BIO-INSPIRED FISHSCALE-CELLULAR COMPOSITE SYSTEM FOR PROTECTION AGAINST PENETRATION LOADS: A PROOF OF CONCEPT STUDY

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Abstract

Fishscale structures have been found to have incredible resistance against penetration, while cellular materials such as cork are lightweight yet able to absorb enormous amount of energy but transmit relatively low forces and stresses when subject to impact loads. In this paper, a novel composite system that combines fishscale structure with cork as an underlying material is explored for protection against penetration loads. Finite element simulations are performed to examine the performance of different configurations of the composite system, which comprises of an assembly of overlapping plates underlain by a cork layer. Experimental tests are also carried out to validate the results from the simulations. It is found that the mechanical behavior and penetration resistance of the system is governed by the geometry and topological arrangement of the overlapping plates. Specimens with curved overlapping plates that are connected along their top edges show better performance compared to those with disconnected flat plates, as well as a plain sandwich panel with the same volume of materials.

1. Introduction

The development of protective systems against impact loads has been gaining worldwide attention due to increasing awareness on safety and security issues. These systems are important for protecting humans and structures from threats that may lead to injury and damage to the projected objects. Such threats may take many forms, ranging from baseballs travelling at a few meters per second, to small arms fire travelling at several hundred meters per second. To defend against these threats and prevent the highly localized deformation that might cause penetration of a protected object, two main protective strategies have been commonly adopted. Firstly, a protective system may be used to cause deformation or fracture of the threat and thus eliminate its ability to penetrate a protected object. Secondly, a protective system may be used to dissipate the impact energy without allowing full penetration. Hence, a good protective system should have an outer layer that has high stiffness and strength to prevent penetration, coupled with an underlying material that has high energy dissipation capacity which is controlled by its microstructure and composition.

Conventionally, rigid plates and highly reinforced concrete have been used to protect structures against penetration loads but they are typically bulky, have low performance-to-weight ratio, generally able to resist penetration but inefficient in distributing the penetration force, and cumbersome to replace when damaged. In contrast, protective systems found in nature are often lightweight but have relatively high load bearing capacities despite being made of inferior building blocks. For example, fishscale structures have been reported to have excellent penetration resistance that arises from their strain-stiffening response, which can play a large role in preventing local unstable deformation that can threaten a fish during predator attack [1]. Another natural material that has good protective qualities is cork, which microstructure is cellular and has been known to have excellent energy absorption capacity under compressive loading as it can undergo large strains while maintaining a low stress level before densification occurs [2]. However, cork has low damage tolerance and suffers from highly localized deformation under concentrated loads. Therefore, combining the fishscale structure as an outer layer with cork as an underlying material may enable these two systems to compensate each other's weaknesses and lead to a composite structure that has improved performance against penetration loads.

Nevertheless, past studies on fishscale structures and cellular materials such as cork have been focused on their mechanical behaviors in isolation. For example, Browning *et al*. [3] examined the performance of fishscale structures underlain by silicon rubber which is an incompressible elastic material, while the behavior of cork under uniform compression was investigated by Moreira *et al*. [4]. Despite the potential of improved impact performance by combining these two systems to create a hybrid structure, such a composite system has not been explored. Therefore, in this paper, the mechanical behavior and feasibility of a fishscale-cellular composite system for protection against penetration loading shall be investigated. A finite element model is used to examine the performance of different configurations of the composite system, and experimental tests will also be carried out to validate the results from the finite element simulations.

2. Methodology

2.1 Finite element model

Finite element simulations using Abaqus/Explicit are adopted to investigate the mechanical response of the fishscale-cellular composite system. As shown by the two-dimensional model of the specimen in Figure 1, an assembly of overlapping inclined plates (i.e. the "scales") is formed by attaching the lower end of each inclined plate to a continuous horizontal plate that connects all the individual plates. This fishscale structure assembly is combined with cork which functions as the underlying layer, and the composite system is used to overlay a protected object or surface.

