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Ballistic Limit of Double Layered Cockleshell Reinforced Carbon Fibre using Numerical Simulation

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Abstract: The current study is based on a numerical analysis of a double layered cockleshell reinforced carbon fibre plate with a ratio of 0.3 (wt%) that was hit by a hemispherical faced bullet. The plate configuration differs between the two models, with the first using a non-spaced double plate and the second using a spaced double plate. Both cockleshell plates have the same material properties. From the simulation results, the ballistic limit velocity and residual velocity for each bullet were compared. In terms of residual velocity, there is no difference between the two models. Same goes to ballistic limit velocity value, there is no difference in ballistic limit velocity for both models. There was a failure of a cockleshell plate. Both models have the same plastic deformation and kinetic energy dissipation, according to the findings. The deformation based on step time is the only difference that can be seen. After complete penetration, the final deformation is still the same. The endpoint of the cockleshell plate subjected to impact by hemispherical face caused major fracture and no plug is ejected. The boundary condition of the cockleshell plate was fractured before the plug could develop, hence no plug formed as a result of the impact.

Keywords: Cockleshell, Ballistic Limit, Numerical Simulation, Failure, Projectile

1. Introduction

Protection is very important and mostly related to impact. Protection is used to prevent the impactor from directly impacting a body. Protective equipment is one of the most important elements in any form of defence system. Self-defense, often known as defensive covering, refers to anything that can protect a person's body, a structure, or a vehicle from harm or attack. As technology advances, the materials used in plate armour continue to evolve, including steel, Kevlar, ceramics, and other materials that can provide better impact and benefit to the user [1]. Protection material especially for bulletproof jackets

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is needed to increase time of impact. Protective equipment is often used as a protective shield that can be used to protect the body from physical danger. It means protection needs to be built or invented by using suitable material [2]. So, it can decrease impact toward the body.

A projectile is defined as any object that causes an impact with a specified ballistic performance. The ability of an object to absorb projectile impact energy is referred to as ballistic resistance. Military vehicles are unique vehicles that are created and engineered to withstand projectiles, bullets, and ballistics. This type of vehicle is built of projectile-resistant or ballistic-resistant materials. The relative velocity of the projectile and the target, the projectile and target form, relative rigidity, target and projectile mass, contact surface, geometry and condition limit, and projectile and target material properties are all complicated ballistic factors [3].

There are tests conducted by Marom and Bodner [4] on layered aluminium plates struck by round-nosed lead projectiles. The resistance was determined by the projectile in terms of speed drop during the perforation process, and plugging failure was seen in the experiment. Multi-layered beams had higher perforation resistance (without spacing) than monolithic beams of identical areal density, according to the study. The laminated beams showed reduced shear resistance and hence more total deformation as a result of bulging and dishing the primary energy absorption structures.

The efficiency of multi-layered steel plates was investigated by Corran et al. [5] and found that layered plates were chosen over monolithic plates with no spacing, and surface stretching rather than bending and shearing was used to manage energy absorption.

Following that, E.A. Flores-Johnson and colleagues explain how three different plates attempt to establish the ballistic limit. The goal of this research is to see how multi-layered armour plates with various geometries, thicknesses, and material qualities affect the structure's ballistic performance [6].The ballistic limit performance of monolithic, double-layered, and triple-layered metallic plates made of steel or aluminium subjected to impact by a 7.62-mm APM2 bullet in the beginning velocity range of 775-950 m/s is investigated numerically in this study. the layers of target and the projectile face affecting the results of residual velocity, ballistic limit velocity and type of deformation that the plate will undergo after impact. A multi-layered plate is more impact resistant than a single plate. Monolithic plates, on the other hand, offer a better ballistic performance than multi-layered plates. The single plate of similar thickness exhibited increasing resistance to piercing as the number of layers was increased.

This research will be studied the ballistic limit using hemispherical faced bullet as impactor and double layered cockleshell reinforced carbon fibre as target material using simulation approach. There are two models will be used which is non-spaced and spaced cockleshell plate. The deformation of the structure after impact also will be observed. A simulation using finite elements is proposed for efficiency and to obtain more detailed and complex data [7]. The numerical results were in accordance with the published experimental results, and the research shows that the material model can replicate the failure properties of steel and aluminium plates as reported in numerous experimental observations [8].

