FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 22, Nº 2, 2024, pp. 343 - 383
https://doi.org/10.22190/FUME240216037D

Review Article

RECENT DEVELOPMENTS IN NATURAL FIBER HYBRID COMPOSITES FOR BALLISTIC APPLICATIONS: A COMPREHENSIVE REVIEW OF MECHANISMS AND FAILURE CRITERIA

Balaji Devarajan[1], Rajeshkumar Lakshminarasimhan[2], Aravindh Murugan[1], Sanjay M. Rangappa[3], Suchart Siengchin[3], Dragan Marinkovic[4,5]

[1]Department of Mechanical Engineering, KPR Institute of Engineering and Technology, Coimbatore, Tamil Nadu, India
[2]AU - Sophisticated Testing and Instrumentation Centre and Department of Mechanical Engineering, Alliance School of Applied Engineering, Alliance University, Bengaluru, Karnataka, India
[3]Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand
[4]TU Berlin, Department of Structural Analysis, Germany
[5]Institute of Mechanical Science, Vilnius Gediminas Technical University, Vilnius, Lithuania

ORCID iDs: Balaji Devarajan https://orcid.org/0000-0002-9121-6215
Rajeshkumar Lakshminarasimhan https://orcid.org/0000-0003-1917-5460
Aravindh Murugan https://orcid.org/0000-0002-6536-6228
Sanjay M. Rangappa https://orcid.org/0000-0001-8745-9532
Suchart Siengchin https://orcid.org/0000-0002-6635-5686
Dragan Marinković https://orcid.org/0000-0002-3583-9434

Abstract. *The use of lightweight natural fiber functional composites in the manufacturing of ballistic protective materials has garnered significant attention in recent years. This is due to their superior mechanical properties, cost-effectiveness, and environmental sustainability. Ballistic panels are constructed using multiple layers of diverse composites, which collectively exhibit excellent mechanical properties. These properties enable them to withstand strong impacts enhancing their capability for different applications in defense, military, and aerospace components. The primary focus of this review is to examine the different influential factors that govern the development of novel polymeric materials for current ballistic applications. It also explores various research approaches, such as*

Received: February 16, 2024 / Accepted July 25, 2024
Corresponding author: Sanjay Mavinkere Rangppa
Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok 10800, Thailand.
E-mail: mavinkere.r.s@op.kmutnb.ac.th

© 2024 by University of Niš, Serbia | Creative Commons License: CC BY-NC-ND

experimental, analytical, numerical modeling, and empirical techniques. The review highlights both internal factors, such as material composition, and external factors, such as projectile parameters (e.g., nose angles, projectile shape, and projectile size). These factors are crucial for optimizing the robust ballistic performance of natural fiber-based polymer composites. In addition, various valuable insights to develop more effective and sustainable ballistic protective materials for applications in bulletproof helmets, defense, aerospace, and military sectors have also been elaborated. Consequently, the article presents a comprehensive review of the impact of utilizing various natural fibers as alternative materials to Kevlar for armor structures, offering a state-of-the-art perspective and challenges faced in full-scale implementation.

Key words: *Ballistic protection, Natural Fiber Composites, Multilayer armor, Ballistic mechanism, Failure criterion*

1. Introduction

Ballistic materials are specially designed materials that can withstand the high-velocity impact of projectiles, including bullets, shrapnel, and other ballistic threats [1]. These materials are used extensively in body armor, vehicle armor, and other protective equipment to prevent serious injury or death in potentially dangerous situations [2]. The development of ballistic materials has played a critical and significant role in the advancement of protective technology, particularly in law enforcement, military, and security applications. They offer enhanced protection against various threats, making them crucial for personnel and assets. Commercial fibers like kevlar, aramid, UHMWPE, and twaron are commonly used in Defense and military armor systems over the past two decades. However, synthetic fiber composites, derived from petroleum-based materials, cause environmental harm, increase manufacturing costs, and require high energy processing, despite their high specific and impact strength [3].The replacement of Kevlar fabric with eco-friendly and sustainable lightweight materials to improve kinetic energy absorption and dissipation has been found to improve the ballistic performance of composite panels [4].

In this context, ballistic materials made from natural fibers have garnered significant interest. Natural fiber-based ballistic materials, such as flax, hemp, jute, bamboo, kenaf, sugarcane bagasse, and coconut sheath, have emerged as potential alternatives to synthetic Kevlar-based multilayer armor systems in various applications. Numerous studies on these natural fibers have revealed their exceptional ballistic properties, demonstrating their suitability for replacing synthetic fibers in body armor and protective equipment and its devices [5–7]. In addition, the densities and costs of different natural fibers used in multi-layered armor systems can vary, depending on the specific type of fiber and its processing method. However, in general natural fibers generally have lower densities and costs compared to Kevlar. For instance, Bamboo fibers have a density of 0.55 g/cc, half of Kevlar's density. Similarly, Amazonian guaruman fibers have a density of 0.6 g/cc, and Curaua fibers have a density of around 0.5 g/cc [8], while sisal fiber has a density of 1.45 g/cc, serving as a substitute for Kevlar in multi-layered armor systems [9]. The application of natural fibers as precursor materials for ballistic applications has several advantages over synthetic materials owing to their being renewable and sustainable, making them a more environmentally friendly and viable option. In this regard, Braga et al [10]. experimented with the replacement of Kevlar composites using 30 % natural fiber composites in ballistic applications of MASs, revealing superior performance and a 275% cost reduction compared to Kevlar fibers, particularly in intermediate layer efficiency under 7.62 mm impact ammunition. Likewise, Garcia Filho et al. [11] conducted experiments to explore the replacement of Kevlar fiber in MAS. They found that using piassava/epoxy composites resulted in a much lesser depth of indentation on the clay body at the back compared to the reference armor with Kevlar composites. Furthermore, it concluded that 70-80% of the cost is lower than Dyneema and Kevlar. In addition, Luz et al. [12] investigated the coir fiber as an intermediate layer to replace the Kevlar fabric-based MAS. Results indicated that an intermediate layer of coir fiber with a 30% volume fraction significantly increased the ballistic performance, which is like that of Kevlar fiber. Similarly, Monteiro et al [13] assessed the ballistic performance of ramie fiber as a potential replacement for Kevlar fiber-based MAS. The results stated that the usage of ramie fibers decreased the overall production cost by 95% compared with Kevlar-based MAS. Likewise, Monteiro et al [14] found that curaua fiber as reinforcement reduced the fabrication cost by around 31.2% by replacing the Kevlar fiber in MAS. Recently, eco-friendly, renewable, biodegradable, low cost and abundant resources were explored as reinforcement material using a 7.62 mm bullet by Silva et al [15]. Results revealed that 30 wt. % of arapaima fish scale-based MAS produced similar dynamic behavior and failure mode as Kevlar fiber. The final impact energy was absorbed by the clay witness. De Oliveira et al. [16] discovered that curaua fiber offered a comparable failure mode to Kevlar fiber using a 7.62mm bullet.

Therefore, understanding the importance of lightweight natural fiber-based ballistic impact is crucial for a wide range of applications, including the design of protective materials, the development of new weapons and ammunition, and the investigation of various forensic and accident scenarios [17]. Thus, most care must be given to material selection to reduce overall manufacturing cost and allow for greater mobility and reduced fatigue for wearers as well as increase the protective strength for the development of anti-ballistic devices under different conditions. In general, high-performance applications such as aerospace and defense industries, for instance, composite structures are often subjected to extreme loading conditions through foreign objects such as impacts from hailstones, bird strikes, runaway debris, bullets, and explosive fragments [18]. Fig. 1 shows ballistic applications such as defense, military, and aerospace.

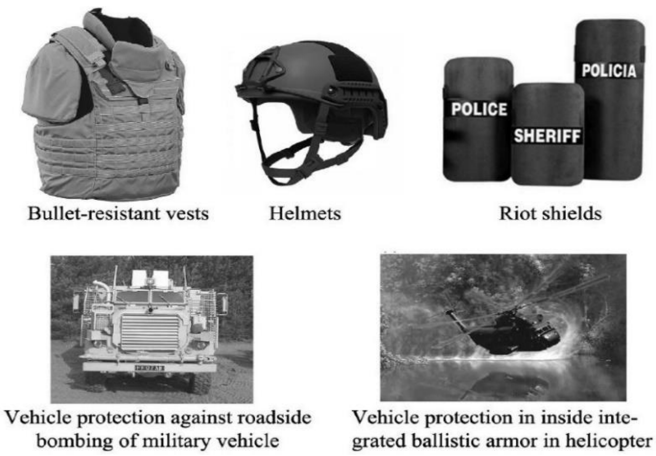

Fig. 1 Ballistic applications defense, military, and aerospace [19]

These types of impacts can cause varying degrees of damage, ranging from indentation to partial penetration or complete perforation of the composite structure. Such damage can compromise the structural integrity of the composite, leading to catastrophic failure and endangering human lives [20]. Therefore, it is essential to thoroughly evaluate and understand the loading conditions particularly those that require protection against high-velocity projectiles. These includes evaluating different influential parameters factors like architecture, stacking sequence, hybridization, ply orientation, shear thickening fluid, and projectile parameters like angle of impact, projectile nose, mass, and velocity. These factors significantly influence the impact of damage mechanisms, energy absorption structure, plate thickness, area density, and fracture toughness. [21, 22]. Fig. 2 shows the classification of natural fibers.