The specimen is subject to a normal penetration force exerted by a rigid projectile with a fixed initial velocity. The projectile is aligned along the centerline of the specimen and presses on only one of the plates at the start of loading. It is constrained from rotation and displacement in the x-direction. On the other hand, the base of the specimen is constrained from displacements in both x and y-directions while the lateral edges are free. The plates are made of aluminum, which is modeled as an elastic-perfectly-plastic material with Young's modulus of 70 GPa, Poisson's ratio of 0.32 and yield stress of 250 MPa. The behavior of cork follows the stress-strain response reported by Moreira *et al*. [4], with density of 180 kg/m^3, Young's modulus of 30 MPa, and Poisson's ratio of 0.

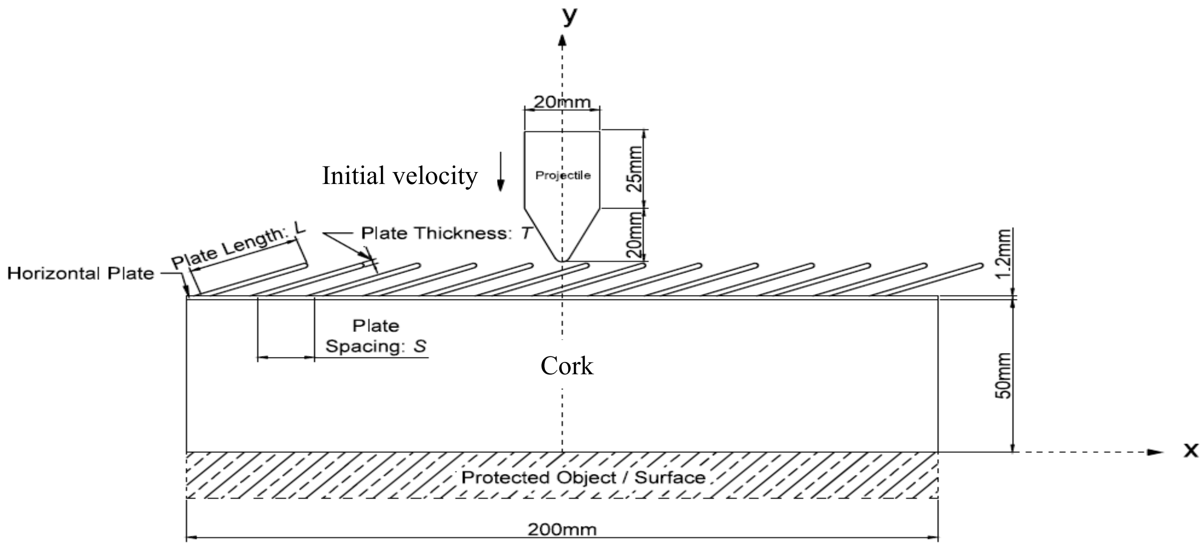


Figure 1. Schematic view of finite element model.

In this study, the mechanical response of specimens with different configurations of the assembly of plates shall be examined. The performance of the specimens will be assessed based on the penetration depth of the projectile into the cork layer and the peak stresses transferred to the protected object or surface. Unless otherwise stated, the total volume of the plates is kept constant for all configurations.

2.2 Experimental validation

Before looking into the mechanical response of the composite system with various configurations, experimental tests are first carried out to validate the finite element model. Figure 2 shows a specimen that is used in the experimental validation. The length L and thickness T of the inclined plates are 50 mm and 1.2 mm respectively, with inclination angle θ of 15° and spacing S between adjacent plates of 20 mm. A small segment of each inclined plate is slightly bent to provide an anchorage length of 10 mm at the base of the plate such that it can be attached to the top horizontal plate using 2-ton epoxy. The length of the specimen is 200 mm while the height of the cork layer is 50 mm.