1.1 Impact velocity

The impact velocity is the velocity of an object when it undergoes collision with another object or the ground. There are two kinds of impacts, which are low velocity impact and high-velocity impact. Low velocity perforation regime in which there is deformation and stretching of the material in a large region leading to a high amount of perforation energy and high velocity regime for which perforation energy is significantly reduced due to a more localized perforation process [9]. The impact circumstance can be related to most engineering applications in our surrounding.

1.2 Ballistic limit prediction

The ‘ballistic limit' is defined as the lowest initial impact velocity that is only enough to penetrate the specimens completely. The maximum impact velocity that the target can withstand without completely perforating it is known as the ballistic limit [10]. Ballistic limits (BL) are practically described by V_{50} , which is the average of a series of impact velocities; at which 50% of impacts will result in a complete penetration of the material. In other words, if the projectile velocity is less than the ballistic limit, the bullet will not pierce the target [11].

1.3 Impact damage

The unique chemical response of reactive materials during penetration is significantly influenced by projectile or target impact conditions, resulting in damage effects and mechanisms that are difficult to understand well. Therefore, several studies have been performed to investigate the impact-induced initiation and damage effects [12]. As the material target is subjected to the effect of velocity, the compression will occur on the target panel and then the material will shear and during impact tiny fragments will be produced. Once the projectile velocity on that panel has decreased, the material target will deform where it will extend and lower the layer to the carrying capacity load. Therefore, when impacting the targets at enough velocity, the reactive projectile will be initiated to induce a deflagration reaction during penetration, resulting in dramatically more structural damage to the targets. Especially, due to the combined effects of the kinetic energy and the chemical energy, the damage to the behind-plate targets may well be significantly enhanced [13].

2. Materials

The cockleshell reinforced carbon fibre with ratio 0.3 (wt%) is subjected to a hemispherical faced bullet. Two type of plate arrangement is made. First, non-spaced cockleshell plate and second is a spaced cockleshell target plate. Using finite element analysis, the impact research between the bullet and the cockleshell target plate will be performed. This research is conducted using explicit, dynamic analysis.

2.1 Model geometry

Shape or geometry for projectile and target was designed by using ABAQUS Explicit (Dynamic) with dimension of Length x Width x Thickness. So, the dimension used in the simulation is 80mm x 10mm x 10mm. Figure 1 shows 3D dimension of target plate. The detail dimension of the bullet is 23.65mm in length with a hemispherical bullet of 6.35mm radius.

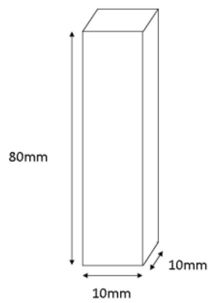

Figure 1: 3D dimension of cockleshell target plate

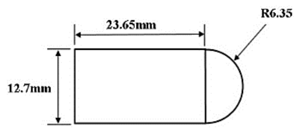

Figure 2: 3D dimension of projectile

Figure 1 shows the detail dimension of the cockleshell plate. Figure 2 shows the detail dimension of the projectile which is the hemispherical faced bullet.

2.2 Material properties

Material properties is the mechanical behavior set to the geometry of components, which are the bullet and target plate in this case.

Table 1: Material properties set for cockleshell mixture carbon fibre ratio 0.3 (wt%)

Density, ρ $(\mathbf{kg/m^3})$	Young's modulus, E $(\mathbf{MPa})$	Poisson ratio, $\mathbf{v}$	Fracture strain, ε	Fracture energy $(\mathbf{Nm^2})$	Friction angle, ∅	Dilation angle, φ	Yield stress compression $(\mathbf{MPa})$
2700	250	0.3	0.011	1900	36.618°	19.18516°	29.51

Table 1 shows the mechanical properties used for the cockleshell based on the mechanical behavior required in this research. For the target plate, the material used is a cockleshell mixture carbon fibre with 0.3 weight percentage. As the bullet would be considered as rigid in the simulation, the bullet property is not necessary.

