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Influence of Impact Velocity on a Two-Layer Glass Fiber Quadriaxial Composite: a Finite Element Study

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Abstract. The selection of impact velocities in finite element method (FEM) simulations of small composite vessels depends strongly on the considered collision scenarios. Representative velocity ranges, derived from typical marine operating conditions, include low-speed harbor impacts (0.5–2 m/s), moderate head-on collisions (3–6 m/s), lateral impacts at medium speeds (5–8 m/s), and extreme cases (10–15 m/s). This paper presents a mesoscale finite element model of a two-layer quadriaxial glass fiber composite subjected to impact by a hemispherical striker at velocities of 2 m/s, 4 m/s, and 10 m/s. The composite architecture is explicitly modeled using yarns with rectangular cross-sections arranged at 0°, ±45°, and 90°, while the matrix behavior is represented by a zero-thickness cohesive zone model. The yarns are described using a bilinear hardening constitutive law, and failure is governed by the equivalent plastic strain at break and by cohesive debonding between yarns. The simulations provide insight into the influence of impact velocity on stress distribution, load transfer, and damage progression within the composite structure. The results highlight the role of quadriaxial architecture in delaying damage localization and improving energy dissipation under increasing impact energy. The study contributes to a better understanding of the impact response of glass fiber composites under representative loading conditions relevant to marine structures.

Keywords: impact simulation, velocity, composite, cohesive zone model, quadriaxial fabric.

Introduction

In the context of FEM (Finite Element Method) impact simulations, impact velocity is an important parameter. The selection of representative impact velocities for small

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vessels (20–50 meters in length), built from fiberglass-based composite materials, depends greatly on the collision scenario considered in the simulation.

Relevant collision types for small composite vessels include:

- accidental harbor collisions or maneuvering errors: 0.5–2 m/s;
- frontal collisions during low-speed navigation: 3–6 m/s;
- side impacts or unintentional contacts at moderate speeds: 5–8 m/s.

Most recreational or light transport vessels with composite hulls do not operate at maximum speed in areas where there is a risk of collision. For example, a 30 m vessel made of glass-reinforced plastic composite can reach speeds of 15–20 knots (7–10 m/s), but actual collisions usually occur at significantly lower speeds due to human reaction time or evasive maneuvers.

Several real-life collision cases, corresponding to different velocity ranges for small FRP/GRP vessels (20–50 m), are presented below as a reference for the selection of representative impact velocities used in the FEM model.

A summary of these real-life collision cases, representative of each velocity range considered in FEM simulations, is presented in Table 1.

Table 1. Real-life collision cases of small composite vessels (20–50 m) corresponding to different velocity ranges

Velocity range [m/s]	Real-life example	Estimated velocity [m/s]	Impact type
1–2	Cornucopia Destiny (28 m)	1.5–2.5	Harbor maneuvering, docking impacts
3–6	Jessica Watson vs. Silver Yang	~2.5–5	Typical cruising, head-on collision
5–8	Winslow Griesser vs. center-console	~6–8 (scaled from case)	Accelerated navigation impact
10–11	Utopia IV vs. tanker	~11	Worst-case, severe frontal collision

For low velocities, in the range of 1–2 m/s, typically associated with harbor maneuvers or light impacts, a relevant example is the Cornucopia Destiny (28 m) tourist vessel. In June 2018, while docking in Hoboken, NJ, it collided with the bow of a small yacht moored at the pier. The estimated impact velocity was around 1.5–2.5 m/s, values characteristic of operations close to docks.

In the case of medium velocities, about 3–6 m/s, one example is the 2009 incident off the coast of Australia, when the yacht sailed by Jessica Watson collided with the cargo ship Silver Yang. The leisure craft was traveling at approximately 2.5–5 m/s, typical of cruising speeds, and the collision occurred head-on in open waters - a representative scenario for this velocity range.

For medium-to-high velocities, in the 5–8 m/s range, relevant especially for impacts during accelerated navigation, we can mention the accident from August 2022 in Puerto Rico. The Winslow Griesser, a 47 m Coast Guard vessel, struck a 7 m fiberglass center-console boat. Although the Coast Guard vessel was traveling much faster (~15 m/s), when scaled down to scenarios involving two small composite

vessels (20–50 m), impact velocities of 6–8 m/s are considered representative just before collision.

Finally, for extreme cases with velocities of 10–15 m/s, the December 2021 accident in the Bahamas is illustrative. The 63 m superyacht Utopia IV collided with a 49 m tanker while traveling at approximately 11 m/s. Such scenarios represent “worst-case” frontal collisions at maximum speed. Although rare, they are the most destructive for the structural integrity of small composite vessels [11]–[15].

These scenarios provide a practical basis for defining representative loading conditions in numerical impact simulations.

The model

Considering this information, the impact simulations were carried out at velocities of 2 m/s, 4 m/s, and 10 m/s on square composite samples (60 mm × 60 mm).

The composite is made of two layers of quadriaxial fabric. Each layer contains four sub-layers. Thus, the composite model consists of eight sub-layers in total. The yarns have rectangular cross-sections and, within each layer, they are arranged at 0°, +45°, 90°, and –45°, similar to the actual fabric (Figure 1). The mesh is detailed in Figure 1a, showing the impactor and one representative yarn.

To reduce the computational domain, the impactor has a shorter length and a cylindrical section, while its density is adjusted in each case to maintain the same impact energy at different velocities.

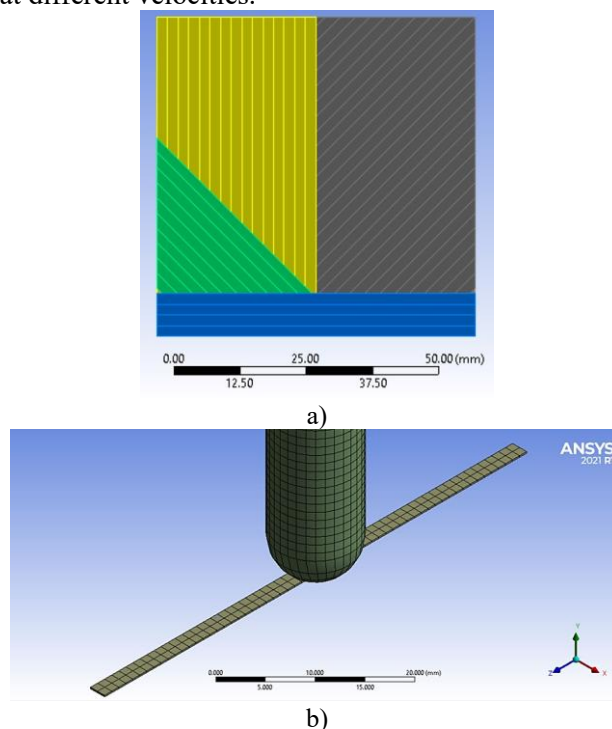


Fig. 1. Geometric representation of the quadriaxial composite model with yarn orientations (0°, +45°, 90°, –45°) in two layers.

To reduce the space in which the simulation takes place, the impactor has a shorter length and a cylindrical section, but its density is calculated each case to keep impact energy and impact velocity the same. The impact energy is kept constant according to:

$$\Delta E = \frac{m_1 \cdot v_1^2}{2} = \frac{m_2 \cdot v_2^2}{2} = \frac{m_3 \cdot v_3^2}{2} \quad (1)$$

If the impactor volume is kept constant, its density can be recalculated as:

$$\Delta E = \frac{V \cdot \rho_1 \cdot v_1^2}{2} = \frac{V \cdot \rho_2 \cdot v_2^2}{2} = \frac{V \cdot \rho_3 \cdot v_3^2}{2} \quad (2)$$

In reality, the yarn consists of hundreds of glass fibers with small diameters (7–14 μm [10]). The composite model developed in this study is at the mesoscale, where the yarn is considered as a homogeneous monolithic body. Its constitutive behavior is described using a bilinear hardening model. The yield limit and tangent modulus were approximated based on experimental results reported for similar glass fiber-reinforced composites [9].

Table 2 presents this model for the yarn and constants for breakable contacts among yarns, considering the influence of the matrix, but assigning a zero thickness to it.