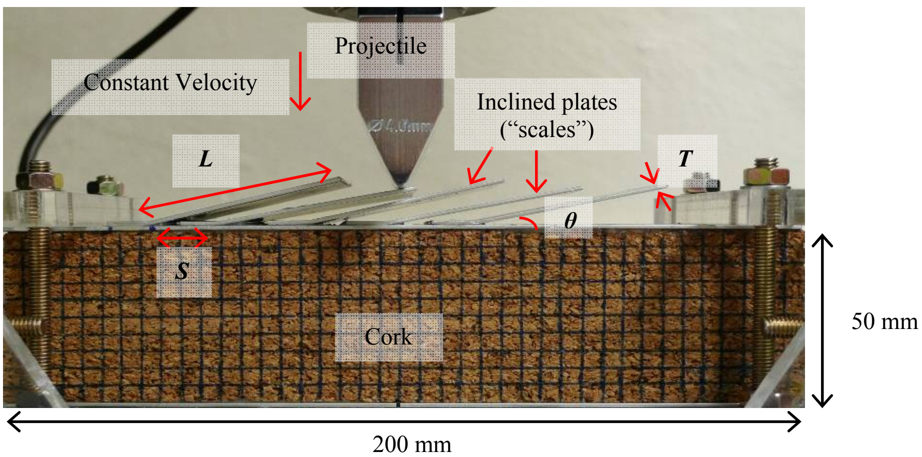


Figure 2. Picture of specimen used for experimental validation of finite element model.

The specimen is subject to a vertical penetration force from a steel upper anvil with tip diameter of 4 mm at a constant displacement rate of 5 mm per minute, while an acrylic rig is fabricated to secure the specimen to an Instron 5969 universal testing machine as shown in Figure 3. The rig consists of a base plate which is used to constrain the specimen vertically, top clamps that are used prevent uplift of the specimen at its two ends, and side restraints to prevent lateral movement of the specimen. A 50 kN load cell is used to measure the penetration force applied on the specimen while the displacement of the projectile is recorded by the testing machine. The same setup is modeled in the finite element simulation of this test.

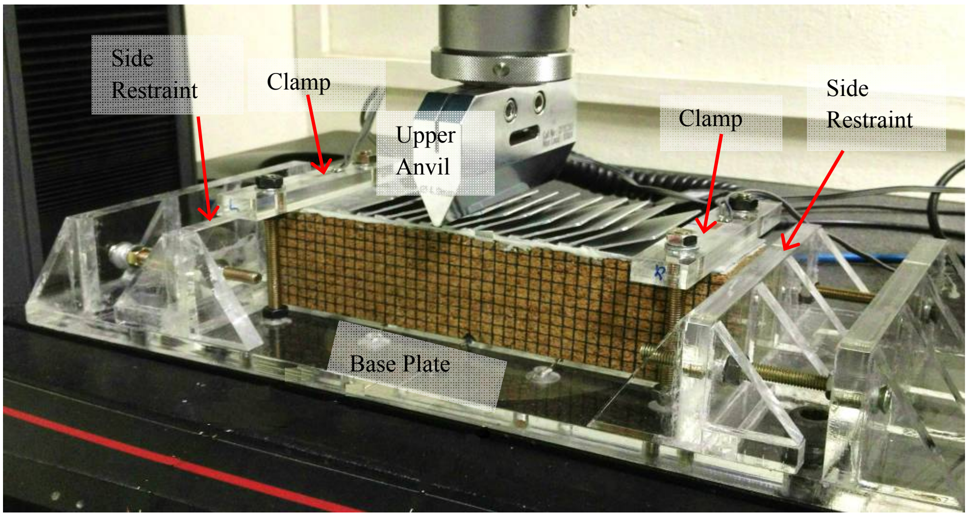


Figure 3. Experimental setup of the validation test.

Figure 4 shows the overall penetration force-displacement response of the specimen. It is clear that the results from both the experiment and finite element simulation show an excellent agreement. Furthermore, the deformation of the specimen obtained from the finite element simulation as shown in Figure 5(a) matches that observed in the experiment as illustrated in Figure 5(b). Therefore, these results show that the finite element simulation is able to accurately capture the actual behavior of the fishscale-cellular composite system, and shall henceforth be used to examine the mechanical response of specimens with different configurations.

