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RESEARCH ARTICLE

Numerical simulation of composite materials with sisal and glass fibers for ballistic impact resistance

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Abstract: Body armor is critical to mitigating penetrating injuries and saving soldiers' lives. However, ballistic impacts to body armor can cause back deformation (BFD), posing a serious threat of fatal injury on the battlefield. The study performs finite element modelling to evaluate the protection of body armor panels. The numerical simulations consider various parameters, including impact velocities, and angles of projectile impact, which are used to estimate the residual velocity and damage patterns of the composite laminate. The simulations are carried out using the LS-DYNA code based on finite element analysis. The main results of the research reveal crucial insights into the ballistic behavior of composite materials with sisal and glass fibers. The study identifies specific responses, damage development patterns, and comparative analyses between sisal and fiberglass composites. The results have practical implications for the development of advanced materials to improve ballistic protection.

Keywords: body armor, finite element model, fiberglass, impact velocity, sisal fiber

1 Introduction

The function of body armor is to protect by softening shock and preventing weapon penetration. However, as weapons advance, it is almost impossible to use only one type of protective gear to prevent injuries. Body armor is now manufactured in many styles and designs to fulfill its functions [1]. The composition of bulletproof materials has evolved from effortless to varying qualities and includes components such as non-Newtonian materials [2], and magnetorheological fluids [3]. The inventive development of advanced materials has significantly improved the capabilities of bulletproof equipment. Fiber-reinforced composite materials are widely used in the field of ballistic security due to their low weight, high quality, high modulus, and high specific retention energy [4], Requests for strategies to address the ballistic response of fiber-reinforced rubber mesh composites typically include ballistic entry testing [5, 6], and limited component replicas [7–10]. Improving the ballistic infiltration resistance of advanced composite materials for ballistic security is significant because it focuses on improving the mechanical properties of high- performance strands [11, 12].

Body armor can be defensive materials used to protect different customers, including military and security forces, from various threats [13]. Today, the combination of advances in high-velocity shooting and increasing demand for body armor places critical importance on designers, forecasters, and producers. This weight arises from the need for constant development of ballistic security systems, which requires not only appropriate planning strategies but also the further development of suitable materials [14].

Due to variations in the angle of incidence of the impacting projectile, a composite structure may be exposed to the ballistic impact force at different points in its life. This is an important equipment. It is important to ensure that laminated structural composites are resistant to penetration and perforation from projectile impacts of different orientations. The transverse normal impact-induced perforation in composite panels has been numerically analyzed in previous publications [15–17]. These studies considered variables such as shot tip shape, stack grouping, and target thickness and provided experience on their effects on target aperture. By combining glass and sisal fibers, a hybrid material can be created that benefits from the strengths of both fibers. Glass fibers provide high thermal stability and corrosion resistance, while sisal fibers reinforce the glass and improve its strength and ductility. This hybridization can result in a material with improved ballistic performance and impact resistance, making it suitable for use in protective applications [18, 19]. The combination of biodegradable and renewable sisal fibers with synthetic and durable glass fibers also provides environmental benefits by using a sustainable and renewable resource [20]. Overall, the hybridization of glass and sisal fibers offers a promising solution to improve the performance and sustainability of materials used in protective applications [21, 22].

The importance of ballistic performance and impact resistance is critical in various applications including military, law enforcement, and civilian scenarios. It is essential to protecting lives and resources. Developing materials and structures that can effectively resist and mitigate ballistic threats is of paramount importance. In addition, the impact resistance of materials is critical to ensuring the durability and reliability of structures and systems subjected to dynamic forces. Research and development efforts focus on achieving optimal ballistic performance and impact resistance in a wide range of applications and address the evolving safety requirements of various sectors [23–25].

Ballistic impact is the study that deals with the behavior of material failure caused by the impact of projectiles/bullets. This is particularly important to protect people and machines in nuclear and military applications. The impact behavior of composite materials depends on the size, shape, mass, impact velocity, and material of the projectile [26, 27], as well as the geometry, mass, composition, and contact condition of the target [28]. For the ballistic investigation of composite materials, numerical analysis using finite element analysis (FEA) is also investigated [29, 30]. Through validation, it was found that FEA methods can predict behavior quite realistically [31–33].