Table 2. Material parameters for the composite

Characteristic	Authors' proposed value	Justification
Young's modulus ($E = 10 \text{ GPa}$)	Lower than fiber modulus (~70–85 GPa)	Valid for modeling fiber misalignment, intra-yarn friction, and waviness at yarn scale, but not due to crimping specifically for woven fabrics.
Tangent modulus ($E_t = 4 \text{ GPa}$)	Low post-yield stiffness	Simulates fiber slippage within yarn bundles, fiber–matrix decohesion inside the yarn, and damage softening.
Yield stress ($\sigma_y = 400 \text{ MPa}$)	Lower than fiber tensile strength	Conservative, but justified due to yarn imperfections, voids, and fiber dispersion effects.
Plastic strain failure (6%)	High strain-to-failure	Reasonable for a fiber-dominated fabric under quasi-static or moderate strain rates, matching observed failure strains.
Cohesive contact limits (80 MPa / 60 MPa)	Yarn–yarn delamination or debonding control	Accurately simulates mode I (traction) and mode II (shear) decohesion in quadriaxial layouts, where inter-yarn bonding is mechanical (compression/epoxy), not woven interlock.

In the Explicit Dynamics model, the “Breakable” contact option was selected, allowing contacts between yarns to fail under specified loading conditions. The connections between yarns are considered debonded when the following failure criterion is satisfied.

$$\left(\frac{G_I}{G_{IC}}\right)^n + \left(\frac{G_{II}}{G_{IIC}}\right)^n = 1 \quad (3)$$

where:

G_I is the Mode I strain energy release rate (normal opening),

G_{IC} is the critical Mode I energy release rate,

G_{II} is Mode II strain energy release rate,

G_{IIC} is the critical Mode II energy release rate,

n is the interaction exponent governing the shape of the mixed-mode failure surface. In this study, $n = 1$ was selected, corresponding to a linear interaction between the two fracture modes. This assumption is conservative and commonly used when Mode I dominates or when a simplified failure surface is preferred. Additionally, $n = 1$ improves numerical stability in explicit simulations and reduces convergence issues in highly dynamic systems.

According to literature such as **Error! Reference source not found.** and the [1] standard for Mode I interlaminar fracture, the linear interaction criterion is frequently applied in composite delamination modeling where the failure is brittle in nature.

Debonding or delamination of the yarns on the same substrate or between yarns in different layers or substrates are discussed also in **Error! Reference source not found.**, pointing out the delamination (or debonding) with a cohesive zone model of zero thickness.

In this model, the interaction between contacting bodies and their resulting fragments is governed by friction, with a constant friction coefficient ($\text{CoF} = 0.1$).

Table 3. Characteristics of the established connections

Interaction Type	Parameter Value	Modeling Role
Cohesive normal traction limit	80 MPa	Governs detachment onset in normal (mode I) opening
Cohesive shear limit	60 MPa	Controls onset of sliding separation (mode II)
Friction coefficient	0.1	Ensures residual friction after decohesion (post-failure sliding resistance)

The determination of the friction coefficient in impact scenarios remains challenging, as most experimental studies reported in the literature are conducted at lower velocities and focus on sliding between solid bodies. In the case of fabrics damaged by impact, however, the friction coefficient plays a key role in the interaction between fibers, yarns, the matrix, and the impactor, and may absorb part of the impact energy **Error! Reference source not found.**. Therefore, determining this value is an experimental challenge and can significantly influence the material's behavior during impact **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**.

In the literature, dynamic loading models have typically introduced friction using a constant friction coefficient—even though in reality this parameter may vary due to changes in the mechanical properties of the contacting bodies, temperature, and other factors—with values ranging from slightly below 0.1 up to 0.4 **Error! Reference source not found.**, **Error! Reference source not found.**. In the real context of the impact process, the friction coefficient is not a fixed value; it varies depending on the material pair in contact and the normal load applied to the surfaces. This coefficient should therefore be considered a dynamic parameter, influenced by multiple factors during impact, and this variability may significantly affect the behavior of materials subjected to such loading.

The yarn was modeled with a rectangular cross-section because its actual shape resembles a highly elongated ellipse, with an almost constant thickness over

approximately 70% of its width, while the edges are slightly rounded, which is consistent with the flattened geometry observed in woven glass fiber yarns. This approximation simplifies the modeling of yarn-to-yarn separation and substrate delamination, based on the detachment condition of nodes at the ultimate tensile and/or shear stress.

Implications of simulation with friction are the following. Before separation, the cohesive traction/shear limits control the behavior and friction plays no significant role, but between the impactor and the yarns in contact with it. After cohesive failure, the friction coefficient ($\text{CoF} = 0.1$) governs the post-failure sliding resistance between yarns and/or their broken fragments. A lower CoF ensures smooth and progressive yarn separation, preventing excessive constraint.

GRP composites exhibit good impact resistance, but they become brittle under high-energy conditions. At velocities above 8–10 m/s, extensive cracking, delamination, and even perforation can be expected.

The composite model consists of two layers of quadriaxial fabric, each layer being divided into four sub-layers, for a total of eight sub-layers. The variable parameter in the simulations is the impact velocity, with three representative values considered: 2 m/s, 4 m/s, and 10 m/s. These selected cases enable a detailed evaluation of how the material responds to increasing impact energy. In particular, the model highlights the progression of failure mechanisms, the redistribution of loads within the structure during impact, and the localization of damage in specific regions of the composite plate.

This model will give good insights into failure progress, load redistribution during impact, and damage localization.

Results & Discussion

The results of the explicit dynamic simulations provide insight into the stress distribution and failure progression within the quadriaxial composite under different impact velocities. Since the material architecture consists of both parallel and diagonal yarns, the analysis of von Mises stress evolution along each yarn direction enables a detailed understanding of how the load is absorbed, transferred, and redistributed during impact.

The following diagrams present the distribution of von Mises stress along the yarn length, for representative sub-layers. Three impact velocities were considered: 2 m/s, 4 m/s, and 10 m/s, corresponding to low-, moderate-, and high-energy impact scenarios. To capture the transient material response, the stress fields were analyzed at several characteristic time steps: 1.25×10^{-4} s, 3.75×10^{-4} s, 6.25×10^{-4} s, 8.75×10^{-4} s, 1.125×10^{-3} s, 1.375×10^{-3} s, 1.625×10^{-3} s, 1.875×10^{-3} s, 2.125×10^{-3} s, and 2.5×10^{-3} s. These moments correspond to the onset of loading, the intermediate redistribution of stresses, and the later stages when significant damage mechanisms become evident.

These results are essential for identifying which yarn (parallel or diagonal) dominate the initial response, how the stress transfer occurs between yarn families, and how the quadriaxial architecture contributes to delaying catastrophic failure. By

comparing the stress evolution across different impact velocities and time steps, the effectiveness of the fabric structure in dissipating impact energy and localizing damage can be assessed. The stress evolution for the yarns at these time steps is illustrated in Figures 2–10, highlighting the progressive changes in load distribution and the onset of damage mechanisms.

This step-by-step analysis allows the identification of the different stages of impact damage: (i) the initial stage, characterized by elastoplastic deformation without yarn breakage; (ii) the yarn breakage stage, which is important for identifying the sequence of yarn failure; and (iii) the final stage, where stresses fall below the strength limit, but friction between the impactor and yarns, as well as local yarn fragmentation and debonding, still occur. These stages can be correlated with the stress evolution presented in Figures 2–10.

At initial time steps ($t < 6.25 \times 10^{-4}$ s, Figures 2–4), the main yarns oriented along the sample edges (1, 3, 5, 7) exhibit sharp stress peaks, reflecting their rapid engagement in carrying the impact-induced load. In contrast, the diagonal yarns (2, 4, 6, 8) show a delayed response, with lower initial stress levels, as they are progressively activated through load redistribution within the composite.