Some examples of natural fibers that are commonly used in ballistic-resistant materials include hemp, flax and jute fibers [23]. Hemp is a natural fiber that is known for its high strength and durability, and is often used in the production of textiles, paper, and other products. In ballistic-resistant materials, hemp fibers can be used in combination with other materials to create a composite that is both lightweight and highly resistant to impact [24]. Flax, a strong and durable natural fiber, is commonly utilized in various industries including clothing, textiles, automotive, and aerospace. In ballistic-resistant materials, flax fibers can be combined with other materials to create a robust and flexible composite. Jute, another natural fiber known for its strength, durability, and moisture resistance, finds applications in products such as rope and twine [25]. In ballistic-resistant materials, jute fibers can be used in combination with other materials to create a composite that is both lightweight and highly resistant to impact [26].

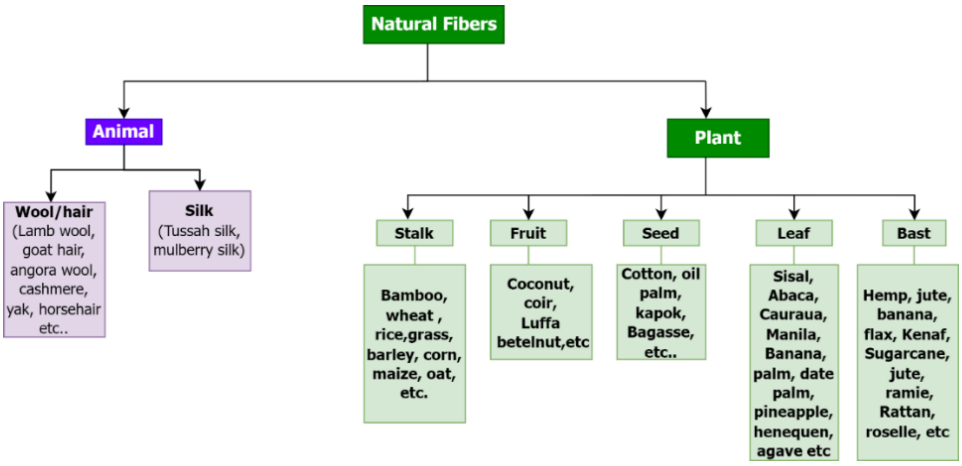

Fig. 2 Classification of natural fibers

By proper understanding of these factors, engineers and designers can optimize the design of the robust MAS-based composite structure, incorporating protective features such as sacrificial layers, increased thickness, and different stacking sequences, to enhance its ballistic resistance and protect against penetration by external projectiles. This enhances ballistic resistance and protects against external threats [27]. Analyzing impact behaviour of influential parameters using theoretical, analytical, and numerical methods helps select the right material.

Therefore, the utilization of different natural fibers as intermediate layers in ballistic materials presents an exciting opportunity to revolutionize the field of protective technology that is not only highly effective but also sustainable and environmentally responsible. The current review focuses on highlighting various natural fiber composites-based MAS and understanding the impact by material designation and damage mechanism on ballistic performance. Several different influential parameters have been discussed to explore the ballistic characteristics and dynamic characteristics of the composites concerning different projectile parameters, target circumstances, and target material qualities.

2. Ballistic Material Structure and Mechanism

Multilayer Armor Systems (MAS) are advanced protective structures utilized for defense in bullets, explosive arms, and shrapnel, which are highly prone to impact threats at higher velocities [28]. These systems comprise various materials in laminates while each material serves its specific purpose of absorbing and dissipating the energy from incoming high-velocity threats. The ballistic impact and damage mechanism of the structure is governed by three important factors such as projectile parameters such as nose geometry and angle, target circumstances, and quality of material in the targets [29]. The primary layer of a MAS is a hard armor plate meant to deform incoming projectiles, while the secondary layer, often made of high-strength synthetic fibers like Kevlar, absorbs the remaining kinetic energy. Additional layers, like soft padding for reducing blunt force trauma and a final layer to stop fragments, may enhance protection.

MAS can be customized to offer protection against a wide range of threats, ranging from small arms fire to improvised explosive devices (IEDs). The selection of specific materials and layering in a MAS is tailored to provide robust protection against various threats. The ballistic impact mechanism and energy-absorbing mechanism are illustrated in Figs. 3 and 4, respectively. When yarn is impacted, tension-induced waves travel along its length, while transverse waves affect warp and weft, creating conical projections until yarn fails. Fig. 5 illustrates a conical projectile with various nose angles.

3. Testing and Standards Of Ballistic Materials

Ballistic materials, including body armor and vehicle armor, are specifically engineered to protect from high-velocity incoming threats such as shrapnel and bullets. To ensure the effectiveness of these materials, they undergo rigorous testing and must meet specific standards. One widely recognized testing standard for ballistic materials is the National Institute of Justice (NIJ) Standard-0101.06, which sets forth the minimum performance requirements for ballistic-resistant body armor. This standard outlines criteria such as projectile velocity, mass, shape, and number of shots, as well as panel size for testing. It also specifies maximum allowable back face deformation, measuring armor plate deformation and energy transfer to the wearer [30, 31]. Furthermore, it serves as a vital guideline to ensure that such armor meets the necessary standards for effective protection.

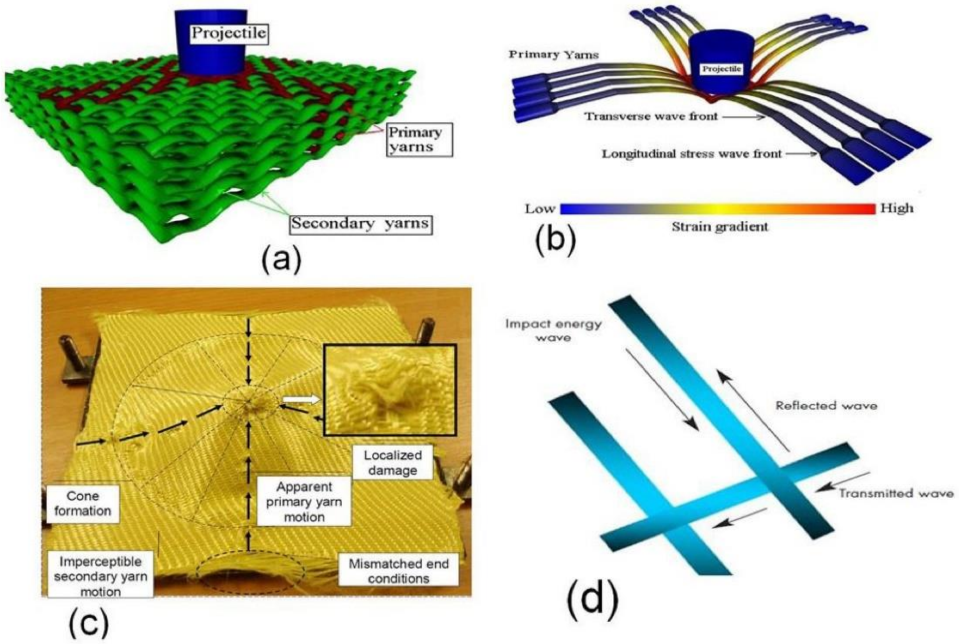

Fig. 3 Ballistic impact mechanism and result: (a) multiple layers by cylindrical projectile [30] (b) schematic of impact response of layer of armor fabric in primary yarn [31], (b) Impacted Kevlar panel [31], and (c) wave propagation and transmission in woven fabrics yarns [31]

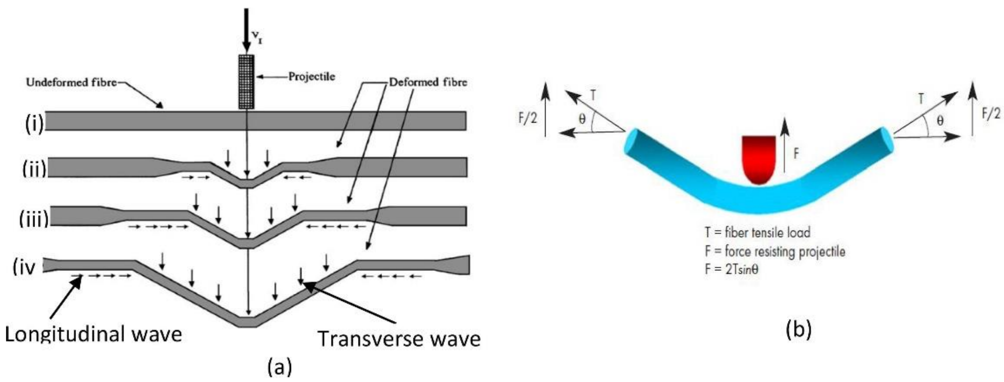

Fig. 4 Mechanism of ballistic protection. Yarn configuration before impact (i), (ii), (iii), (iv) [32] and (b) Mechanism of energy absorption of single layer [32]

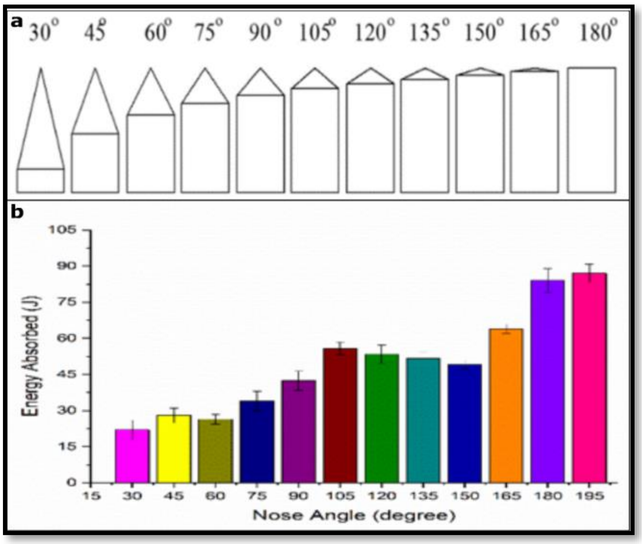

Fig. 5 a) Conical projectile with various nose angles [33], (b) Variation of energy absorption with nose angle variation [33]

Ballistic materials, including body and vehicle armor, are crucial for shielding against bullets and shrapnel threats, requiring rigorous testing and compliance with standards like the NIJ Standard-0101.06. These standards detail projectile specifications, panel dimensions, and maximum backface deformation, establishing minimum performance requirements for ballistic-resistant body armor [34-36]. The following testing specifications for ballistic materials are provided by the standard.

