overlapping, volume fraction, and aspect ratio of the scales on deformation mechanisms of the scale structure such as scale bending, scale rotation, and tissue shear. These deformation mechanisms were found to govern the ability of the composite structure to protect an underlying substrate.

Another form of natural materials that have good impact protection qualities is cellular structures. They are lightweight yet able to deform up to large strains while maintaining low stress values (Gibson et al., 1995; Castro et al., 2010). Examples of cellular structures found in nature include cork, wood, and skins of fruits that drop upon ripening. Generally, the mechanical behaviour of cellular materials depends highly on the shape and structure of their cell walls, as well as density and material properties of which they are made (Gibson et al., 1995). It has also been reported that natural cellular materials such as cork has good recovery capacity which is attributed to its corrugated cell walls (Gibson and Ashby, 1997). However, cellular materials have relatively low damage tolerance and exhibit highly localized deformation under concentrated loads due to their relatively weak tensile resistance (Gameiro et al., 2007). Moreover, cellular materials are only effective in maintaining low stresses when they are not densified i.e. they have not been compressed to the extent that the cells or voids within them have fully collapsed. Consequently, when used for protective purposes cellular materials must be designed such that they are thick enough to prevent densification.

In a recent paper, Chua et al. (2015) examined the impact performance of a two-layer composite structure that was made of an assembly of ductile scales with an underlying cellular layer. In this study, the cellular layer was made of cork that generally has irregular cell shape with cell size that ranges from 10 µm to 50 µm. They found that effective impact protection could be achieved when the scales were able to prevent penetration of an impactor and dissipate most of the impact energy as they deform, while the keeping the underlying cellular layer from reaching densification. They theorized that the novel composite structure which combined the scale assembly with a cellular layer potentially had improved performance against impact and enabled these two systems to compensate each other's weaknesses. Such a structure may be used as a sacrificial layer to protect objects against localized impact loading. Using finite element simulations, they demonstrated that a configuration with curved scales could perform better than one with flat scales as well as a conventional sandwich design with the same amount of materials, provided the right geometrical design and material properties were selected for the assembly of scales and cellular material. This was because the impact performance of the composite structure was governed by the formation of plastic hinges in the scales that led to impact energy dissipation by the assembly of scales, which in turn protected the cellular layer from densification and thus allowed it to perform its stress-minimizing function effectively.

However, all other past studies on scale structures and cellular materials have examined their mechanical behaviours individually. To date, there has been no other past work that looked into the behaviour of composite structures made of an assembly of ductile scales that is underlain by a compressible material with foam-like properties. In their analytical study, Vernerey and Barthelat (2010) adopted an assembly of elastic scales that was assumed to deform with a constant curvature. This may not accurately reflect the deformation behaviour of a scale structure which is coupled with a compressible underlying layer. In Browning's (2012) work, the scale structure prototypes were made of acrylonitrile butadiene styrene (ABS) and underlain by silicone rubber which is an incompressible elastic material.

While Chua et al. (2015) had shown the potential of combining an assembly of ductile scales with foam-like cellular materials for the purpose of impact protection, their original study had not examined the influence of various design parameters on the mechanical response and impact performance of the composite structure. Therefore, the objective of this paper is to optimize the design of the scale-cellular composite structure first proposed by Chua et al. (2015) such that it can achieve the desired mechanical response for effective impact protection. Following a proposed design approach, the effects of geometrical configuration, material properties, and amount (i.e. volume) of materials were investigated in this study using finite element simulations in order to determine their optimum combinations.

However, it should be pointed out here that this study did not intend to fully mimic the properties and behaviour of real scale structures found in nature. Instead, based on the original concept presented in Chua et al. (2015), the assembly of ductile scales was formed primarily for its ability to form plastic hinges in order to dissipate impact energy when coupled with an underlying cellular layer. Furthermore, the type of cellular materials considered in this study was limited to those with foam-like properties i.e. small voids that are dispersed in a disordered fashion (e.g. cork, polymer foam, and metallic form) instead of those with large voids that are arranged in a regular pattern (e.g. honeycombs). The former have characteristic void size in the order of tens of micrometers hence the properties of the underlying cellular layer are effectively homogenous when compared to the assembly of scales.

2. Finite element model

The finite element simulations in this study were performed using Abaqus/Explicit. For simplicity and following Chua et al. (2015), a two-dimensional plane strain model of the scale-cellular composite specimen, as depicted schematically in Fig. 1, was adopted. The composite structure comprised an assembly of curved overlapping plates (representing the "scales") and an underlying cellular material. The assembly of scales was formed by attaching the bottom end of each scale to a continuous top plate while the top ends of the scales were free.

This composite structure was used to protect an object or surface from transverse impact by a rigid impactor of width D. An initial velocity of 10 m/s was adopted to simulate low-velocity impact which was the focus in this study. For all cases used in this study, the width D of the impactor was 100 mm, its total length was 150 mm, while its mass was 64 kg per mm (in the out-of-plane direction). It was aligned along the centerline of the specimen and constrained from rotation and displacement in the x-direction. The underside of the composite structure was constrained from displacements in both x and y-directions while its lateral edges were free. Contact interaction between the impactor and the external surfaces of the scale assembly was defined using the surface-to-surface penalty contact algorithm whereas contact interaction within the external surfaces of the scale assembly itself was assigned using a self-contact kinematic contact algorithm in Abaqus. To prevent penetration between contacting surfaces, the default "hard" contact option was used in the normal direction whereas the tangential direction was assumed to be frictionless.

Aluminium was chosen as the material for the scales, and it was modelled as an elastic-perfectly plastic material with mass density of 2700 kg/m^3, Young's modulus of 70 GPa, Poisson's ratio of 0.32, and yield strength of 250 MPa. On the other hand, cork was selected as the underlying cellular layer because of its high com-