The purpose of this study is to investigate the perforation behavior of glass and sisal fiber composite panels when exposed to blunt projectiles from different angles and velocities. The study aims to analyze the influence of impact angle (45° and 90°) and impact velocity in the range of 100-200m/s on the perforation properties of the target plate through numerical simulation using LSDYNA.

2 Numerical simulation

2.1 Finite element modelling

The target plate considered for investigation is a square plate of exposed area dimension of 100 mm × 100 mm × 10 mm having 20 layers of bullet fabric(glass, and sisal). Each layer of the target is modelled using Belytchko-Tsay shell elements with a layer thickness of 0.5 mm. To arrive at the optimum finite element, a detailed mesh convergence study with different element sizes is carried out. As per the investigation, 2 mm element sizes are converging to the same residual velocity. Hence for computational efficiency, a 2 mm element size is used for subsequent studies. The finite element model of the target plate consists of 340,000 elements and 344,008 nodes. The projectile is modelled using the three-dimensional solid elements available in the LSDYNA code. The hemispherical nose projectile model is made up of 3950 elements and 4344 nodes. The finite element model of the target plate and the projectile is shown in Figure 1. In modelling the projectile, the shank diameter of 9 mm is kept constant for the hemispherical-nosed projectile, and the length of 19 mm for the hemispherical-nosed projectile is considered to maintain the 8 g of projectile mass.

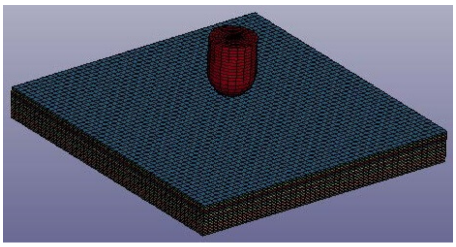

Figure 1 Finite element modelling

2.2 Material model

To simulate the ballistic impact effects on Sisal and glass fiber plate numerically, MAT 54 Enhanced composite damage material-based Chang – Chang failure criteria, available in the non-linear finite element code LS DYNA is used [42]. For composite backing panels, the

MAT_ENHANCED_COMPOSITE_DAMGE model(MAT54) was used and the Chang/Change criteria are given as follows [43]:

$$e_f^e = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0 \ failed \\ < 0 \ elastic \end{cases} \tag{1}$$

$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0 \tag{2}$$

For the compressive fiber mode, $\sigma_{aa} < 0$:

$$e_c^2 = \left(\frac{\sigma_{aa}}{Xc}\right)^2 - 1 \begin{cases} \geq 0 \ failed \\ < 0 \ elastic \end{cases} \tag{3}$$

$$E_a = \nu_{ba} = \nu_{ab} = 0 \tag{4}$$

For the tensile matrix mode, $\sigma_{bb} > 0$:

$$e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 \ failed \\ < 0 \ elastic \end{cases} \tag{5}$$

$$E_b = \nu_{ab} = 0 \Rightarrow G_{ab} = 0 \tag{6}$$

For the compressive matrix mode, $\sigma_{bb} < 0$:

$$e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\left(\frac{\sigma_{bb}}{S_c}\right) + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 \ failed \\ < 0 \ elastic \end{cases} \tag{7}$$

$$E_a = \nu_{ba} = \nu_{ab} = 0 \Longrightarrow G_{ab} = 0 \tag{8}$$

Where is the stress in the fiber direction, σ_{bb} is the stress in the matrix direction, G_{ab} is the inplane shear stress, Xt is the longitudinal tensile strength, Xc is the longitudinal compressive strength, Yt is the transverse tensile strength, Yc is the transverse compressive strength, Sc is the shear strength, β is the weighting factor for the shear term in tensile fiber mode. The material properties used in the numerical simulation are given in Table 1 and 2.