Ballistic-resistant body armor undergoes rigorous testing, including Backface Signature (BFS), Ballistic Limit (BL), and V50 tests, ensuring its effectiveness against threats. Armor is designed to withstand environmental conditions, with maximum allowable BFS set for each level to minimize blunt force trauma. V50 values measure armor effectiveness, while quality control tests ensure consistency and adherence to standards. Environmental conditioning before and after testing maintains performance, and visual inspections prevent damage.

Ballistic limit velocities are measurements used to determine the ability of a material to resist penetration by a projectile. There are different varieties of ballistic limit velocities, including V0, V50, and V100. V0 is the maximum velocity that a projectile can be fired at a material without causing any penetration [37]. It is the highest velocity that a material can withstand without failing. V0 is typically used as a baseline for ballistic testing, and materials that can withstand higher velocities without penetration are considered to have superior ballistic resistance. V50 is the velocity at which there is a 50% probability of complete penetration. In other words, if a material is struck by a projectile traveling at V50, there is a 50% chance that the projectile will penetrate the material completely. V50 is commonly used in ballistic testing to determine the effectiveness of Armor and other protective materials [38]. V100 is the velocity at which there is a 100% probability of penetration. This means that if a projectile strikes a material at V100, it will always penetrate the material completely. V100 is often used to test the vulnerability of structures, such as buildings or vehicles, to high-velocity projectiles. Therefore, the higher the ballistic limit velocity of a material, the better its ability to resist penetration by projectiles. However, other factors like the shape, size, and angle of impact also play a significant role in determining penetration. Ballistic limit velocities should be used in conjunction with other testing methods to fully evaluate a material's resistance.

By adhering to these testing requirements, manufacturers can ensure their ballistic-resistant body Armor provides the necessary level of protection against high-velocity threats. The Standardization Agreement (STANAG) 4569, a NATO standard, sets the minimum level of protection required for military vehicles, including threat types, projectile velocity, mass, Armor plate size and orientation, maximum allowable deformation and penetration, and protection requirements [39]. Ballistic materials may also be tested using other methods, such as simulating specific threats or testing under extreme conditions. By adhering to established testing protocols and meeting minimum performance requirements, manufacturers can ensure their products are effective and reliable in real-world situations. Table 1 and 2 describe the standard armors and testing conditions for ballistics and the nomenclature of ballistic panel arrangement, respectively. Fig. 6 illustrates the configuration of test range of a ballistic setup.

Table 1 Standard armors in ballistic testing [40]

Armor type	Bullet description	Bullet mass (g)	No. of rounds of test	Diameter of the bullet – Nominal (mm)	Testing Velocity of Armor (m/s)	Maximum back face signature (mm)
II A	FMJ RN	8.0	1	9.0	373	44
II	40,S&W FMJ	11.7	2	11.7	352	44
IIIA	FMJ RN	08.0	1	08.0	398	44
	JSP	10.2	2	10.2	436	44
	TMJ	08.1	1	08.1	448	44
	JHP	15.6	2	15.6	436	44
III	FMJ	09.6	1	09.6	847	44
IV	FMJ	10.8	1	10.8	878	44

Table 2 Ballisitc panel arrangements nomenclature

Notations	Layers	Material	Thickness (mm)
A	Front Layer	Ceramics	10
B	Intermediate layer	Aramid or Jute, coir, bamboo, mallow, guaruman, curaua	10
C	Backing layer	Aluminum layer	5
D	Rear layer	Clay witness	50

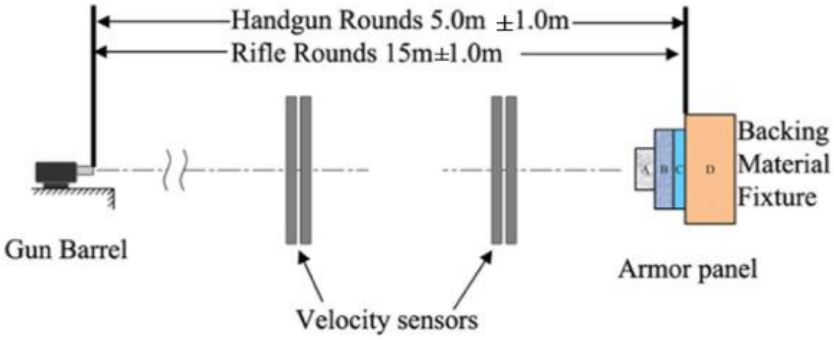

Fig. 6 Ballistic test setup and test range configuration [19]

4. FACTOR INFLUENCING BALLISTIC PHENOMENON

4.1. Hybridization

Hybridization is a technique that involves combining two or more different types of materials to create a composite material with properties that are superior to those of its individual components [41, 42]. When it comes to ballistic resistance, hybridization of natural fibers can provide several benefits, including improved strength, reduced weight, and improved environmental sustainability. There are two types of hybridization: intraply and interply. As a laminate level process, inter-ply hybridization involves using different materials and stacking sequences. In contrast, intra-ply hybridization involves using different fiber bundles in parallel within a single laminate. A few inter-ply studies have demonstrated with the aid of hybridization technique. Sinan Üstün et al [43] explored the ballistic performance of multilayer composite laminate using 172 g/m^2 aramid with twill woven fibers and 282 g/m^2 E-glass with plain woven fibers and V50 test method via 1.1 g fragment simulating projectile. Results portrayed that the hybridization of E-glass fibers with the aramid fibers improved the energy absorption capability of the hybrid composite panel. Vasudevan et al [44] investigated the mechanical and viscoelastic properties of interply Kevlar-E-glass/epoxy with two different stacking orientations such as 30K/0G/30K) and 45K/0G/45K. They concluded that stacking orientation of 30K/0G/30K displayed highest tensile, flexural and modulus, while 45K/0G/45K possessed higher elongation owing to its long fiber placed diagonally.

The effect hybridization on mechanical and impact properties of basalt/UHMWPE hybrid composites using low velocity impact and high velocity impact with different loading environment was investigated. It was observed that hybridization displayed higher ballistic properties compared to plain composites [45]. Similarly, hybridizing Kevlar fibers with glass/polyester composite had different effects under different projectile geometry such as blunt-ended, hemispherical and conical and found that damage mechanism and penetration resistance has highly sensitive to projectile shape. It was concluded that hybridization increased the penetration resistance [46]. Different stacking sequences of aramid/glass hybrid composite has been analyzed. It was found that aramid fiber had higher impact energy than glass fiber, which is attributed to the fact that fibrillation and pullout play a significant role in the dissipation of impact energy [47]. The effect of carbon to

Kevlar ratio on shear and flexural behavior and strain of 3D braided carbon/Kevlar hybrid composites was evaluated. In 3-D braided hybrid composites, absorbed energy and flexural strength were found to be decreased with increasing proportion of carbon fiber. Furthermore, hybrid composites made from ductile 3D braided Kevlar fabric and stiff carbon fabric exhibit comparable flexural strength and impact damage tolerance to all Kevlar composites [48].

Additionally, there is ongoing research being conducted by many researchers using 3D orthogonal woven composites with hybridization in intra-ply laminates. A drop weight test was performed by Alikurusan [49] with different projectile shapes using a 12 mm diameter. Results indicated that a hemispherical, ogival, or conical shape indenter exhibited large homogenous deformations, whereas the flat shape indenter possessed brittle damage, like stamping, with less deformation around the contact area. It was also described that the three-dimensional propagation of stress waves resulted in better resistance of stab attacks for the triaxial fabric interlaced at 60°. In addition to stacking aligned layers of fabric over each other, orthotropic woven fabric layers can also be stacked angularly to create soft armor panels for better dissipation energy [50]. The residual velocity of ballistic performance of Kevlar/glass hybrid composite was evaluated using finite element analysis (unit cell modelling) and experimental approach. The ballistic penetration was calculated using a user-defined subroutine VUAMT and ABAQUS/Explicit, a commercially available FEA code. FEA results and experimental results were in reasonable agreement and portrayed the better capability of unit-cell model for the prediction of ballistic properties [51].