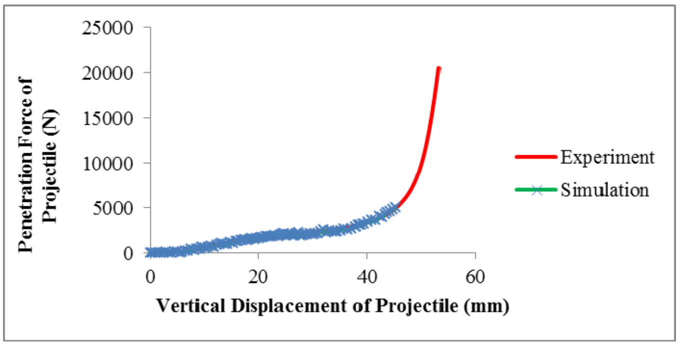


Figure 4. Penetration force versus vertical displacement of projectile from experimental test and finite element simulation.

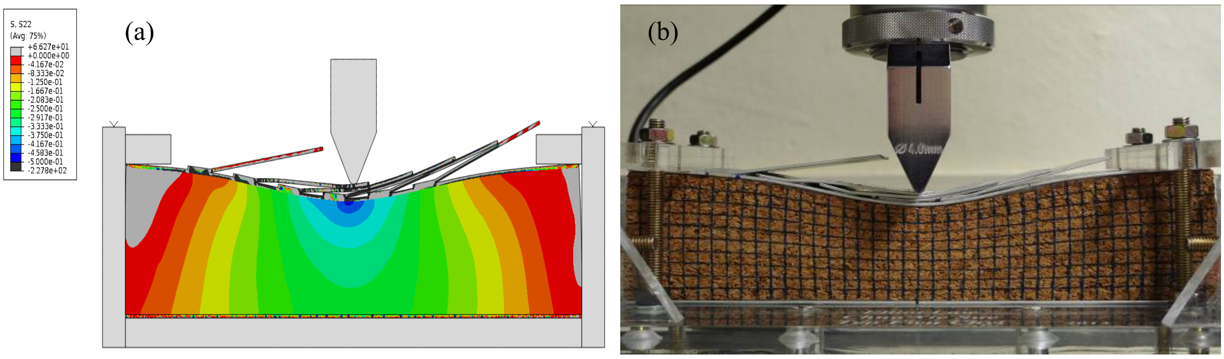
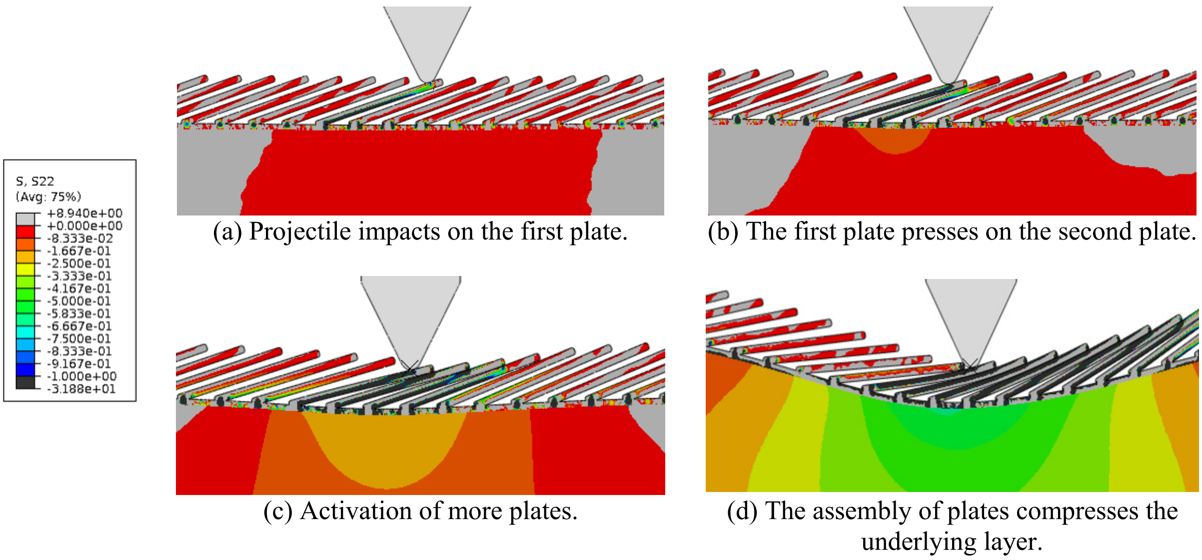


Figure 5. Deformation of specimen at projectile displacement of 20 mm obtained from (a) finite element simulation, and (b) experimental test.