Table 1 Mechanical properties of sisal and glass fiber [39, 40]

Properties	Sisal	E-Glass
Density (g/cm^3)	1.5	2.5
Longitudinal Elastic Modulus: E_1 (GPa)	28	53.48
Transverse Elastic Modulus: E_2 (GPa)	2.5	17.7
Radial Elastic Modulus: E_3 (GPa)	2.5	5.83
Shear Modulus: G_{12} (GPa)	1.85	5.83
Poisson's Ratio: V_{12}	0.265	0.278
Tensile Strength: Xt(MPa)	600	1140
Compressive Strength: Xc (MPa)	450	570
Tensile Yield Strength: Yt (MPa)	30	35
Compressive Yield Strength: Yc (Mpa)	100	114
Shear Strength: Sc (MPa)	60	72

Table 2 Material properties of steel projectiles [41]

Properties	Steel
Density [kg/m^3]	7830
E_1 (GPa)	210
v	0.3

3 Impact conditions

To understand how composite panels respond to different ballistic scenarios, it is crucial to incorporate various impact parameters into the simulation. These parameters include impact velocity and angles. The behavior of composite panels based on glass fiber woven fabrics and a bi-component epoxy resin under ballistic impacts was evaluated using a finite-element model at the meso scale [20] while considering parameters such as projectile material, size, and speed [44]. The development of a comprehensive framework for the design of composite structures at different levels requires accurate mathematical and computational models that can simulate the dynamic impact on composite panels [45]. Numerical studies have been conducted to investigate the damage effects on composite panel high-velocity impacts, considering different composite laminates and stacking sequences [46,47]. These studies provide insights into the ballistic behavior, energy-absorbing capacity, and damage of composite panels' performance under different impact scenarios.

4 Energy absorption

The assessment of energy absorption is a critical aspect in the numerical simulation of composites with sisal and glass fibers for ballistic impact resistance. The simulation involves modelling and analyzing how the composite materials absorb and dissipate energy when exposed to ballistic impacts. Several studies have investigated the impact resistance and ballistic performance of different composite materials. The results have shown that the difference in velocity and angle significantly affects the energy absorption capacity of the composites [48,49]. Additionally, the orientation of the fibers in the impact direction has been found to improve the impact energy absorption and overall mechanical response of the composites [50,51]. Finite element simulations have been used to evaluate the behavior of composite panels under ballistic impacts, providing insights into the number of layers broken, delamination effects, and deformation patterns [20].

5 Result and discussion

Understanding the failure mechanisms in numerical simulations of composites for ballistic impact resistance is crucial for assessing their performance under extreme conditions. Different failure mechanisms can occur depending on factors such as impact velocity, angle, and the properties of the composite. The failure mechanisms that may be investigated in such simulations include the energy absorption/dissipation capabilities and failure mechanisms of hyper-elastic target materials [52,53]. The impact of the target surface will be affected by different velocity ranges and angles observed in the simulation. The numerical simulation using the same thickness of the target sample was made. The numerical simulation results are to indicate the effect of the parameters and identify better materials and control parameters. In Figure 2(a), the illustration shows that the kinetic energy absorption of the composite panels varies. Glass fiber exhibits superior ballistic impact resistance, withstanding velocities of 120 m/s at a 90-degree angle better than sisal fiber in terms of energy absorption and dissipation. Figure 2(b) demonstrates that sisal fiber target panels are easily penetrated by bullets due to their lower strength compared to glass fiber. Figure 3(a) indicates that the residual velocity of sisal fiber is lower because it easily damages the target panel, whereas glass fiber maintains a higher residual velocity due to its rigidity. This difference in material properties highlights glass fiber's superiority over sisal fiber. Figure 3(b) further emphasizes that residual velocities are influenced by both the angle of projection and material properties.

Figure 4 and 5 describe the Von Mises stress effect on the composite panel when impacted by bullets at different angles and velocities, resulting in distinct damage patterns. The higher damage to the fibers occurs when the projectile tip contacts the panels and spreads perpendicular to the loading direction. The strength of the fibers in their respective layers significantly influences the overall strength of the panels [26,54]. Upon impact with a 9 mm FMJ (Full Metal Jacket) projectile, the fully damaged shear area on the impact side is smaller compared to the backside across all panels.

Figure 6 illustrates the comparison between sisal and glass fiber regarding their ballistic impact resistance behavior and stress resistance in composite materials. According to finite element analysis, sisal fiber exhibits greater rigidity properties compared to glass fiber, as it tends to break more easily without stretching. When impacted at a velocity of 150 m/s at a 90-degree angle, sisal fiber experiences a higher damage pattern. On the other hand, glass fiber outperforms sisal fiber in terms of ballistic impact resistance and higher energy absorption capabilities.