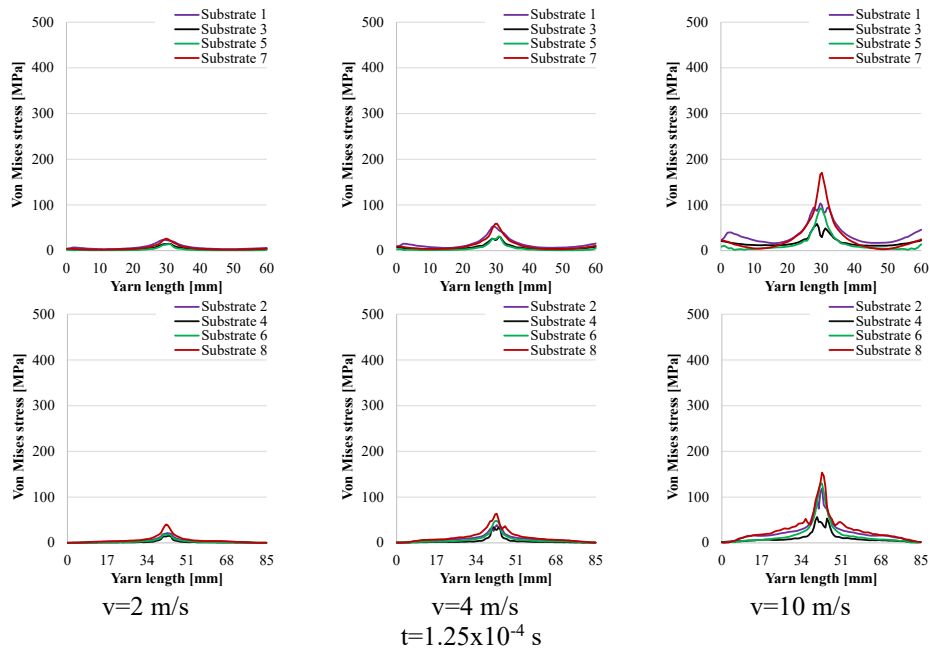


Fig. 2. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 1.25 \times 10^{-4}$ s.

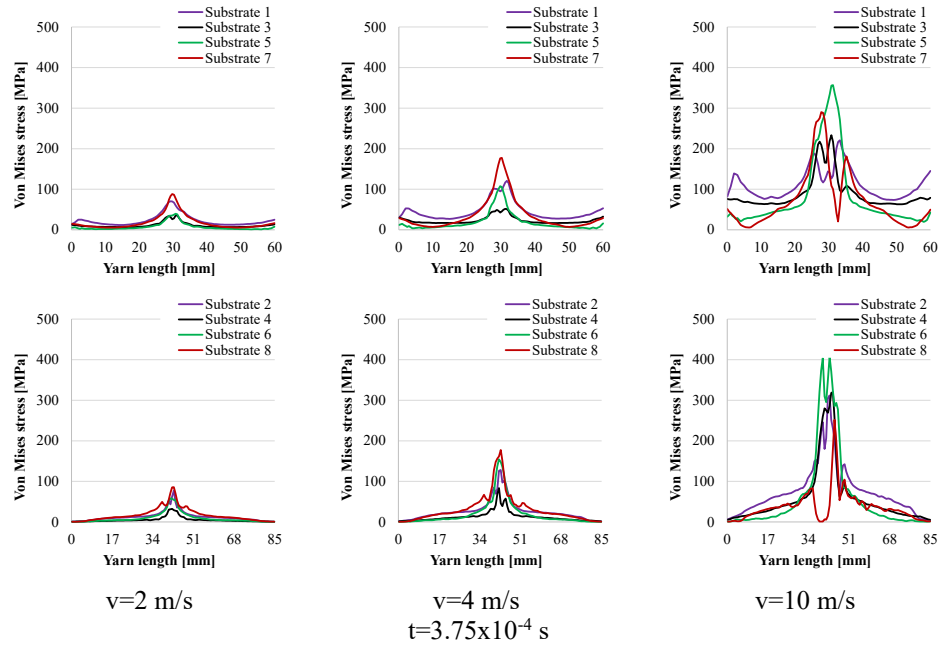


Fig. 3. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 3.75 \times 10^{-4}$ s.

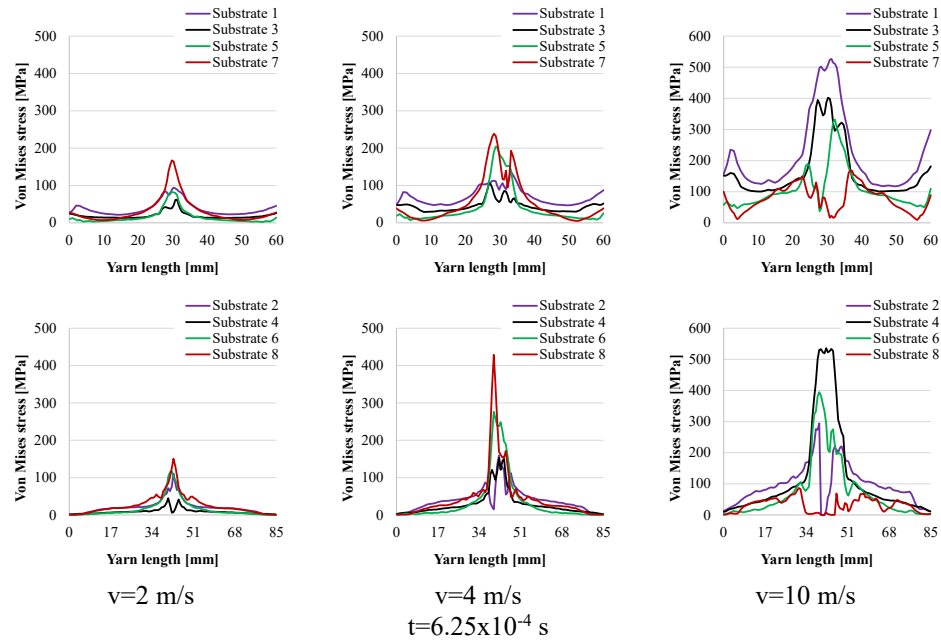


Fig. 4. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 6.25 \times 10^{-4}$ s.

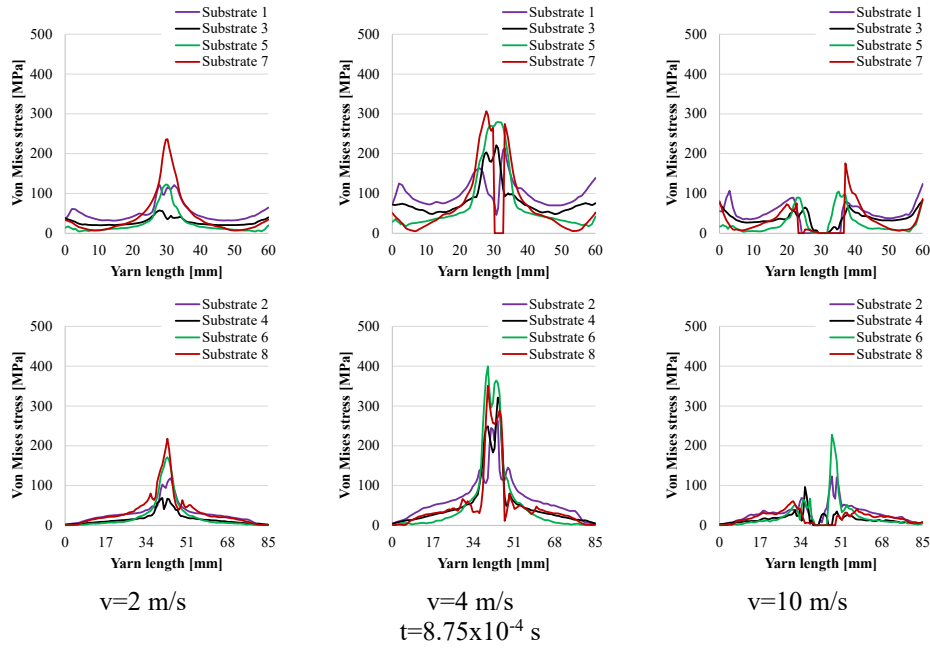


Fig. 4. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 8.75 \times 10^{-4} \text{ s}$.

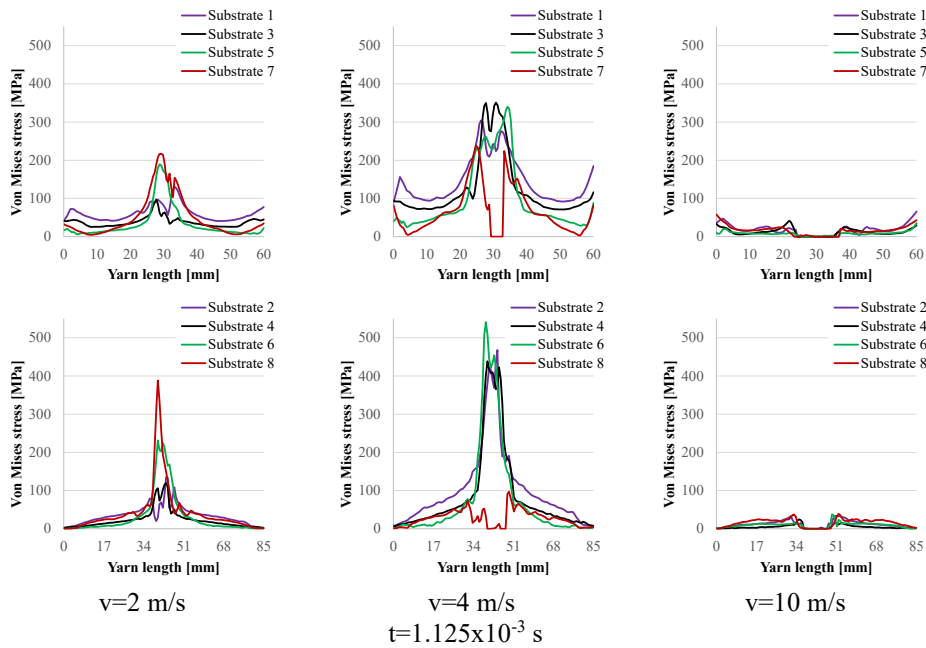


Fig. 5. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 1.125 \times 10^{-3} \text{ s}$.