3. Typical response of the fishscale-cellular composite system

The typical response of the fishscale-cellular composite system is first examined to understand its general mechanical behavior under penetration loading, prior to assessing the performance of specimens with various configurations. Figure 6 displays the deformation and vertical stress contours at various instants for a specimen with L = 30 mm, T = 1.5 mm, S = 7.5 mm and $\theta = 20°$. At the start of impact, the projectile presses on the first plate as shown in Figure 6(a). This plate deforms through bending and rotation about its joint until it presses on the second plate as shown in Figure 6(b). The second plate will then also deform in the same manner until it presses on more plates as shown in Figure 6(c). The activation of adjacent plates in the assembly helps to distribute the impact force over a wider region. Thereafter, the plates begin to compress on the underlying layer as shown in Figure 6(d). The maximum penetration of the projectile occurs when all its initial kinetic energy has been expended, after which it begins to rebound from the specimen. Therefore, these results show that the penetration resistance of the composite system arises from three primary modes of deformation: (a) bending and rotation of individual plates about their joints, (b) load transfer between adjacent plates, and (c) compression of the underlying layer. It is expected that altering the configuration of the system will change the relative contributions of these modes toward the penetration resistance of the system.



(a) Projectile impacts on the first plate.

(b) The first plate presses on the second plate.

(c) Activation of more plates.

(d) The assembly of plates compresses the underlying layer.

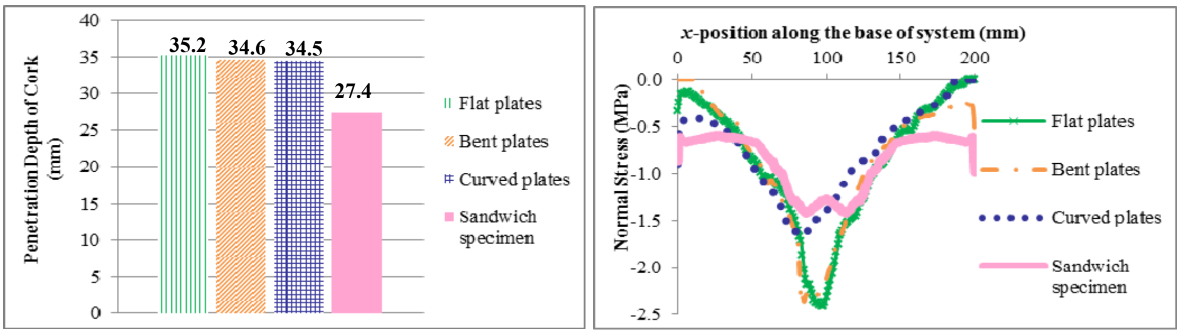
Figure 6. Deformation and vertical stress contours for specimen with flat scales with L = 30 mm, T = 1.5 mm, S = 7.5 mm and $\theta = 20°$.

4. Performance of fishscale-cellular composite system with various configurations

Specimens with different design configurations of the composite system are examined in order to compare their performance against penetration loading. Firstly, the shape of the overlapping plates is varied to investigate their effect on the mechanical response of the system; flat, bent and curved plates shall be considered here. Secondly, the influence of connectivity between adjacent plates is explored. Furthermore, the performance of the fishscale-cellular composite specimens is also evaluated against that of an equivalent sandwich specimen. For a fair comparison, the total volume of materials is kept constant for all cases. The performance of the specimens will be assessed based on the penetration depth of the projectile into the cork layer and the peak stresses transferred to the protected object or surface.

4.1 Shape of overlapping plates

Figures 7(a) and 7(b) show the penetration depth of the cork layer and the normal compressive stress envelope along the base of the specimens for various shapes of the overlapping plates as well as a sandwich specimen, while Figure 8 displays the deformation of the specimens at the point of maximum projectile penetration. It can be clearly seen that the cork layer in the sandwich specimen suffers the lowest penetration depth, while the cork layer under the assembly of flat scales undergoes the highest deformation. Also, among the four specimens, the peak normal stress along the base of the specimen is the lowest for the sandwich specimen. These results show that sandwich specimen has the highest penetration resistance due to the high bending resistance of the thick top plate. The high bending stiffness of this plate also leads to a more uniform compression of the cork layer as shown in Figure 8(a), hence the penetration load can be spread out more effectively which results in the lower peak stress observed.