2.3 Model arrangement

In ABAQUS Explicit, the model arrangement is one of the important things to be considered because it will affect the time required to solve the simulation analysis.

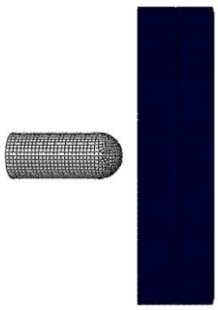

Figure 3: Arrangement between hemispherical-face bullet and non-spaced cockleshell target plate

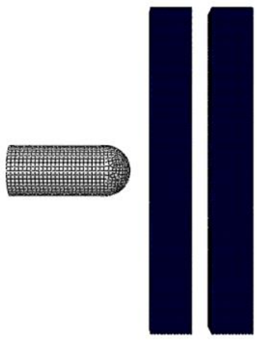

Figure 4: Arrangement between hemispherical-face bullet and spaced cockleshell target plate

The model arrangement for the hemispherical bullet before impacting on the cockleshell target plate were shown in Figure 3 and Figure 4. The set distance between the bullet and the target face is 0.005m for this analysis, so the bullet moves slightly before impacting the target plate when the simulation begins. The purpose for this distance set is to easily observe the early crack of the structure.

2.4 Boundary condition

To acquire the analysis solution, ABAQUS Explicit simulation needed the user select at least one initial condition or constraints for the model. For instance, translational velocity was used in this study for the projectile's collision with the target.

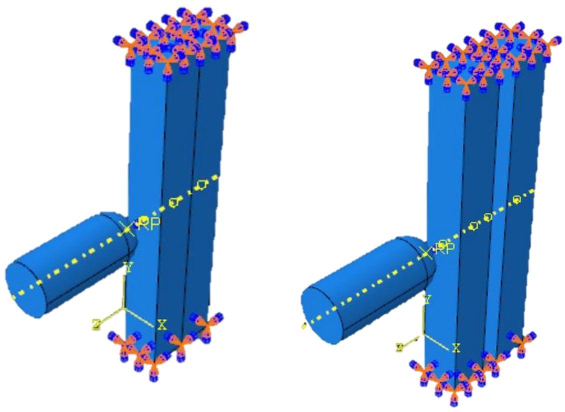

Figure 5: Boundary condition set for the non-spaced cockleshell target plate

Boundary condition was set at every side of the plate as shown in Figure 5 so that it became fixed. The boundary condition was set that way so that the plate position will not change after being subjected to impact.

2.5 Meshing analysis

In the simulation process, meshing is the factor affecting the accuracy of the result because it organized the arrangement of a discrete point on a model [14]. The existence of different shapes of elements, such as square and triangular, is in order to allow more refined mesh to be used for example in areas of high stress concentration where greater accuracy is needed, especially if the shape geometry of model structures is complex.

Figure 6: Meshing of target plate

Figure 6 shows the meshing of the target material. Mesh used in the simulation is 0.0004 and the element generated is 125000 elements.

3. Results and Discussion

3.1 Ballistic limit velocity

The simulation was used to determine the ballistic limit velocity by increasing the impact velocity from 14m/s until the bullet began to breach the cockleshell plate.