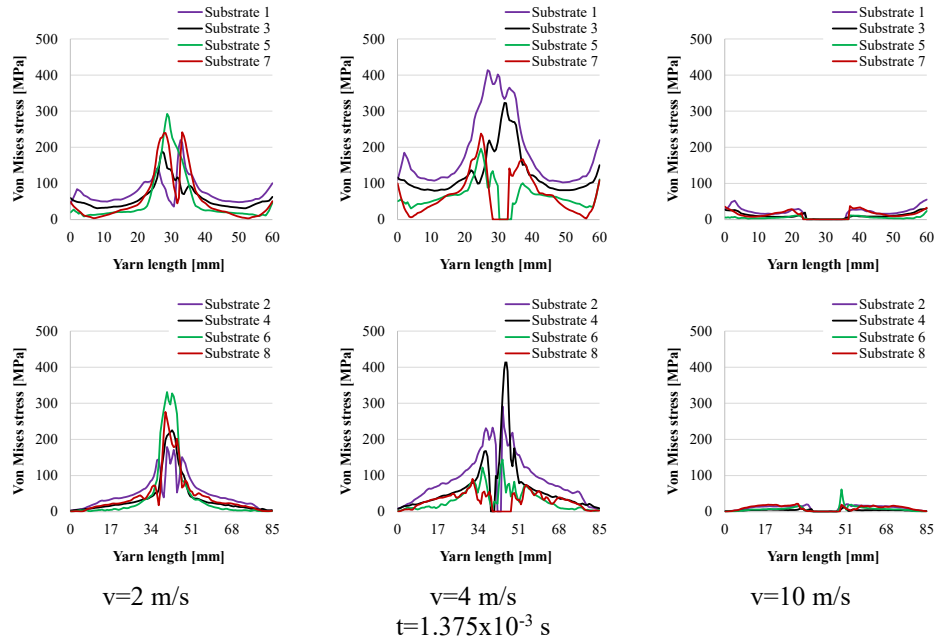


Fig. 6. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 1.375 \times 10^{-3}$ s.

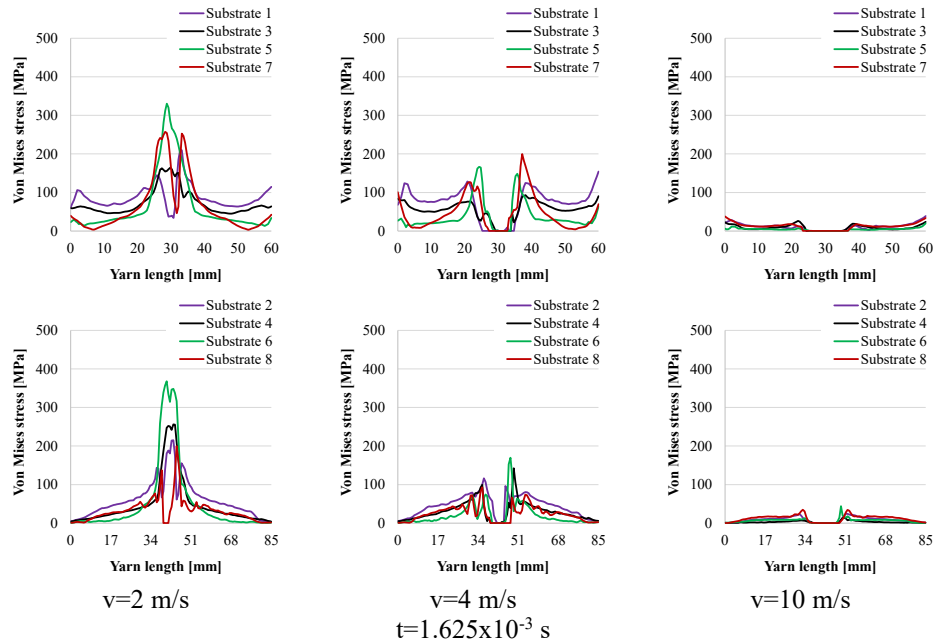


Fig. 7. Distribution of Von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 1.625 \times 10^{-3}$ s.

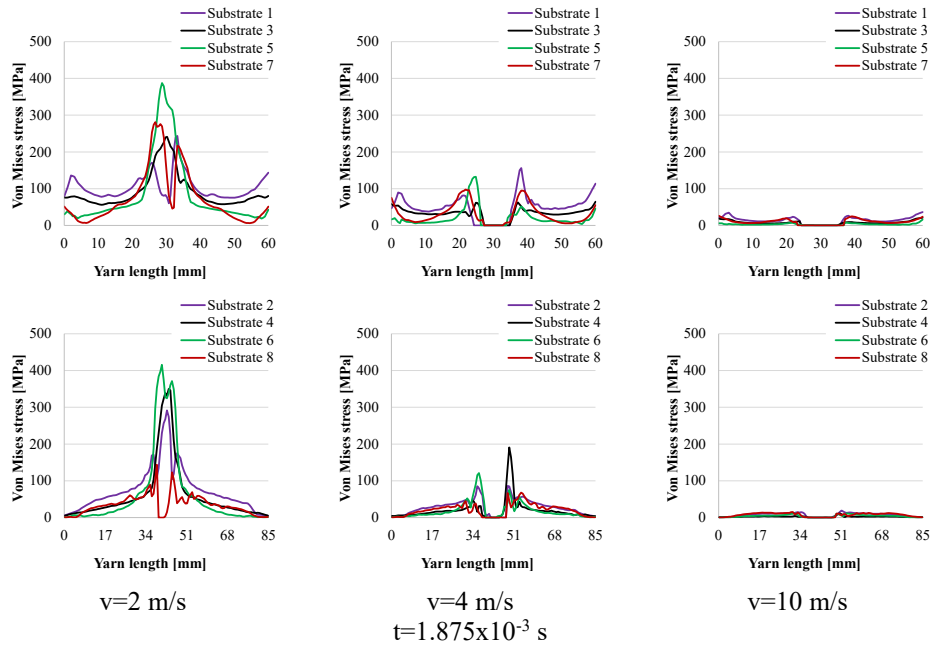


Fig. 8. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 1.875 \times 10^{-3}$ s.

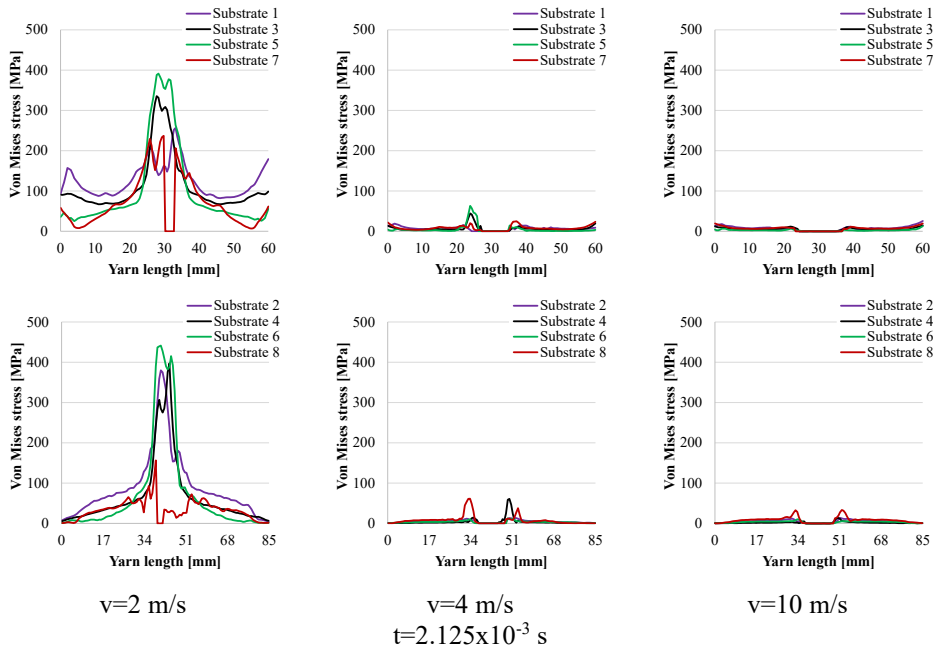


Fig. 9. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 2.125 \times 10^{-3}$ s.