(a) (b)

Figure 7. (a) Penetration depth of cork, and (b) normal compressive stress envelope along base of specimens with different shape of overlapping plates.

On the other hand, the specimen with flat plates suffers the highest cork penetration depth and also the highest peak stress along the base of the system. This is because only the plates on one side of the projectile are mobilized to transfer the penetration force through interaction between the plates, whereas the plates on the other side of the projectile are not activated since they are disconnected as shown in Figure 8(b). Also, the flat plates deform through bending and rotation about their joints when subject to transverse impact. Plastic hinges are easily formed in the assembly of flat plates since the plates are subject to bending. The formation of plastic hinges leads to localization of stresses and reduces the interaction between adjacent plates. Moreover, when the cork layer is densified, its deformation becomes highly localized underneath the projectile, which in turn leads to further weakening of the interaction between the plates. Therefore, even though the individual plates help to transfer the penetration force from the projectile to a wider region of the specimen, the deformation of the specimen is still governed by the bending resistance of the top layer which comprises of the assembly of plates and the horizontal top plate. Consequently, the performance of the specimen with flat plates is worse than a conventional sandwich specimen due to the reduced bending stiffness of the top layer as a result of the discretization of the top layer into individual plates. The same drawback is observed for the specimen with flat plates that are bent at their tips so that they are in contact before loading, as shown in Figure 8(c).

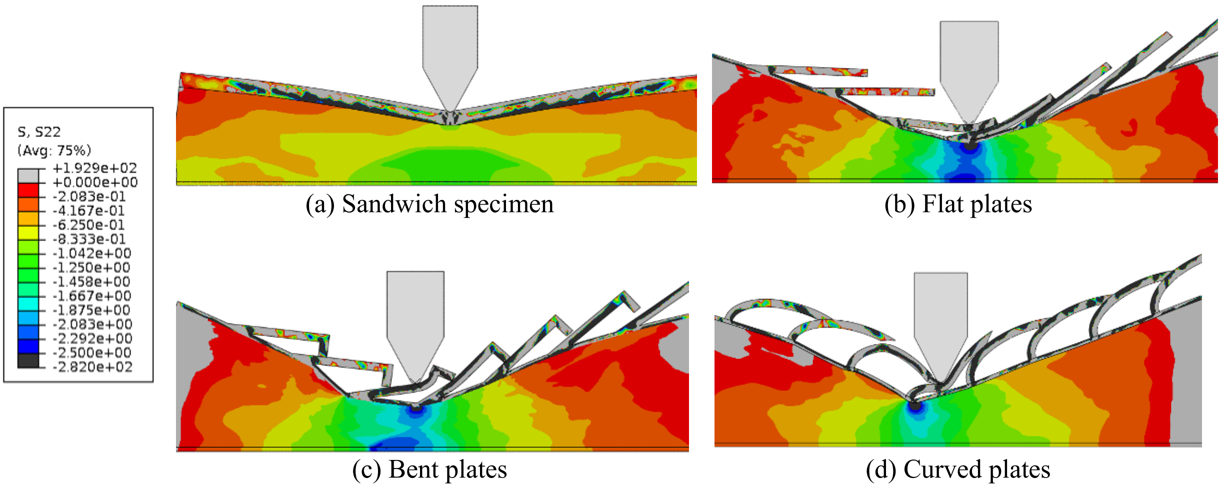


Figure 8. Deformation and vertical stress contours for sandwich cork and composite specimens with various shapes of overlapping plates.

Compared to specimens with other shapes of the overlapping plates, the specimen with curved plates has the lowest cork penetration depth and also the lowest maximum peak stress along the base of the system. This is because the curvature of the plates provides additional lateral resistance to counter the penetration loading and enhances the transfer of forces between adjacent scales as shown in Figure 8(d). Consequently, the assembly of curved plates has higher penetration resistance and is able to distribute the penetration force over a wider region of the specimen, leading to lower peak stress along the base of the specimen. However, the performance of the specimen with curved scales is still poorer than that of the sandwich specimen as shown in Figure 7.