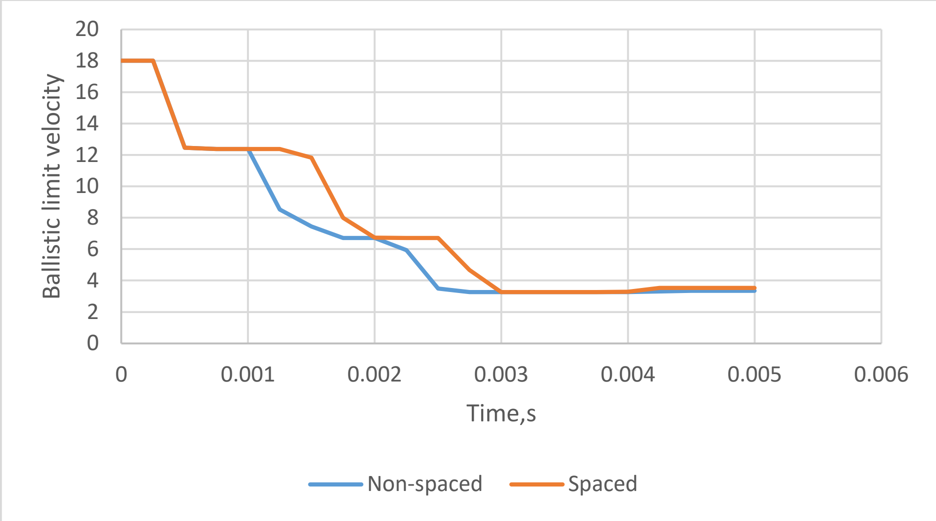

Figure 7: Graph ballistic limit velocity for both non-spaced and spaced plate

Figure 7 shows the graph of the bullet's ballistic limit velocity after impacting both a non-spaced and a spaced plate. The ballistic limit of a non-spaced plate is 18 m/s, and the ballistic limit of a spaced plate is also 18 m/s. The velocity decreases are a bit different since the bullet experience different stage of impact on non-spaced and spaced plate. On non-spaced plate, the bullet has continuous impact since there is no space between the plate. Compared to spaced plate, after the bullet impacting the first plate, the bullet moves along empty space before impacting the second plate. Thus, the decreasing in velocity of bullet slightly different at time step 0.001s to 0.0003s. The velocity decreases faster for non-spaced plate compared to spaced plate because the non-spaced plate is harder to break than spaced plate.

3.2 Residual velocity

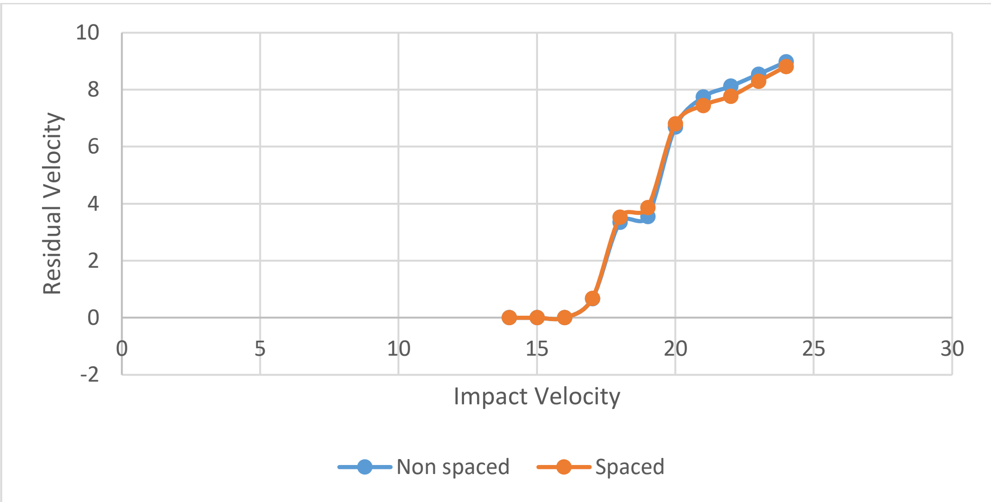

Figure 8: Residual velocity vs Impact velocity of bullet after hitting both non-spaced and spaced plate

As the bullets begin to penetrate, a certain amount of residual velocity is produced. The residual velocity of an impact velocity that failed to break the plate is 0ms. Figure 8 shows the bullet's residual velocity vs impact velocity after impacting both non-spaced and spaced plate. From the residual velocity result obtain of bullet for both spaced and non-spaced plate, it can be seen that the residual velocity for bullet start at 17m/s for both non-spaced and spaced plate. And then it rapidly increases at 18m/s since the bullet is completely penetrate the plate. From the graph, there is not much different between non-spaced and spaced plate.

3.3 Energy dissipation

Because of the damage formation and tearing of target material, the bullet's kinetic energy lost faster, indicating that the energy required for the bullet to pierce the target is higher. Figure 9 shows the bullet's kinetic energy dissipation on both non-spaced and spaced plates.