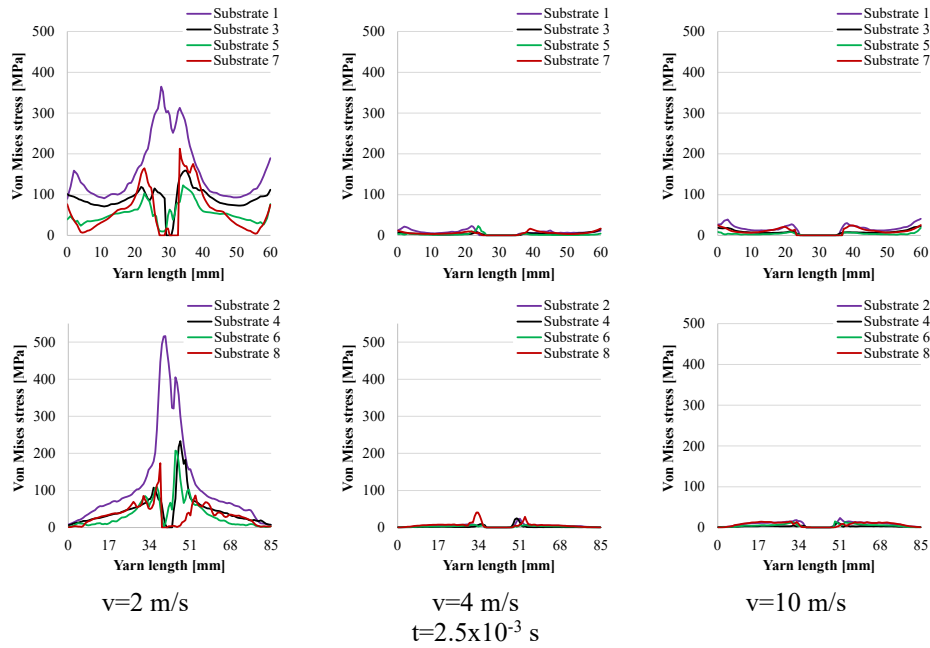


Fig. 10. Distribution of von Mises stress along yarn length for parallel (Substrates 1, 3, 5, 7) and diagonal yarns (Substrates 2, 4, 6, 8) at an impact velocity of 2 m/s, 4 m/s, and 10 m/s, respectively, for time $t = 2.5 \times 10^{-3}$ s.

In the following, the term *main yarns* refers to the yarns located in the immediate impact zone, directly interacting with the impactor.

Parallel yarns (Yarns 1, 3, 5, 7) are shorter and, therefore, their strain is more limited, making them more prone to early breakage, especially the yarns in direct contact with the impactor and the last straight yarn (7). They experience dominant tensile and compressive stresses along their length. Under impact, these yarns reach higher peak stresses at earlier stages. The stress evolution in these yarns reflects how the axial load is absorbed and resisted.

Diagonal yarns (Yarns 2, 4, 6, 8) are longer, as they are oriented at $\pm 45^\circ$ relative to the plate edges. Under impact, these yarns experience predominantly shear and bending effects, along with torsional and tensile stresses. They engage slightly later than the yarns aligned with the sample edges, as the load redistributes within the structure. These yarns play a crucial role in energy dissipation and in delaying progressive delamination.

At the initial time steps ($t < 6.25 \times 10^{-4}$ s), the main yarns aligned parallel to the sample side (1, 3, 5, 7) display sharp and sudden stress peaks, reflecting their direct engagement in absorbing the impact energy. In contrast, the main diagonal yarns (2, 4, 6, 8) exhibit a delayed response, with lower initial stress levels, as they are progressively activated by load transfer from the parallel yarns.

During the intermediate stages ($t \approx 1.125 \times 10^{-3}$ s), the stress carried by the diagonal yarns increases significantly as redistribution occurs within the composite architecture. Meanwhile, some of the parallel yarns located near the impact zone

begin to show signs of stress relaxation, which may be attributed to local yielding, decohesion, or damage initiation at the yarn–matrix interface.

At later stages ($t \approx 2.5 \times 10^{-3}$ s), the main parallel yarns tend to experience stress reduction due to cumulative damage, yielding, or fracture. From this point, the diagonal yarns take on a more prominent role, bearing redistributed loads and contributing to maintaining the structural integrity of the composite plate. This mechanism highlights the complementary role of diagonal reinforcement in sustaining residual load and delaying catastrophic failure.

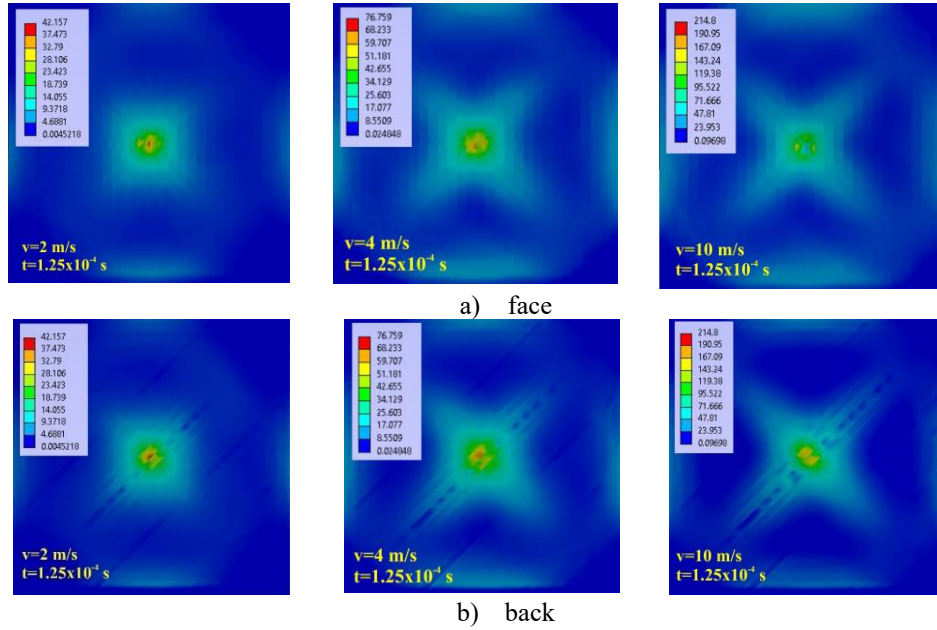
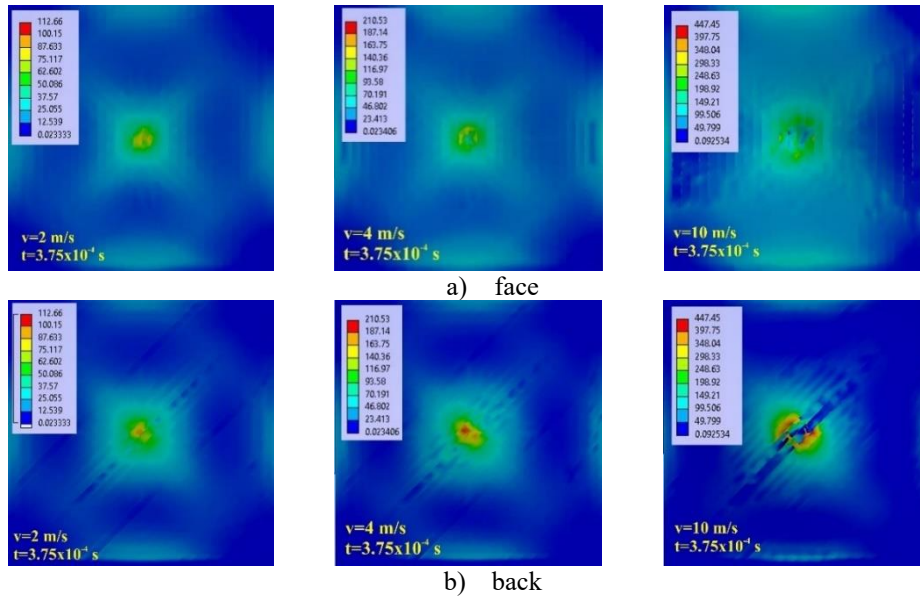
Yarns parallel to the plate edges (Yarns 1, 3, 5, 7) show dominant stresses, with peak values reached early in the impact stage. They absorb a significant portion of impact load. Diagonal yarns (Yarns 2, 4, 6, 8) engage progressively, exhibiting stress build-up due to shear and tension as the load redistributes from the more heavily loaded parallel yarns. The stress evolution indicates that the quadriaxial architecture effectively distributes the impact energy through both axial and diagonal yarn systems, enhancing the fabric's damage tolerance.