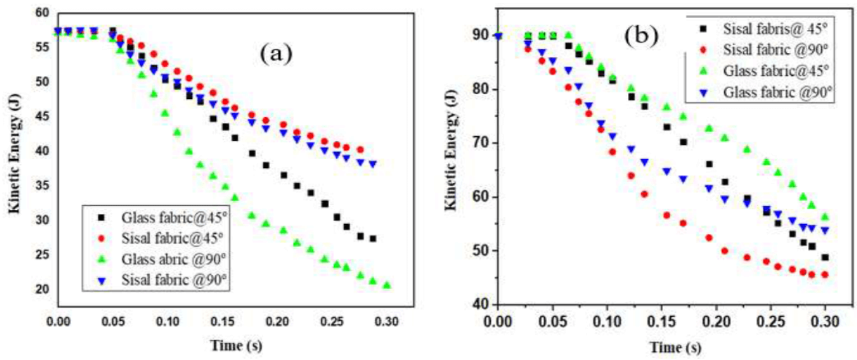

Figure 2 Illustrates kinetic energy vs time (a) for glass &sisal fabric @ velocity of 120m/s with different angles, and (b) for glass &sisal fabric @ a velocity of 150m/s with a different angles

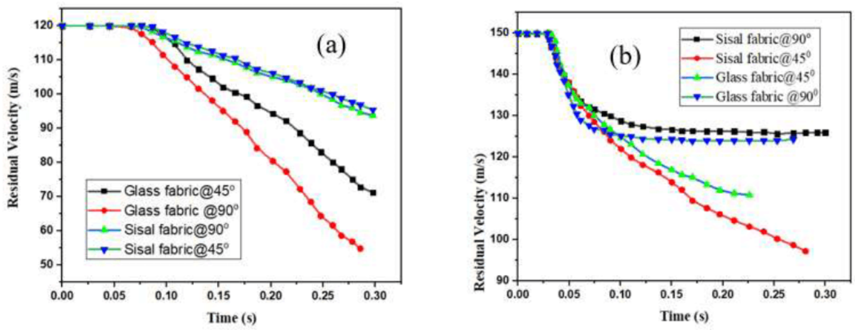

Figure 3 Illustrates Residual velocity vs time (a) for glass &sisal fabric @the of the velocity of 120m/s with a different angle, and (b) for glass &sisal fabric @the of the velocity of 150m/s with a different angle

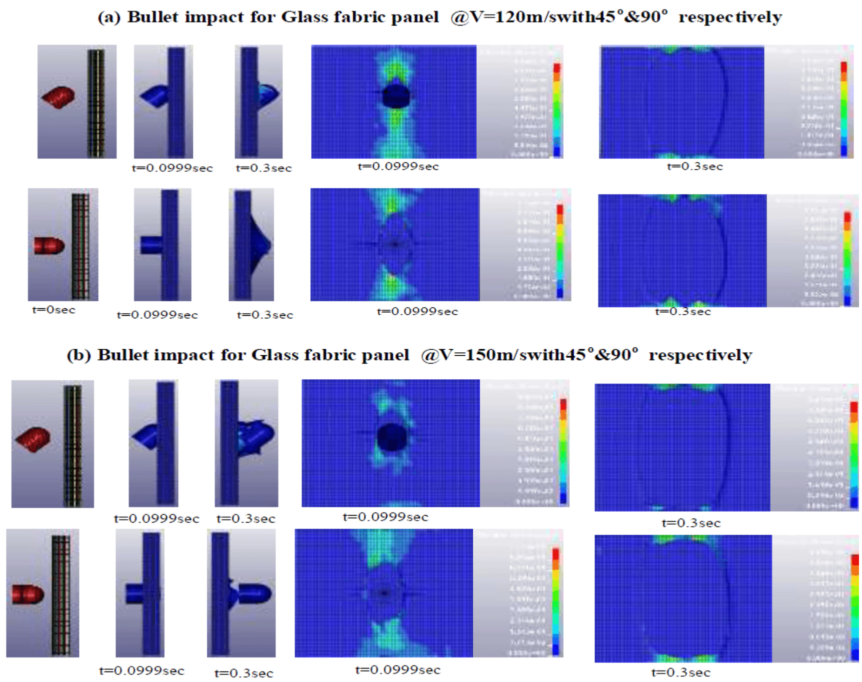

Figure 4 V.Mises stress of bullet impact for Glass fabric panel @ velocity of 120 m/s & 150 m/s with 45^o & 90^o respectively