The energy absorption of aramid/glass (3D) woven hybrid composites was investigated using modified split Hopkinson pressure bar. They examined the strain rate sensitivity of energy absorption by obtaining load–displacement curves of the composites in transverse impact. It was observed that energy absorption of composite increased with increases the impact velocity and exhibited same failure mode in warp and weft directions [52]. The transverse impact behavior of aramid/glass was explored using FEA (unit cell modelling) and Experimental approach (modified split Hopkinson pressure bar). To determine the composite's deformation and damage when impacted by a hemisphere-ended steel rod, they developed a unit-cell model based on the composite microstructure [68]. Studies were also carried out by introducing nano Al_2O_3 on Kevlar/snake grass hybrid composite by different weight fractions. Results revealed that the addition of 2 wt. % alumina nanoparticles enhanced the tensile, flexural impact and interlaminar shear strength by 6.42, 53.11, 11.08 and 6.11% respectively, while 8 wt. % nanofiller demonstrated a 68.80% increase in energy absorption [53]. Experimental studies were conducted to explore the energy absorption of hybrid and non-hybrid composites of aramid/veneer with same thickness using 9mm luger ammunition as per NIJ0108.01. results from their study indicated that aramid/densified veneer ration of 2:1 by volume increased the energy absorption by 78.64% (354.70J) than non-hybrid panel [54].

Kenaf fibers were used in the development of multilayer kenaf/aramid hybrid composite to analyze the energy absorption and failure behavior using ballistic limit (V50). It was found that incorporation of kenaf fiber resulted in enhanced in thickness and areal density, thereby increasing the energy absorption from 14.46% to 41.30% via different failure modes including fiber shear, fiber fracture and delamination. As a result of this phenomenon, specific energy absorption was lower for hybrid composites [55]. The mechanical and ballistic properties of polyaramid/vinyl ester composite were evaluated using split Hopkinson pressure and ballistic limit (V50) with different fiber content (different layers 4,5,6). Results indicated that polyaramid hybrid composite consist of 6 layers enhanced energy absorption by 35% compared to other configurations. This is because of increased the layer, enhanced the strength and strain rate [56]. The kenaf/aramid polyvinyl butyral laminated hybrid composite was subjected to low-velocity impact response using V50 ballistic limit. Results indicated that the same hybrid volume fraction and thickness of woven kenaf with aramid 29 layers alternated with aramid 29 layers had a lower ballistic limit velocity than woven kenaf together with aramid 29 layers separately. It was concluded that proper configuration kenaf fiber reduced fabrication cost and increased the ballistic performance [57].

The ballistic behavior of Kevlar/kenaf hybrid composite was investigated using 1.1 g fragment simulating projectile and V50 ballistic limit. Results indicated that a Kevlar/kenaf ratio of 14:2 displayed better ballistic performance. Furthermore, thickness and areal density were increased with increased ballistic properties [58]. In the energy absorption evaluation experiments conducted using glass/Kevlar hybrid composites with the aid of two span support ratios in a quasi-static penetration examination, carbon/Kevlar/carbon laminate arrangement performed better in terms of perforation and ballistic resistance under both span ratios of 2 and 5 [59]. It can be observed from earlier studies that, to create a hybrid material that is suitable for ballistic-resistant applications, natural fibers can be combined with other materials such as aramid fibers, ceramic materials, or metals. The specific combination of materials will depend on the desired level of protection and the specific requirements of the application. By combining different materials in this way, it is possible to create a composite material that is both strong and lightweight, while also being environmentally sustainable.

4.2. Stacking Sequence

Ballistic material design involves using fibers arranged in a particular weave architecture to create structures that resist high-velocity projectile penetration. Several studies have been conducted to evaluate the effectiveness of fiber architecture on the failure mechanisms and energy absorption capabilities of the fabrics [60]. Stacking sequences of ballistic composite panels are influenced by weave patterns, ply orientations, optimal reinforcement, type of material of constructed laminates influence their structural response and failure mechanisms [61]. Recent developments in new materials and innovative weaves have allowed for the creation of textile structural laminates that are lighter in weight but offer similar mechanical strength as traditional laminates [62]. Several publications have explored the ballistic impact behaviour of composite laminates reinforced with various fabric architectures [63]. In unidirectional plies all the fibers within a single layer are aligned in the same direction. This allows for maximum strength and stiffness in a particular direction, which can help to stop projectiles from penetrating the material [64]. Unidirectional plies are often used in areas where high levels of protection are required, such as in the front panel of a bulletproof vest. In woven plies fibers are woven together in a pattern that distributes load across multiple directions [65]. This can provide greater flexibility and impact resistance, making it ideal for applications such as vehicle Armor or blast-resistant structures. Fibers are randomly arranged within each layer in randomized plies. This can provide a more isotropic material, meaning it has similar properties in all directions, which can be beneficial for some applications [66].

Various experimenters evaluated natural fiber woven fabrics reinforced polymer composites for ballistic applications using numerical, experimental, and analytical techniques.

The energy absorption capability of interplay stacks with carbon, Kevlar, and S-glass fibers hybridized with E-glass fibers was determined using low-velocity impact tests. The outer layer Kevlar fibers enhanced energy absorption by 8%, while the S-glass and carbon as outer layers decreased it by 14% [67]. The effects of different ply orientation, layering sequence, and ply combination of aramid-based ballistic composite were investigated. Results demonstrated that an angled fabric panel consistently absorbed more energy than an aligned panel, and the energy absorption of angled fabric panels was 15%-20% higher based on the number of plies [68]. Researchers investigated the ballistic response of UHMWPE-based 3-ply panels impacted by projectiles in both aligned and angular orientations and demonstrated that when compared to aligned fabric panels, angled fabric panels consistently absorbed more energy [69]. They found that angled fabric panels absorbed more energy than aligned panels. Experimental validation of woven aramid multilayer composites using ABAQUS or LS-DYNA revealed that 3D angle interlocks are more resistant than plain woven fabrics with 2D angle interlocks. Warp and weft directional fibers absorb most energy during ballistic impacts in 3D woven hybrid interlocking composites [70, 71].

Similarly, a low-velocity impact test was conducted to compare woven S-glass fabric with twill woven carbon fabric by Sayer et al [72]. According to them, material bending stiffness significantly influences rear-side impact behaviour. Besides, altering the stacking sequence of fiber laminates altered load paths, creating a hybrid material with better stress distribution and structural behaviour. An analytical model was developed considering in-plane, isotropic, and elastic properties of multilayer fibrous material against 5.56 mm FSM hollow projectile and ballistic limit [73]. Several experimental tests were conducted to observe the effect of different fabric and layer-wise response via projectile geometry, impact velocity and boundary condition [74, 75]. Kevlar fibers were arranged using different fabric architecture and their ballistic performance was explored. Results indicated that plain weave fabric had higher energy absorption capability than basket and twill woven fabric composites during low-velocity impact tests [76]. The effectiveness of number of laminates of the material and weight of each layer for begetting an enhanced ballistic performance to stop the against 9 mm parabellium projectile with different grades such as 160GSM, 200GSM and 400GSM for 2D Kevlar and ballistic gel plain weave composite was investigated. Results indicated that 200GSM Kevlar grade was increased the effectiveness of ballistic performance among other grades [77].

Analytical modeling was conducted on 2D plain weave fabric with multiple layers composite subjected to ballistic impact. The study demonstrated direct compression beneath the projectile, revealing various failure modes including stretching, shear plugging, and tensile failure of primary yarn layers. Additionally, secondary yarn layers experienced conical deformation on the back face. Friction between the projectile and fabric, along with in-plane yarn friction, contributed to energy absorption during the impact [78]. Low-velocity impact behavior and mechanical behaviour of 2D and 3D Kevlar/polypropylene composite were tested. It was discovered that the study found that 3D weaves exhibited superior energy absorption due to their interlocking arrangement, emphasizing the influence of z-direction yarns. Various damage mechanisms, including fiber cracking, breakage, shear plugging, and delamination, contributed to this enhanced performance [79, 80]. The ballistic behavior of Kevlar/polyester composites with orthogonal woven arrangement was evaluated using Finite element analysis at microstructure level. Results indicated that tensile and shear failure mode is the main failure mode at the bottom surface, while compression and shear at top surface during the impact caused by conical and cylindrical projectiles [81]. Detailed investigations of ballistic response of glass/polyester composite with various reinforcement types, ranging from 80m/s to 160m/s. Results showed that cross-ply unidirectional and plain weave composites with thicknesses of 3mm and 6mm provided the best ballistic resistance. However, 3mm composites failed due to tension and shear failure, while 6mm composites failed due to severe delamination [82]. Fig. 7 presents different weave arrangements used to manufacture composites and subject them to ballistic applications.