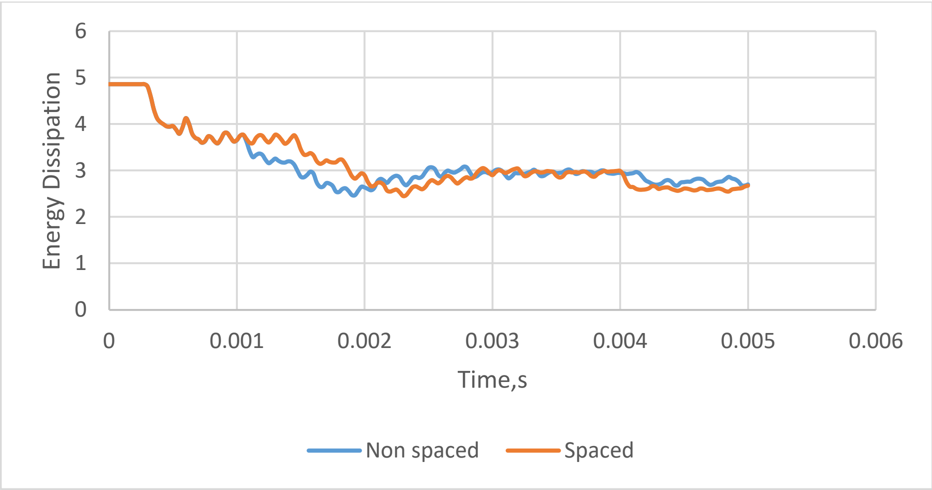

Figure 9: Dissipation of kinetic energy of bullet after hitting both non-spaced and spaced plate

As shown in graph, bullet after impacting both non-spaced and spaced plate have a continuous decreasing in energy. The difference is energy loss of the bullet after impacting non-spaced plate is slightly high at 0.001s until 0.002s compared to when impacting spaced plate. However, the energy left after complete penetration is still the same.

3.4 Damage sequence

The damage sequence is significant for analyzing and comparing the damage characteristics of both types of plate arrangements. In 0.005s, the damage sequence was captured. By capturing the damage sequence at a specified time during the impact simulation, the difference and comparison may be made. The damage sequence will be taken in increments of 0.001s, 0.002s, 0.003s, 0.004s, and 0.005s until the simulation duration finishes completely.

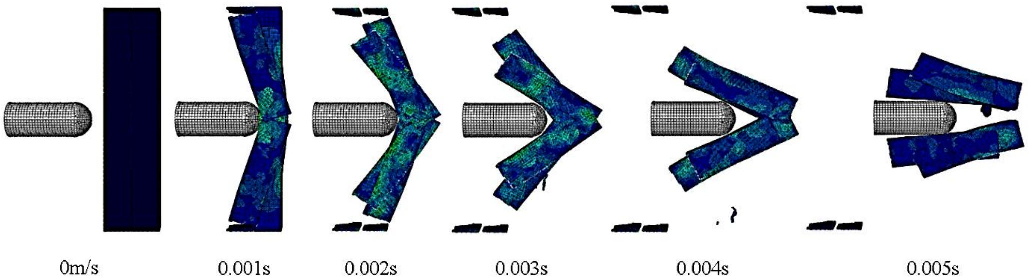

Figure 10: Damage sequence for non-spaced plate

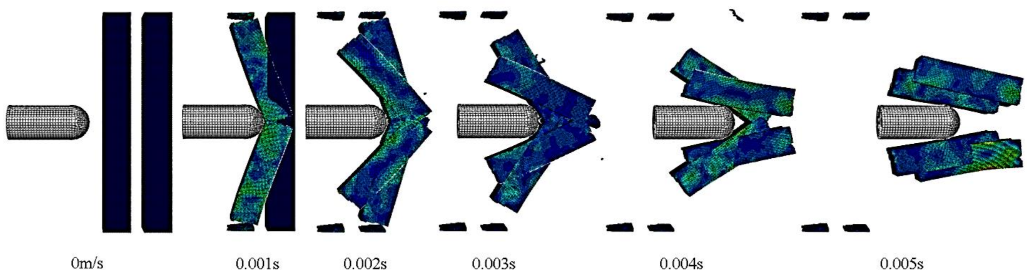

Figure 11: Damage sequence for spaced plate

The plate's damage sequence when exposed to projectile has been determined. Damage sequences for non-spaced and spaced plate are shown in Figures 10 and 11, respectively.