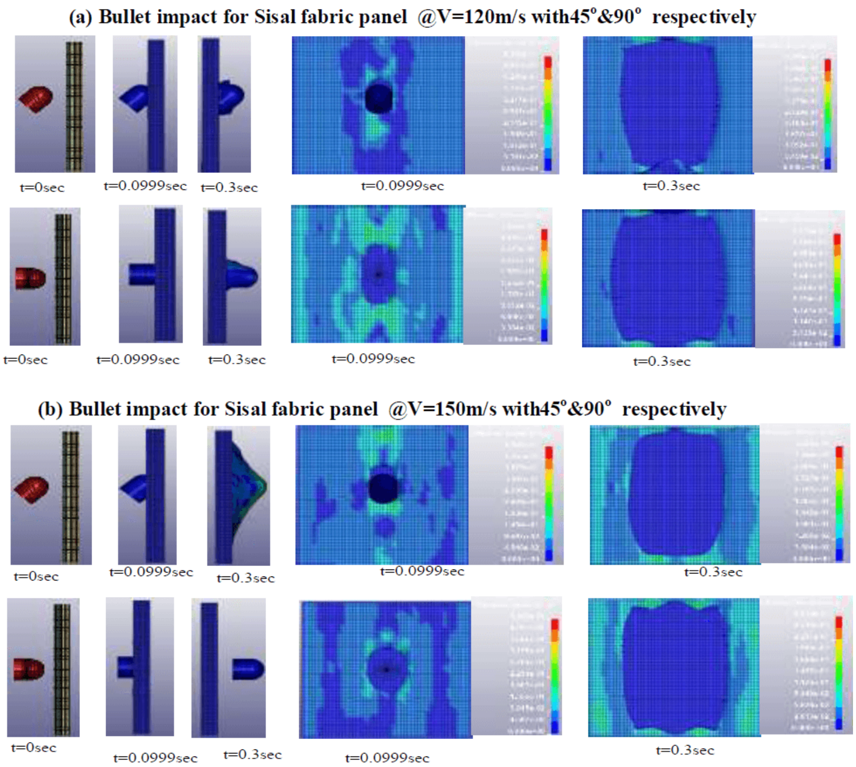

Figure 5 V.Mises stress of bullet impact for sisal fabric panel @ velocity of 120 m/s & 150 m/s with 45^o & 90^o respectively

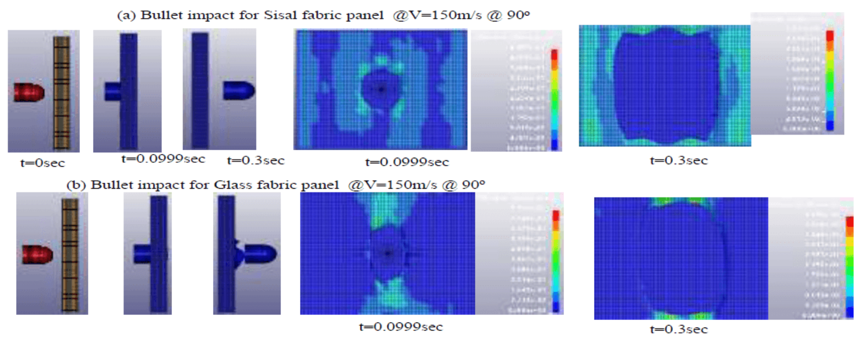

Figure 6 V.Mises stress of bullet impact for Sisal fabric and glass fabric @ velocity of 150 m/s with 90^o

6 Conclusion

The finite element modelling of the glass and sisal fiber composite panels is developed and simulated by considering various parameters. Damage initiation and damage propagation-based failure are developed. The glass fiber panel demonstrated better performance than sisal fiber with a ballistic limit velocity of 150 m/s, whereas sisal fiber performed worse with a ballistic impact of 120 m/s. due to glass fiber grater damage dissipation energy and higher extension of fiber tension than sisal fiber lamina, glass fiber as their backing layer showed excellent resistance to ballistic impact with a velocity of 120 m/s. natural fiber is particularly biodegradable and significantly reduces the overall cost compared to glass fiber with approximately the same performance.

Conflicts of interest

The authors declare that they have no conflict of interest.

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