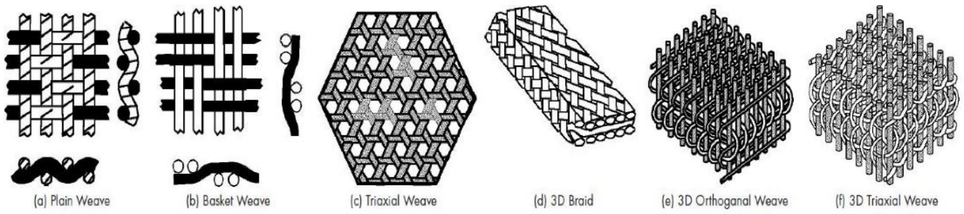

Fig. 7 Weave arrangements (a) Plain; (b) Basket; (c) Triaxial and 3D structures (d) Braid; (e) Orthogonal woven – 3D; (f) Triaxial woven 3D [32]

Different failure modes of spectra polyethylene using both angle ply unidirectional and woven fabric was investigated. They reported that angle ply and woven fabric reinforced possessed subsequent delamination, combined modes of shear and tensile failure of fibers. Furthermore, it was noticed that angle unidirectional composite superior ballistic limit [83]. The perforation behavior of specta, Kevlar and twaron with four kind of different architecture such as 2D, 3D woven fabric, 3D braided and needle-punched nonwoven fabric subjected impact velocity from 200 to 1100 m/s was investigated. they demonstrated that 3D braided composite exhibited high perforation, and penetration resistance for increasing the structural integrity [84]. Fig. 8 shows hybrid fiber and its corresponding energy absorption ability. Different failure mechanism of various glass/polyester composite with different fiber arrangements, including woven and stitched arrangements, was investigated and subjected to impact velocity of up to 571 m/s and found that all kind of fabric pattern exhibited similar failure modes [85]. The ballistic behavior of basket 2×2 aramid fabric composite was evaluated by oblique impact. They found that basket weave composites cause less ricochet than plain weave composites [86]. Fig. 9 presents energy absorption by 5 layered panels of Kevlar 802 F fabrics [87]. Therefore, meticulous design of the various stacking sequence including different weave architecture, ply orientation in ballistic material design becomes essential since the structure of the fabric can significantly affect desired level of protection its performance while maintaining other important properties such as flexibility, weight, and durability [88].

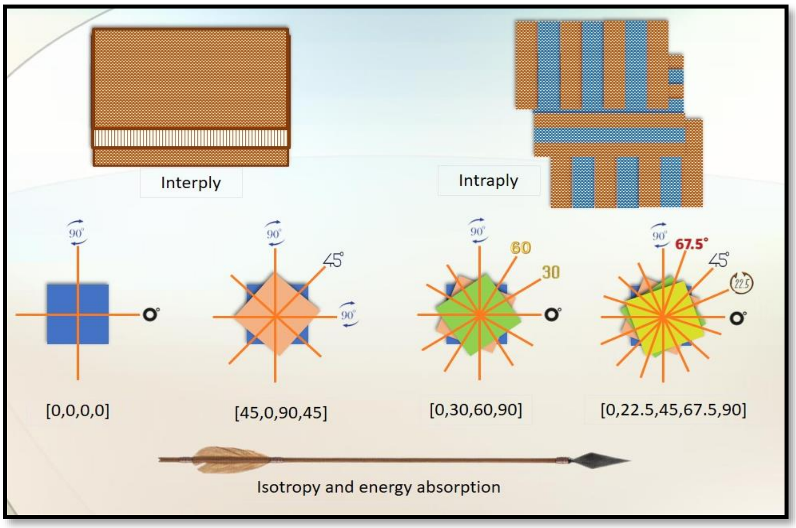

Fig. 8 Hybrid fiber configurations a) interply b) Intraply and corresponding energy absorption ability

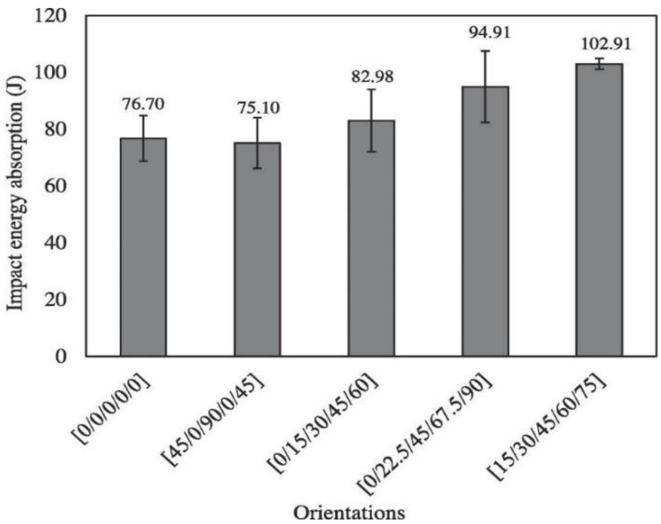

Fig. 9 Variation of energy absorption of Kevlar 802F fabric panels with various arrangements [87]

4.3. Surface Treatment

Natural fibers like flax, hemp, jute, and sisal are being increasingly used in the field of ballistic applications. However, these natural fibers have several limitations such as poor mechanical properties, low resistance to moisture, and poor adhesion with matrix materials.

To overcome these limitations, various surface treatments can be applied to natural fibers to improve their mechanical properties and adhesion with matrix materials, which are essential for achieving the desired ballistic performance [88]. Surface modification is a process that involves changing the surface of a material to improve its characteristics, such as adhesion and biocompatibility. There are various ways to modify the surface of cellulose fibers, including chemical treatment, enzymatic treatment, corona or plasma treatment, and addition of coupling agents. These techniques primarily target the amorphous region of cellulose, which contains hydroxyl groups that make the fiber polar and difficult to bond with the polymer matrix [89]. Fig. 10 shows commonly used lightweight natural fiber in ballistic applications.

Some of the commonly used surface treatments for natural fibers in ballistic applications are Alkali treatment, silane treatment, acetylation treatment, plasm treatment, grafting, and gamma irradiation treatment. In the Alkali treatment removes impurities and hemicelluloses from fiber surfaces, increasing surface area and energy. Silane treatment uses a silane coupling agent to improve interfacial adhesion between fiber and matrix, enhancing composite material mechanical properties [90]. Acetylation treatment reduces fiber hydrophilicity, improves moisture resistance, and increases surface energy, enhancing fiber adhesion. This process reduces the hydrophilicity of the fiber and improves its resistance to moisture. It also increases the surface energy of the fiber, which enhances the adhesion between the fiber and the matrix material [91].

Fig. 10 Commonly used natural fiber in ballistic applications (a) Sugar palm fiber, (b) Pineapple fiber, (c) Hemp fiber, (d) Corn fiber, (e) Jute fiber, (f) Flax fiber, (g) Coir fiber, (h) Kenaf fiber, (i) Empty fruit bunch fiber [91]

Plasma treatment involves the use of plasma to modify the surface of natural fibers. The plasma treatment can be used to introduce functional groups on the fiber surface, which improves the wettability of the fiber and enhances the adhesion between the fiber and the matrix material. Grafting treatment involves the grafting of monomers onto the fiber surface. The monomers are selected based on their ability to react with the matrix material and improve the adhesion between the fiber and the matrix material [92]. Recently, Gamma radiation is a method of modifying materials that involves exposing them to high-energy gamma rays, typically emitted by a Cobalt-60 source. This process can cause crosslinking, chain scissions, decomposition, and unsaturation within the polymeric chains of the material, which can result in hardening, toughening, and strengthening of the material [93]. Gamma-ray irradiation is commonly used in industrial processes to improve the properties of polymeric materials. This can include improving the durability and resistance to wear and tear of fibers, as well as enhancing their overall strength and toughness.

Gamma-ray irradiation has been widely used in research on lignocellulosic substrates, with a preferred dose range of 1 to 50 kGy. However, it's important to note that irradiation at higher doses can lead to chain scissions and degradation of biopolymers, which can result in a significant loss of the original properties of the natural fibers. Therefore, researchers typically try to limit the irradiation dose to not more than 30 kGy when working with lignocellulosic substrates. This ensures that the desired modifications can be achieved without causing excessive material degradation [94]. Moreover, careful selection of the appropriate irradiation dose is critical to achieving the desired properties and avoiding any negative effects on the material. The effect of gamma radiation on the trauma penetration depth and ballistic properties of kenaf hybrid/X-ray composite materials has been investigated to improve the interfacial bonding adhesion between the fibers in the laminate [95]. The study found that the configuration sample using the combination of surface-treated X-ray and NaOH solution produced the optimum formulation with hybrid composite properties for bulletproof vest applications. This formulation exhibited significant improvements in tensile, impact, and flexural strength compared to untreated samples.

Few researchers found that gamma-irradiated 25 kGy UHMWPE composites showed better ballistic resistance compared to 250 kGy composites. The ballistic performance of Kevlar fiber-reinforced composites was also enhanced by the addition of SiC nanoparticles [96]. The impact characteristics of alumina/UHMWPE composite irradiated with gamma radiations using different doses were investigated**.** They found that 50 kGy irradiated with 80 wt.% alumina displayed better ballistic resistance compared to other irradiated composites. Gamma irradiation enhances the interface properties of ceramic and polymer interfaces [97]**.** Two different chemical pretreatments, such as silane and potassium permanganate-di cumyl peroxide solution on different failure modes of sisal/epoxy composite were investigated. Results indicated that better energy transfer was obtained by performing silane treatment [98]. Few experimental results pointed out that the energy absorption of bamboo fiber is governed by coarse fiber bundles, fiber pullout, high volume fraction, and crack deflection [99]. Different failure modes with different contents (1 wt. % and 3 wt. %) of alkali-treated micro cork particles with E-glass were explored. Results demonstrated that 3wt% of micro cork particles had significant enhancement in energy mechanisms such as crack initiation and propagation improved by 130% and 35% respectively [100, 101]. Table 3 presents the chemical composition of different natural fibers.