4.2 Connectivity between adjacent plates

The results shown above for specimens with different shapes of the overlapping plates indicate that discretization of the top layer into individual plates instead of having a conventional sandwich specimen reduces the penetration resistance of the composite system. Also, the interaction between adjacent plates is weakened when deformation of the cork layer becomes highly localized underneath the projectile, as the overlapping plates are discontinuous. Therefore, to improve the interaction between adjacent plates, connectivity between the plates may be introduced. Figure 9 shows that the penetration depth of the cork layer and the normal compressive stresses along the base of the specimen are drastically reduced when the curved plates are connected to each other at the tip of the plates, as shown in Figure 10. The performance of the specimen with the connected curved plates is also significantly better compared to that of a sandwich specimen, as shown in Figure 9. These improvements may be attributed to the higher bending resistance of the top layer of overlapping plates when they are connected to each other. As a result, a larger region of the specimen can be mobilized to resist the projectile, and the penetration loading can be distributed more uniformly over the specimen.

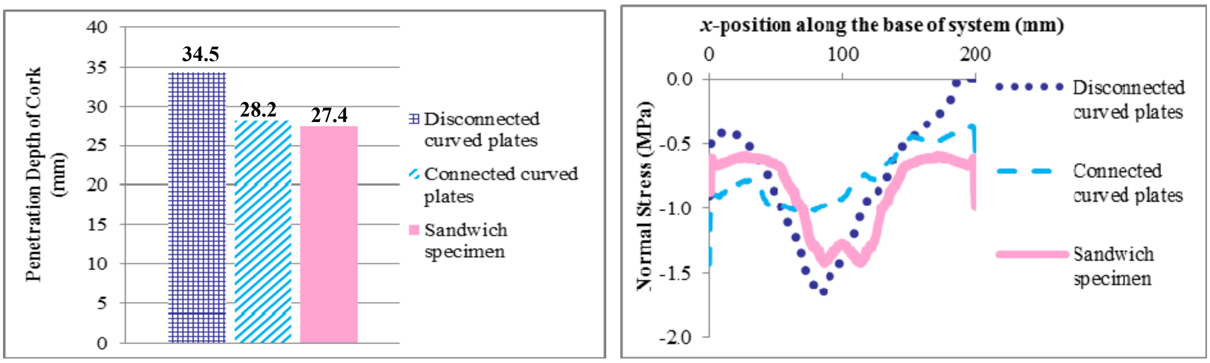


Figure 9. (a) Penetration depth of cork, and (b) normal compressive stress envelope along base of specimens with different connectivity between adjacent plates.

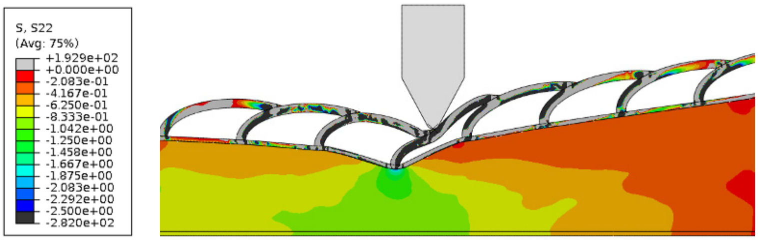


Figure 10. Deformation and vertical stress contour for composite specimen with connected curved plates.

Conclusion

In this paper, finite element simulations are carried out to investigate the mechanical behavior and feasibility of a novel bio-inspired composite system, which comprises of an assembly of overlapping plates underlain by a cork layer, for protection against penetration loading. The performance of different configurations of the composite system is assessed based on the penetration depth and peak stresses transferred to a protected object or surface. The results show that the conventional sandwich specimen performs better than those with an assembly of discontinuous plates. However, by introducing connectivity between adjacent plates, the performance of the specimen with curved plates is improved significantly and is even better compared to a sandwich specimen.

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