Figure 11 presents the von Mises stress distributions for impact velocities of 2 m/s, 4 m/s, and 10 m/s, at different time steps during impact. As the impact velocity increases to 4 m/s, the maximum von Mises stress increases from ~42.15 MPa to 76.75 MPa on both the front and back faces of the composite. At higher impact velocity (10 m/s), the maximum von Mises stress is almost three times higher, reaching approximately 214.8 MPa on both faces of the composite. This similarity in stress values between the front and back faces at lower velocities suggests that the composite response remains largely within the elastic domain.

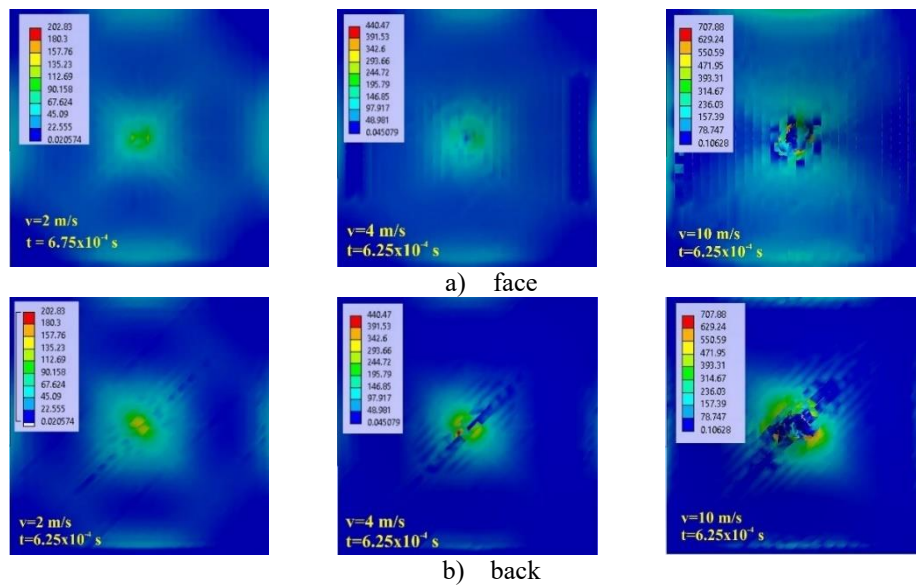
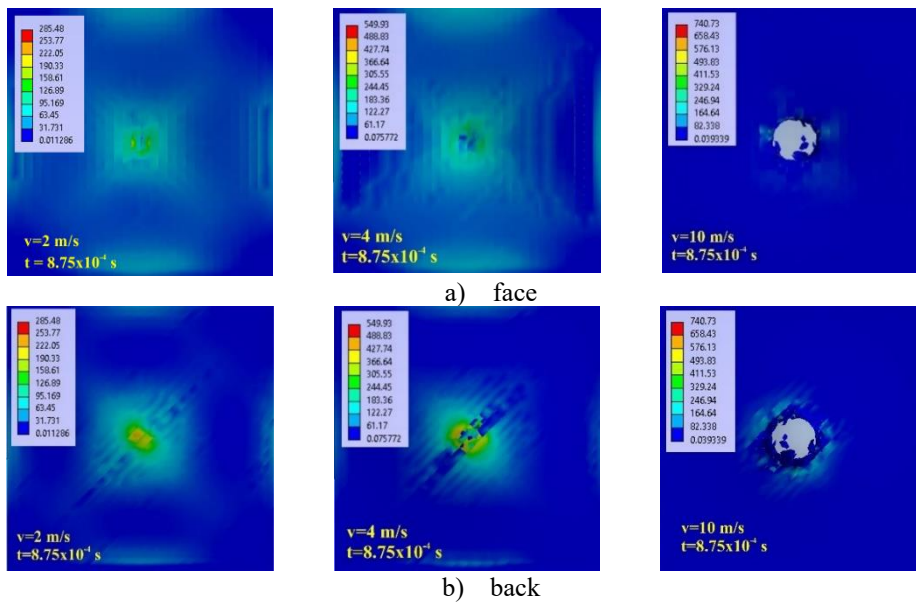
Comparing the images in Figure 11, the following maximum values of von Mises stress can be observed: approximately 42 MPa at $v = 2$ m/s, 76 MPa at $v = 4$ m/s, and 215 MPa at $v = 10$ m/s. Stress localization increases with impact velocity, with stresses concentrating at the yarn crossover points. On the back face of the composite, similar stress patterns are observed, but with lower magnitudes due to attenuation through the fabric thickness. A clearer difference between the front and back faces appears at higher velocities ($v = 10$ m/s), where front-face stresses exceed 200 MPa, while back-face values are around 100 MPa. At higher velocities, stress wave propagation becomes more pronounced along the diagonal yarn architecture.

At $t = 3.75 \times 10^{-4}$ s (Figure 12), the von Mises stress continues to intensify, particularly for the impact velocity of 10 m/s, where stress waves propagate further along the yarn orientations. The front face shows pronounced stress localization, while the back face exhibits attenuated stress patterns. For impact velocities of 4 m/s and 2 m/s, the stress remains concentrated near the impact zone, with limited wave propagation through the thickness.

At $t = 6.25 \times 10^{-4}$ s (Figure 13), stress concentration becomes more pronounced in the impact zone, especially for 10 m/s, where stress waves expand radially and follow the yarn architecture. The back face exhibits higher stress levels. For 4 m/s, stress patterns develop in a similar manner, but with delayed propagation toward the front face.


Fig. 11. Von Mises stress distribution for $t=1.25 \times 10^{-4}$ s

Fig. 12. Von Mises stress distribution for $t=3.75 \times 10^{-4}$ s.

At $t = 8.75 \times 10^{-4}$ s (Figure 14), the 10 m/s case shows stress waves propagating farther from the impact zone. The front face exhibits higher stress levels compared to the back face, where attenuation is evident. The 4 m/s case follows a similar but less intense pattern, while the 2 m/s impact remains confined near the contact area.

Fig. 13. Von Mises stress distribution for $t=6.25 \times 10^{-4}$ s.Fig. 14. Von Mises stress distribution for $t=8.75 \times 10^{-4}$ s.

At $t = 1.125 \times 10^{-3}$ s (Figure 15), the stress distribution becomes more clearly defined, and the 10 m/s case already shows total penetration of the composite. The back face exhibits delayed but similar propagation patterns. For 4 m/s, the stress front continues to expand, while the 2 m/s case still shows highly localized stresses near the impact center.

At $t = 1.375 \times 10^{-3}$ s (Figure 16), the 4 m/s impact exhibits a more dispersed stress field. The back face mirrors this trend, but with lower stress magnitudes. The 2 m/s impact remains primarily localized.

At $t = 1.625 \times 10^{-3}$ s (Figure 17), the stress field on the back face reflects yarn damage, including high local strains and even breakage. For the 2 m/s case, the stress remains concentrated in the contact area, with minimal spatial propagation.

At $t = 1.875 \times 10^{-3}$ s (Figure 18), the 10 m/s impact shows stress relaxation in the central zone, with stress energy being transferred to yarns located away from the impact site, due to total penetration. The 4 m/s impact exhibits a delayed but similar stress distribution.

At $t = 2.125 \times 10^{-3}$ s (Figure 19), for the 4 m/s and 10 m/s cases, high stresses remain localized, mainly due to friction between the yarns and the impactor. The 2 m/s case shows only one or two broken yarns. The 10 m/s impact can be considered complete, as the von Mises stress values fall below the yield limit; the impactor travels through the orifice, bending the broken yarn ends, while the matrix may undergo debonding.