Table 3 Chemical composition of natural fibers [102]

Natural fiber	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)
Flax	70.5	16.5	2.5	0.9	-
Hemp	81	20	4	0.9	0.8
Henequen	60	28	8	-	0.5
Coir	46	0.3	45	4	-
Bamboo	34.5	20.5	26	-	-
Areca	53.2	35-64.8	13-24.8		
Abaca	62.5	21	12	0.8	3.0
Alfa	45.4	38.5	14.9		2.0
Bagasse	37	21	22	10	-
Banana	62.4	12.5	7.5	4	
Cotton	89	4	0.75	6	0.6
Coir	34.5	20.5	26	-	-
Curaua	73.6	5	7.5	4	-
Jute	67	16	9	0.2	0.4
Kenaf	53.5	21	17	2	-
Kapok	13.16	-	-	-	-
Isora	74	-	23	-	-
Sisal	60	11.5	8	1.2	-
Pineapple	80.5	17.5	8.3	4	-
Ramie	72	14	0.8	1.95	-
Pissava	28.6	25.8	45	-	-

4.5. Aerial Density

Aerial density, also known as areal density or mass per unit area, is an important parameter in the design of ballistic fabrics for use in body armor and other impact-resistant applications [103]. In general, increasing the aerial density of a ballistic fabric will improve its ballistic performance. The higher the aerial density, the more surface area in the path of an incoming projectile, providing greater resistance for increasing the ballistic performance. This can be achieved with the aid of increasing the ply thickness or arranging the more no of the ply layer in a striking direction [104]. However, too high thickness and additional layers lead to increasing weight, which can negatively impact the wearer's comfort and mobility for body armor applications. Furthermore, it was observed that simply increasing aerial density is not the only factor that influences the ballistic performance of a fabric. The composition and arrangement of fibers or other materials in the fabric also plays a crucial role in the development of high-performance ballistic body armor. For example, a fabric that uses high-strength fibers, such as aramid or UHMWPE, will exhibit superior ballistic behaviour when compared with fabric made from lower-strength materials [105]. Furthermore, the specific arrangement of fibers within the fabric can affect how the fabric responds to a ballistic impact. For example, fabrics that use woven or knitted constructions may have different ballistic performance characteristics than those that use non-woven or laminated constructions [106]. Aerial density is an important parameter in the design of ballistic fabrics, and increasing aerial density can generally improve ballistic performance [107]. However, the benefits of increasing aerial density must be balanced against the potential drawbacks, such as increased weight and reduced mobility. Additionally, other factors, such as the composition and arrangement of fibers, also play important roles in determining the ballistic performance of a fabric [108].

Investigations were made to assess the influence of areal density on the impact energy absorption of aramid fabric composites using gas guns and drop weight tests. The penetration and perforation limits were determined using energy profile diagrams. It was observed that a thin plate absorbed more energy than a thick one beneath the limit of penetration. In contrast, the trend reverses above the perforation limit [109]. The influence of continuous and discontinuous plain weave fabric reinforcement in the composites was evaluated using ballistics tests. It was found that when compared with the randomly oriented fabric composites, the continuous fabric-oriented composites exhibited 9.5% more ballistic resistance and 20% more energy absorption capability [110]. The influence of areal density on the ballistic limit and failure mechanism of UHMWPE was explored and found that the natural fibers enhanced the energy absorption capability [111, 112].

4.6. Matrix and Interface System

An important function of a matrix in ballistic composites is to distribute stresses between fibers. Furthermore, the matrix provides some level of protection against adverse effects of the environment as well as protection against mechanical abrasion of the fiber surface [113]. The main role of matrix in a composite structure is a load-bearing structure. Generally, Thermoset and thermoplastic are two types of polymers with different properties and characteristics. In the context of ballistic mechanisms, matrices and interface systems can be used to model and optimize the behavior of these materials. Matrices can be used to represent the stress and strain relationships in both thermosets and thermoplastic materials. Specifically, a 3x3 matrix can be used to represent the state of stress at a given point in the material, while a 6x6 matrix can be used to represent the full stress-strain relationship. Nevertheless, there is a significant effect to increase the interfacial adhesion between fiber and matrix that can influence the high performance of polymer-reinforced composite. This can be achieved with the aid of fullerenes which are zero-dimensional, carbon nanotubes which are one dimensional, graphene nanoplatelets (GNPs) which are two-dimensional, Nano graphite and nanofibers which are three dimensional are often employed to develop lightweight advanced bulletproof materials [114-117].

Interface systems can be used to optimize the performance of both thermosets and thermoplastic materials. Thermoset and thermoplastic materials can both be used in ballistic applications, although they have different properties and are used for different purposes. Thermoset materials are typically used for applications that require high strength, stiffness, and resistance to heat and chemicals [118]. They are also often used for applications where dimensional stability is important. Epoxy is a thermoset resin that is widely used in composites for ballistic protection. It is known for its high strength, stiffness, and resistance to impact and penetration. Phenolic resins are commonly used in the production of ballistic composites for use in armor and other protective applications which possess high resistance towards chemicals and heat along with elevated strength and stiffness. Polyurethane resins are used in the production of ballistic materials such as helmets and body armor. They are known for their high strength, flexibility, and impact resistance.

Thermoplastic materials, on the other hand, are typically used for applications that require high-impact resistance, flexibility, and ease of processing [119]. Polycarbonate is a tough, transparent thermoplastic that is often used in the production of ballistic lenses and visors for helmets and face shields. Polyethylene is a lightweight thermoplastic that is often used in the production of body armor and protective shields. It is known for its high-impact resistance and flexibility. Acrylonitrile-butadiene-styrene (ABS) is a versatile thermoplastic that is commonly used in the production of protective equipment such as helmets and shields. It is known for its toughness, impact resistance, and ease of processing [120]. In general, thermosets and thermoplastic materials are used in ballistic applications, but they are chosen for different properties and characteristics based on the specific requirements of the application. Han et al [121] investigated the effect of matrix on ballistic performance using the quasi-static test, ballistic test and numerical tests. It was observed that Surplus matrix (at least 20 percent) increased composite stiffness, inhibiting delamination and bending deformations like thermosetting matrix composites, and reducing energy absorption. Furthermore, the main ballistic damage mechanisms of AF/PCC changed from compression-shear failure to delamination and tensile failure as the matrix content decreased from 30% to 10%. Fig. 11 shows the physical, mechanical, and thermal properties of common polymer matrices.

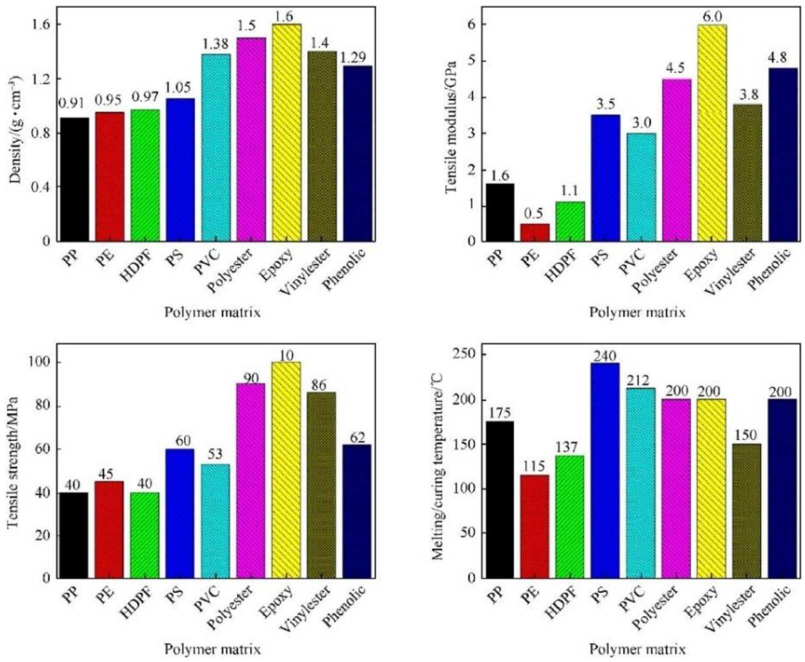

Fig. 11 Characteristics of various polymers [122]

4.7. Target Thickness

The thickness of a composite also has a significant effect, as thick composites have a better performance against external loads. The thickness of a target plate can significantly influence its ballistic performance, which refers to how well the plate is able to resist and stop incoming projectiles. Generally, thicker plates are more effective at stopping projectiles than thinner plates. The thickness of the target plate affects its ability to absorb the kinetic energy of an incoming projectile [123]. As the projectile hits the plate, it transfers its energy to the plate, causing it to deform and potentially break. The thicker the plate, the more material there is to absorb the energy of the projectile, and the less likely it is to penetrate through the plate. However, there is a limit to how thick a target plate should be. If the plate is too thick, it may become too heavy or difficult to handle, and may not be as effective at stopping certain types of projectiles. There is also a tradeoff between thickness and other factors, such as cost, weight, and mobility. The specific thickness of the target plate needed for effective ballistic performance depends on a variety of factors, including the size and velocity of the incoming projectile, the material and composition of the plate, and the specific application for which the plate is being used. A unique pattern of deformation or damage along the direction of through-the thickness was observed during the impact process which portrays that the thickness of the composite material and the induced stress are directly proportional along the thickness direction. Hence, it could be concluded that the thickness of the composite plays a vital role as it has a very high influence over the failure mechanism, energy absorption and total damage area of the composites [124].