There were comparisons and differences that could be analysed based on the damage sequence from non-spaced and spaced plates. First, the angle of plate deflection at 0.001s is larger for spaced plates than for non-spaced plates. This demonstrates that spaced plates are more easily broken than non-spaced plates. Next, in a spaced plate, the bullet has already entirely broken one of the plates at 0.004s, whereas in a non-spaced plate, both plates have not yet been completely broken. The bullet penetrates the spaced plate more easily than the non-spaced plate, as can be seen. However, at the end of simulation, the plate still breaks for both non-spaced and spaced. The only difference is the damage occur to the plate at different time step. At the top and bottom end points of the cockleshell plate, the target plate's boundary condition has been set.

3.5 Mode of failure

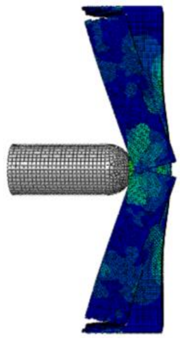

Figure 12: Failure mode of non-spaced Plate

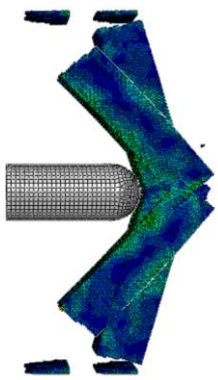

Figure 13: Failure mode of Spaced Plate

Figures 12 and 13 show the mode of failure for non-spaced and spaced cockleshell plate impacted by a hemispherical-face bullet, respectively. The failure mode is the same for both non-spaced and spaced plates. After penetrating the target, the bullet does not carry any plug. This simulation result was obtained by impacting a hemispherical-face bullet, which resulted in a plastic deformation in the shape of the bullet's face. The boundary condition of the cockleshell plate was fractured before the plug could develop, hence no plug formed as a result of the impact.

3.6 Endpoint fracture and deformation

The boundary condition has been fixed at the end point of both plates in this simulation. The cockleshell plate had been impacted by a bullet with a hemispherical face. As soon as the hemispherical faced bullet makes contact with the layered target plate, it bends it. The rate of bending is highest at the point of contact, where the target plates being hit by the projectile. The maximum Von Mises occurs in the same area. Following the perforation of the target plate, the Von Mises stress and equivalent plastic strain rapidly increase as soon as the target plates are fractured. According to, the hemisphere projectile will be induced necking, causing both the rear and front of the cockleshell plate to fracture due to their inability to withstand the ultimate tensile strength. After the hemispherical-face bullet penetrated the plate, the cockleshell endpoint fractured as shown in Figure 14.

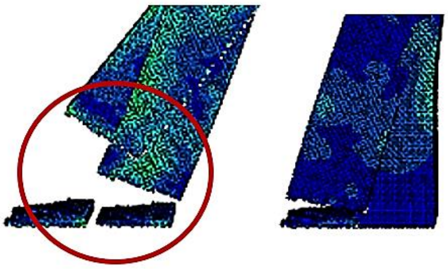

Figure 14: Major fracture of cockleshell plate's endpoint

4. Conclusion

In this research, the simulation of two different arrangement of target plate impacted by hemispherical faced bullet is observed. The ballistic limit of the non-spaced plate was gained from the simulation have the same ballistic limit as spaced plate which when bullet is shot at velocity 18m/s. Thus, it can be concluded that both non-spaced and spaced has no difference in ballistic limit. This is due to the material of both plate is the same and the distance of space only 10mm. The kinetic energy left for both non-spaced and spaced plate is the same. But non-spaced plate reduced energy faster compared to spaced plate. So, in conclusion non-spaced absorbed more energy and reduce the velocity of the bullet faster compared to spaced plate. The damage characteristic of the cockleshell plate also had been analyzed and both arrangement of plate has same characteristics of damage. The end point of the target plate subjected to hemispherical bullet also undergo same type of fracture. From overall results, it has been proved that non-spaced cockleshell plate is more effective to be used in engineering application compared to spaced cockleshell plate.

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