At $t = 2.5 \times 10^{-3}$ s (Figure 20), the 10 m/s case exhibits a low, quasi-steady stress distribution, suggesting that the impact process is nearing completion. In contrast, the 2 m/s impact is not yet complete, with stress levels remaining within the elastic domain.

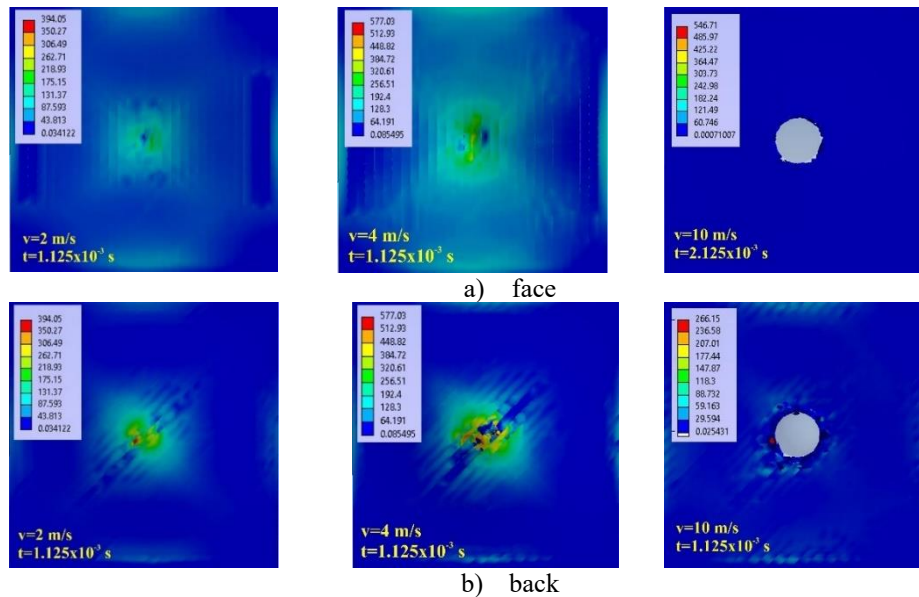
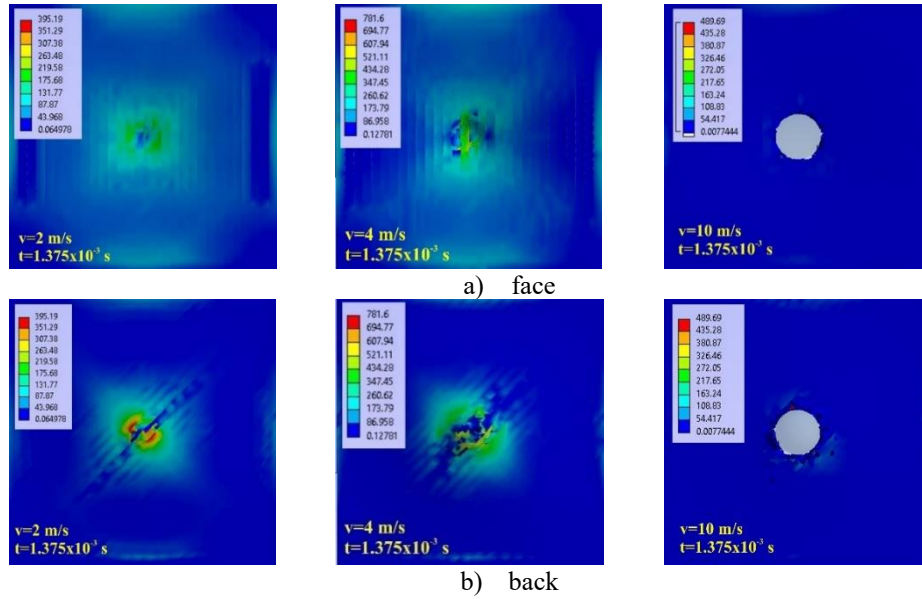
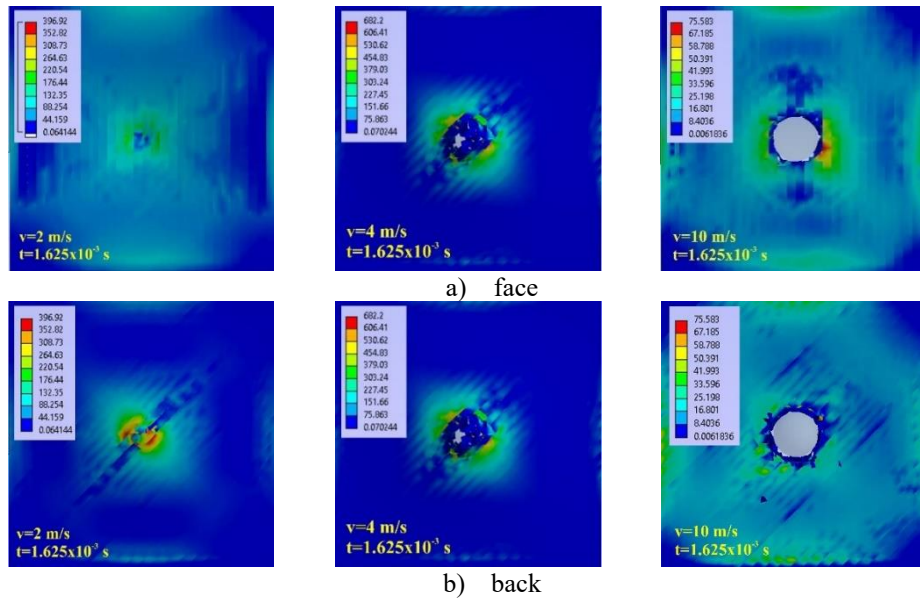


Fig. 15. Von Mises stress distribution for $t=1.125 \times 10^{-3}$ s.

Fig. 16. Von Mises stress distribution for $t=1.375 \times 10^{-3}$ s.Fig. 17. Von Mises stress distribution for $t=1.625 \times 10^{-3}$ s.

The impact event can be considered complete when the stress within the yarns decreases below the yield limit of 400 MPa, as defined in the constitutive model. Post-impact, the structure remains within the elastic domain, indicating that no further plastic deformation occurs. However, small-scale damage, particularly matrix microcracks and fiber-end breakage, may still be present as a result of localized effects during the peak loading phase.

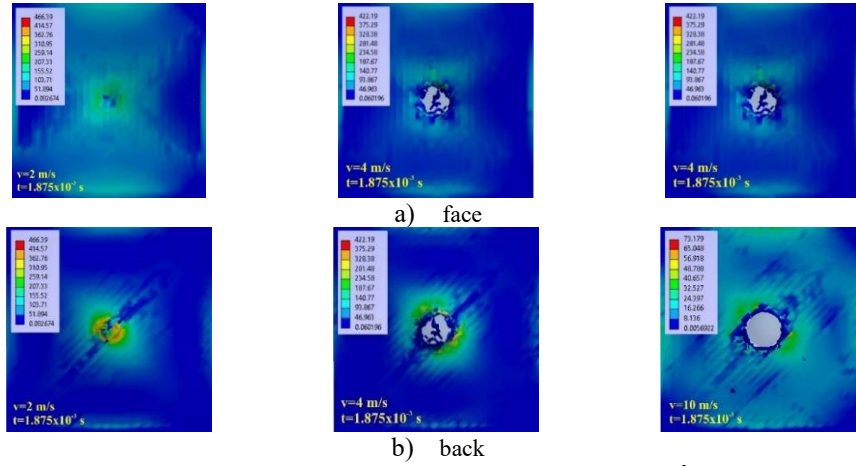


Fig. 18. Von Mises stress distribution for $t=1.875 \times 10^{-3}$ s.