Few researchers investigated the relationship between thickness and impact behaviour of woven glass fiber composites using a series of impact tests, which subjected 1 to 5 mm thick laminates to impacts from a hemispherical-nosed projectile propelled by a one-stage gas gun [125-128]. The findings indicate that the ballistic limit velocity of laminates with thickness ranging from 1 to 5 mm increases in a linear fashion. Specifically, the ballistic limit velocity of the 5 mm thick laminate was discovered to be 2.8 times higher compared to that of the 1 mm thick laminate. Furthermore, as the projectiles impact velocity increases, the energy absorption of the laminated plate initially decreases to approximately 10% before stabilizing [129, 130]. Ballistic response of Kevlar/epoxy plate with thickness ranging from 4.5 mm to 14.5 mm was evaluated using experimental and numerical. Results indicated that plate thickness significantly influenced the failure modes and energy absorption capacity [131]. It was stated by some researchers that thicker plates have a greater effect to increase the penetration capacity using low-velocity impact. Therefore, thin ballistic composite plates have a higher possibility of failure risk inferred from thicker composite plate [132]. A few experimenters assessed the effect of thickness on impact characteristics of carbon woven epoxy composite using low-velocity impact. Researchers found that laminate thickness significantly influenced peak contact force, threshold energy, and load for primary crack initiation [133].

The study conducted by De Morais et al [134] assessed the effect of laminate thickness on the low-energy impact characteristics of carbon/glass/aramid hybrid composites. The thickness of the composite laminate was found to be the most important factor for evaluating the ballistic performance of the hybrid composites by the researchers. Furthermore, glass fiber composites exhibited maximum ballistic protection due to the broader area coverage provided by the increased thickness of the laminate. Additionally, the isotropic properties of the glass fibers enhanced the ballistic resistance when compared with the anisotropic nature of the aramid and carbon fibers. The authors concluded that thicker laminates could withstand higher impact energies before reaching the failure threshold, resulting in primary failure. The effect of laminate thickness to prevent perforation was investigated using a 7.62 mm ammunition standard test and the minimum thickness required was also estimated. It was observed that increasing thickness led to exhibit high energy absorption to stop the 7.62mm bullet [135]. A few researchers examined the UHMWPE composite with different thickness ranging from 13 mm and 20 mm using fragment simulating projectiles. The thickness of the laminate significantly influenced the contact force at its peak, energy threshold, and damage initiation load. The panels demonstrated two stages of penetration failure modes with increased thickness: shear plugging during initial penetration, followed by formation of a transition plane and bulging of the rear panel [136]. The effect of velocity of impact, diameter of the projectile, thickness and mass of the target during the contact and ballistic velocity was investigated. It was discovered that the shear plugging is a significant failure mode in energy mechanism [137, 138]. A major factor affecting perforation is laminate thickness, which is directly relationship with laminate density (composite mass per square meter). Several Researchers have studied the effects of these parameters on both projectile perforation velocity and perforation threshold energy of laminates with different fiber compositions and resin matrices [139, 140]. Both linear and non-linear relationships have been observed to attain the minimum perforation velocity or minimum perforation energy and the thickness in composite plates [141, 142]. Fig. 12 shows the effect of different projectile geometry on energy absorption.

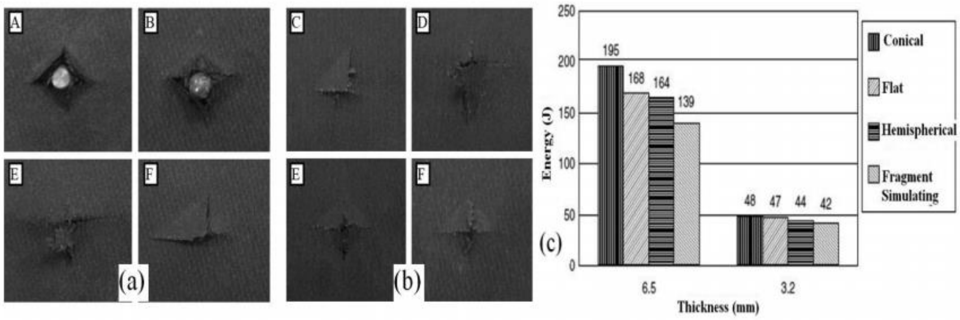

Fig. 12 (a) Back face damage of (A, E) fragment simulating, (B, F) hemispherical, (C, G) Conical, (D, H) flat projectiles for 6.5mm thick panels (c) Energy vs thickness variation for 3.2mm thick panels [143]

5. Ballistic Impact Mechanisms And Approaches

Ballistic impact is a highly complex and dynamic phenomenon in which the ballistic projectile interacts with the target. Understanding the mechanics of ballistic impact is crucial for a wide range of applications, including the design of protective materials, the development of new weapons and ammunition, and the investigation of various forensic and accident scenarios. The study of ballistic impact mechanisms involves a multidisciplinary approach, encompassing the fields of mechanics, materials science, physics, and engineering. Researchers have developed a variety of approaches to investigate the behavior of materials under ballistic impact, ranging from analytical and numerical models to experimental tests and simulations. This field has seen significant progress over the past few decades, with the development of advanced computational tools and testing methods that have enabled researchers to get a deep insight in complex physics and material behavior that occurs during ballistic impact. In this context, this topic remains an active area of research, with ongoing efforts to refine and improve our understanding of the underlying mechanisms and develop new approaches to enhance the effectiveness and safety of various materials and devices.

5.1. Experimental Approach

Energy absorption mechanisms of fabric composites are best explored with the aid of direct experimental methods. Research has been conducted on ballistic impact mechanisms in numerous experimental studies [144, 145]. Experimental work will examine back-face signatures, residual velocities, damaged targets and caught bullets [34]. Optical microscopes, scanning electron microscopes, and high-speed cameras were used for examinations, further analysis, and interpretations [146]. The absorption and transfer of energy beyond the target was evaluated by the experimental approach. This transferred energy absorption of energy depends on various cone angles, types of projectiles [127, 147]. In addition, the energy performance of the target material was influenced by woven arrangement, geometry of the projectile, impact angle and velocity, density and other fiber properties and boundary conditions [148]. Generally, the energy dissipation during the ballistic impact would be due to the energy absorbed by the secondary yarns, the tensile failure energy dissipation of the primary yarns and the kinetic energy of the moving projectile cones [149]. Meanwhile, there are several other energy-absorbing mechanisms such as shear plugging, interface friction, matrix cracks and delamination [150].

Trauma resistance refers to the target's ability to prevent the occurrence of inner wounds. As a result of the depth and diameter of the trauma, it is possible to evaluate the target energy absorption amount and communicated to the target's back, as well as the overall ballistic impact of the armor solution [95]. Moreover, in addition to evaluating the performance effectiveness, the depth of the trauma must be less than 44 mm according to the National Institute of Justice standards. The projectile will cause fatal damage to the wearer's essential organs at higher values of trauma depth [151, 152]. In general, the high-speed camera has been used by researchers to record and assess the backface signature values on typical back clays in different ways to support the packaging at the target’s back. An experimental ballistic testing procedure that could determine a target armor's V50 ballistic limit [153]. The ballistic limit velocity is the minimum velocity of the projectile at which full penetration of the target is possible and the value of maximum velocity at which the penetration is impossible [154]. The residual velocity of the projectile is necessary to evaluate the composite's energy absorption.

Numerous researchers have assessed the ballistic limit velocity, energy absorption and structural absorption and other parameters such as wave propagation including local and global damage caused by compression and cone formation. These parameters influence the deformation, bowing stretching, projectile-target friction value, delamination and matrix cracks initiation. Ballistic performance of aramid woven composites with different thermoplastic matrix was investigated. It was noticed that composites made from polypropylene composite matrix exhibited better ballistic behaviour when compared with unreinforced composites. Different energy absorption mechanisms were associated including secondary yarns’ huge deformation, delamination/debonding of matrix and the reinforcement and cracks in the matrix [155]. According to the study made by Karahan et al [156], fabric plies orientation has no significant effect on ballistic behavior, but energy absorption, ballistic limit, and thickness are bi-linearly related. Experimental tests were performed to assess the influence of composite ply blocking and spacing on UHMWPE based composite ballistic resistance. It was also found that the specific ballistic limits of thin laminates and the multiple thin laminate stacks of laminated panels were higher than a thick laminate panel made of many thin laminates bonded together [157]. Fig. 13 shows the effect of impact velocity on energy absorption.