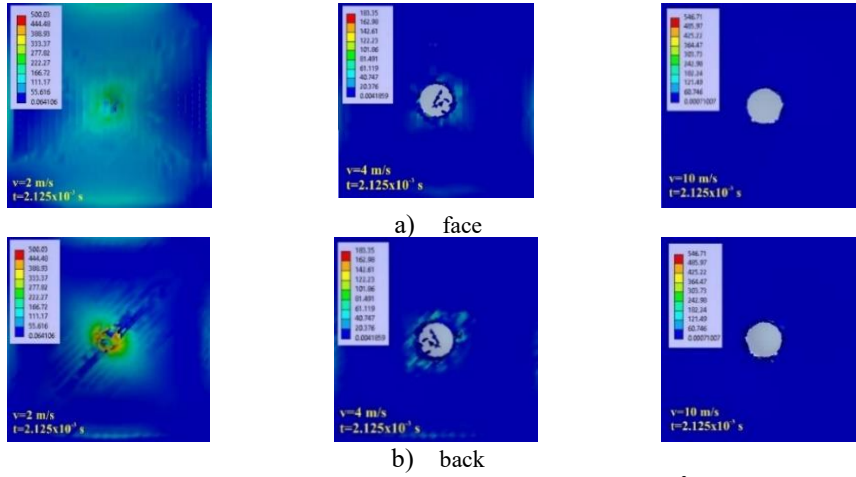


Fig. 19. Von Mises stress distribution for $t=2.125 \times 10^{-3}$ s.

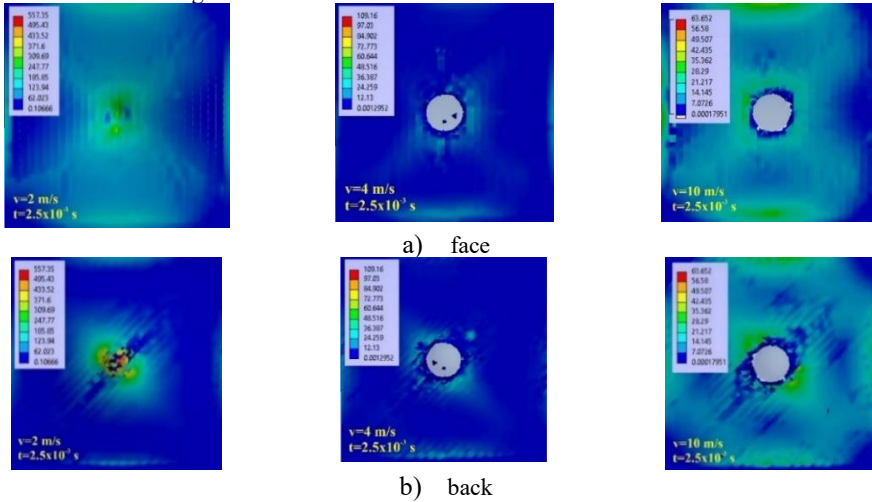


Fig. 20. Von Mises stress distribution for $t=2.5 \times 10^{-3}$ s.

At $t = 2.5 \times 10^{-3}$ s, for an impact velocity of 2 m/s, the stress levels within the yarns remain below the defined yield limit of 400 MPa, indicating that the yarns are predominantly in the elastic domain. However, local stresses are still observable, particularly in the vicinity of the impact zone. This suggests that the impact process is approaching completion but has not yet fully stabilized. Small localized stress fluctuations may persist as the structure returns to equilibrium.

Based on the stress evolution observed in Figures 1–10, the impact response of the quadriaxial fabric differs significantly with impact velocity. For an impact velocity of 2 m/s, at $t = 2.5 \times 10^{-3}$ s, the stress levels within the yarns remain within the elastic domain (below the yield limit of 400 MPa), indicating that the impact process is approaching completion. However, minor stress wave activity and localized deformations are still present in the vicinity of the impact zone, suggesting that full stabilization has not yet been achieved.

For the 4 m/s impact, the fabric is in an advanced stage of stress redistribution. The stress magnitudes decrease progressively as energy is dissipated through the yarn architecture, but oscillations and structural adjustments are still ongoing at this stage. In the case of the 10 m/s impact, significant stress redistribution and localized damage zones have formed, particularly in the yarn crossover regions. While stress levels begin to stabilize, the impact process continues in terms of energy dissipation and residual oscillations, with the structure requiring additional time to reach a fully stabilized state. In all cases, small-scale fragmentation, due to matrix microfractures and fiber-end breakage, may occur locally, especially in the vicinity of the impactor–composite contact during its advance after penetration. However, these localized damages do not significantly affect the global load-carrying behavior once the structure returns to the elastic domain.

Conclusions

The finite element model was developed to evaluate the behavior of a composite consisting of two layers of quadriaxial fabric embedded in an epoxy matrix under the impact of a hemispherical striker. The simulations, performed at different impact velocities (2 m/s, 4 m/s, and 10 m/s), allow visualization of yarn breakage and the sequence of failure. At higher impact velocities, peak stresses arise earlier and concentrate near yarn crossover regions, while the $\pm 45^\circ$ yarn systems progressively carry the load through shear, facilitating energy redistribution. This staged engagement delays catastrophic localization and enhances damage tolerance, with the structure returning toward the elastic regime once interface traction limits are exceeded and sliding friction governs post-failure behavior.

From a design perspective, the quadriaxial architecture provides beneficial redundancy for marine collision scenarios: at 2–4 m/s, it confines damage and favors elastic recovery; at 10 m/s, it still promotes progressive load redistribution rather than abrupt perforation. This suggests that calibrated interface strengths and a balanced axial/diagonal stiffness distribution can improve structural resilience without excessive mass increase.

Key limitations remain: the homogenized yarn model and the assumption of a constant friction coefficient simplify rate- and temperature-dependent phenomena. However, these simplifications remain realistic, as the model is able to distinguish between different impact responses, such as full penetration, partial penetration, and indentation. In addition, sensitivity to mixed-mode interaction, mesh density, and boundary conditions requires further investigation. Future work should include targeted dynamic testing for parameter calibration and model validation, enabling robust scaling from coupon-level behavior to panel- and hull-level structures.

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References

- [1] ASTM International. *ASTM D5528-13: Standard test method for Mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites*, 2014, Pittsburg, USA.
- [2] Cai P., Wang Y., Wang T., Wang Q., *Effect of resins on thermal, mechanical and tribological properties of friction materials*, Tribology International, **87**, 2015, p. 1–10.
- [3] Carvelli V., Lomov S. V. (Eds.), *Fatigue of textile composites*, 2015, Elsevier.
- [4] Camanho P.P., Dávila C.G., *Mixed-mode decohesion finite elements for the simulation of delamination in composite materials* (NASA Technical Report TM-2002-211737), NASA Langley Research Center.
- [5] Chowdhury U., Wu X.F., *Cohesive zone modeling of the elastoplastic and failure behavior of polymer nanoclay composite*, Journal of Composites Science, **5**, 5, 2021, p. 131.
- [6] Chu Y., Min S., Chen X., *Numerical study of inter-yarn friction on the failure of fabrics upon ballistic impacts*, Materials & Design, **115**, 2017, p. 299–316.
- [7] Ingle S., Yerramalli C.S., Guha A., Mishra S., *Effect of material properties on ballistic energy absorption of woven fabrics subjected to different levels of inter-yarn friction*, Composite Structures, **266**, 2021, 113824.
- [8] Meyer C. S., O'Brien D. J., Haque B. Z. G., Gillespie J. W. Jr., *Mesoscale modeling of ballistic impact experiments on a single layer of plain weave composite*, Composites Part B: Engineering, **235**, 2022, 109753.
- [9] Naresh K., Shankar K., Rao B. S., Velmurugan R., *Effect of high strain rate on glass fiber reinforced epoxy laminated composites*, Composites Part B: Engineering, **100**, 2016, p. 125–135.
- [10] Ojoc G. G., *Un studiu teoretic și experimental al pachetelor de protecție balistică pentru blindaje pe bază de fibre de sticlă*, Doctoral thesis, „Dunărea de Jos” University, Galati, Romania, 2022.
- [11] *Small vessel collisions*, Practical Sailor. https://www.practical-sailor.com/page/2/?s=collision&_sort=date_desc (accessed 19.01.2026)
- [12] Superyacht News. (2021, December 23). Crewmember claims yacht was unseaworthy when it collided with 49 m tanker. *Superyacht News*. <https://www.superyachtnews.com/operations/crewmember-claims-yacht-was-unseaworthy-when-it-collided-with-49m-tanker> (accessed 19.01.2026)
- [13] U.S. National Transportation Safety Board. (2022, August 8). *Coast Guard cutter collision near Puerto Rico*. NTSB. <https://www.nts.gov> (accessed 19.01.2026)
- [14] Yacht collision with people aboard caused severe damage (2018, June), *Yachtharbour*. <https://yachtharbour.com/news/yacht-collision-with-people-aboard-caused-severe-damage-2526> (accessed 19.01.2026)
- [15] Yachtharbour, *Homepage*. <https://yachtharbour.com> (accessed 19.01.2026).