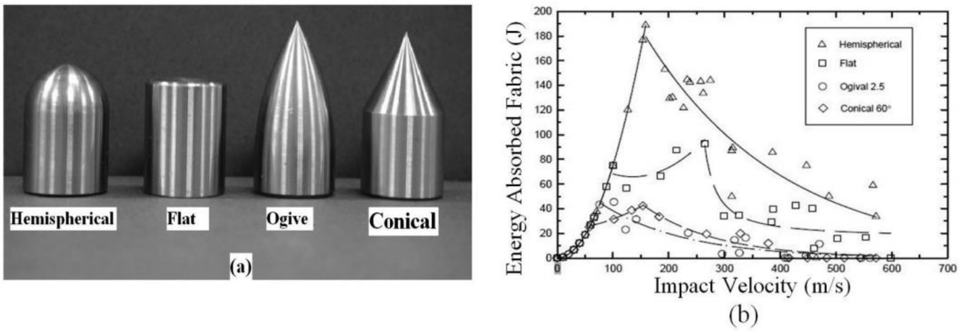

Fig. 13 (a) Various projectile shapes (b) Variation of energy absorption of the fabrics with different impact velocities [158]

5.2. Analytical Approach

The analytical approach is the study of the motion of projectiles using mathematical and physical principles. It can be leveraged to forecast the trajectory of a projectile, the penetration depth of a projectile into a target, and the energy transfer between the projectile and the target. A method that can describe the physical and mechanical phenomena during an impact [30]. The ballistic impact of the textile materials was assessed under transverse impact loading conditions by developing an analytical model for the stress-strain relationship of the textile yarn-based composites [159]. The conservation of energy during the impact were assessed through energy method by the aid of various analytical models derived out of it. In this method, the imparted kinetic energy is converted into various forms of energy during impact, including kinetic and strain energy in the deformed area of impact, strain energy in the object being hit, and heat generated by friction [160]. Thin woven fabric-based composites were analyzed for various energy absorbing and damage mechanisms using some analytical models which took the shear plugging effect into account [161]. By incorporating the kinetic energy balance between the target and the projectile and the elastic wave theory, an analytical model was developed to assess the ballistic impact. Some of the outcomes of the ballistic impact on the target include the deformation in secondary yarn, tensile force in the primary yarn, delamination of the composites, friction, matrix cracking, cone formation at the target's back face and shear plugging [162, 163].

Few researchers concluded that composite mass acceleration, tensile strain, matrix cracking and delamination contribute little to energy absorption [164]. Likewise, numerous studies have been studied on the various types of energy dissipation mechanisms of the woven UHMWPE-based composites during the ballistic impact phenomenon [165, 166]. Some experiments were carried out to determine the ballistic impact behaviour of plain-woven fabrics reinforced polymer composites, which takes the energy dissipation amount during laminate compression and plate bending into account [167]. It is intended to study the ballistic impact process considering various factors, including materials, mechanism and target system, etc., that affected the process of ballistic impact directly. Numerous experimental works have typically employed three strategies: geometrical laminate deformation models, Momentum equation models and Energy conservation law, which have a direct contribution to the ballistic phenomenon to assess the effectiveness of ballistic performance. In recent years, various researchers have made significant contributions to the development of material-based analytical modeling formulations to predict such behavior and mechanisms across different length scales, ranging from micro to macro levels [168]. Additionally, wave propagation (wave theory) and energy balance based analytical simulations can predict the ballistic behaviour of fiber-reinforced composites and textile materials. Overall, the development of material-based analytical modeling formulations has provided researchers with a powerful tool for materials behavior prediction and structures under ballistic impact. These models have helped in the development of new materials and structures that can withstand ballistic impact and have contributed to the advancement of various fields such as military, automotive, and aerospace engineering. Fig. 14 shows strain gradient of the contact region of a projectile in a single fabric layer primary yarn present in MAS systems.

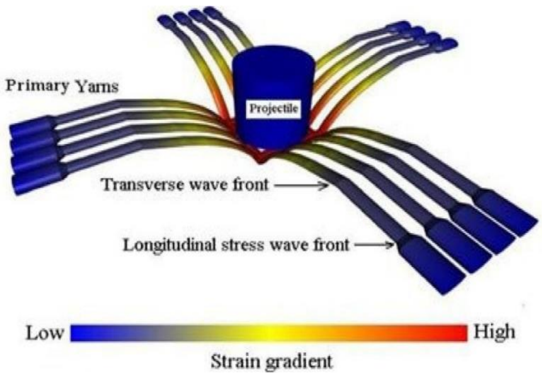

Fig. 14 Schematic of analytical model of primary yarn in single fabric layer [32]

5.3. Numerical Approach

Extensive utilization of finite element (FE) and finite difference (FD) methods occurred as a part of numerical modeling techniques. Simulation of projectile fabrics and ballistic impact behaviour of the materials were carried out using various software including ANSYS, ABAQUS, LS-DYNA and DYNA-3D. These numerical approaches aim to develop a more robust ballistic impact model for the composites and aid in predicting the target composite material's performance. At the micro-level, the behavior of materials under ballistic impact is governed by factors such as material microstructure, phase transformations, and deformation mechanisms. Researchers have used techniques such as finite element analysis and molecular dynamics simulations to develop material-based models that can predict the response of materials at this level. These models help in understanding the mechanisms that contribute to the deformation and failure of materials at the micro-level. At the meso-level, researchers have considered the behavior of individual layers of composite materials and their interactions under ballistic impact [169].

Similarly, considering the behavior of the entire structure under ballistic impact, including the effect of boundary conditions and the interaction between different components of the structure at the macro-level, researchers have focused on the behavior of composite materials under ballistic impact. The development of material-based analytical models at this level has been motivated by the need to predict the response of composite materials used in armor applications. Modeling yarn-fabric interactions and projectile-yarn interactions renders the complex interactions at the fundamental architecture of the yarn, but they tend to be computationally expensive. Because yarn-level interactions are neglected in homogenization methods, they cannot accurately describe individual yarn failures or deformations. To dodge this complexity, the ballistic impact behaviour of fabric-based composites was assessed using multi-scale modeling techniques.

Numerous researchers have studied and compared the experimental with numerical results to predict the different failure modes of ballistic performance of advanced composite materials [170, 171]. An FEA model was introduced to investigate the impacted region using a 3D solid modeling element to predict the energy mechanism and failure mode precisely. On the other hand, the impact zones which are far away from the target were modeled using 3D shell elements for more efficiency [172, 173]. A sub-yarn numerical model was proposed to observe the various deformation and energy dissipation mechanism of Kevlar fiber using conventional finite element formulation [174]. An FE model to evaluate the ballistic behaviour of the single Kevlar yarn fabric under the action of impact loading in transverse direction was developed by various researchers [175]. To understand the ballistic impact behaviour of the fabrics and the composite laminates, MAT162 which is a progressive failure model developed using LS-DYNA was utilized [176].

Finite element models were developed to predict impact characteristics and failure evolution of 3D braided and warp-knitted composites, 3D orthogonal and angle-interlock subjected to ballistic impact [177, 178]. Some experiments were carried out using fabric-based composites with fabrics aligned in various orientations such as unidirectional, plain-woven and multiaxial arrangements to evaluate the blunt trauma resistance by considering both numerical and experimental results. Results showed that the multiaxial fibers exhibited better bunt fracture resistance while all the fabric arrangements had shown similar failure modes [179]. Hybrid epoxy composites reinforced with carbon and aramid fibers were subjected to flexural property and ballistic impact tests and their behaviour was also analyzed through numerical simulations. Results revealed that the addition of carbon fibers along with the aramid fibers enhanced the flexural behaviour, projectile resisting force and shear resistance of the hybrid composite laminates [180].

The models developed at this level consider the behavior of developed material-based models to predict the response of structures under ballistic impact. The different failure criteria such as matrix damage, fiber matrix damage in view of harsh environments such as static and dynamic loading, various temperature, and pressure through FEM. In addition, the micromechanical modeling composites numerically can be solved by representative volume element (RVE) to deal with microstructural features such as shape, size, and fiber, and matrix interface, distribution of fibers. The response of micromechanical modeling such as elastic constant displacements, strains, and stress will be established at different distant fabric scales via the equilibrium of forces and potential energy method. Besides that, the Galerkin method, Rayleigh-Ritz method, and Reissner variational method are also used. In addition, multiscale modeling was governed by the rule of mixtures, Voigt and Reuss approximation and Mori-Tanaja method.

5.4. Ballistic performance of natural fiber composites

Experiments pertaining to the indentation resistance of natural fiber composites with fiber reinforcements including bamboo, sisal, jute, curaua, bagasse and Amazonian guaruman were considered equivalent to traditionally used Kevlar fiber mat owing to their cost effectiveness and were suggested as potential alternatives to the Kevlar fibers in ballistic systems. The lower density of some of the natural fibers used in the multi-layered armor systems, such as bamboo fibers, guaruman, and curaua fibers, is an advantage because it means that the armor can be lighter and more comfortable to wear for the user, without compromising on protection. The lower density also means that the armor can potentially be thinner while still providing the same level of protection as thicker Kevlar layers, which can also increase mobility and comfort. Therefore, the use of natural fiber-reinforced polymer composites in MAS has the potential to offer a cost-effective and lighter-weight alternative to traditional ballistic materials such as Kevlar, while providing similar levels of protection and minimizing body trauma to the user. In terms of cost, natural fibers tend to be less expensive than Kevlar. For example, the cost of bagasse fiber composite, which is made from sugarcane waste and has been used in multi-layered armor systems, can be as low as $1.35/kg [3]. Mallow fibers, which have also been used in armor systems, can be as low as $0.28/kg [4]. Jute fibers, which have been used in non-woven mats for armor, can be around $1.50/kg [181]. In comparison, the cost of Kevlar is around $63.6/kg [1]. Thus, natural fibers used in multi-layered armor systems tend to have lower densities and lower costs compared to Kevlar, making them potentially more cost-effective and lightweight alternatives. However, the specific properties and costs of natural fibers can vary widely, and careful consideration should be given to the selection and processing of natural fibers for use in armor systems. Fig. 15 shows a comparison of cost and density with existing Kevlar fiber.

Tables 4, 5, and 6 consolidate the use of natural fibers in polymer composites for ballistic applications along with their failure modes

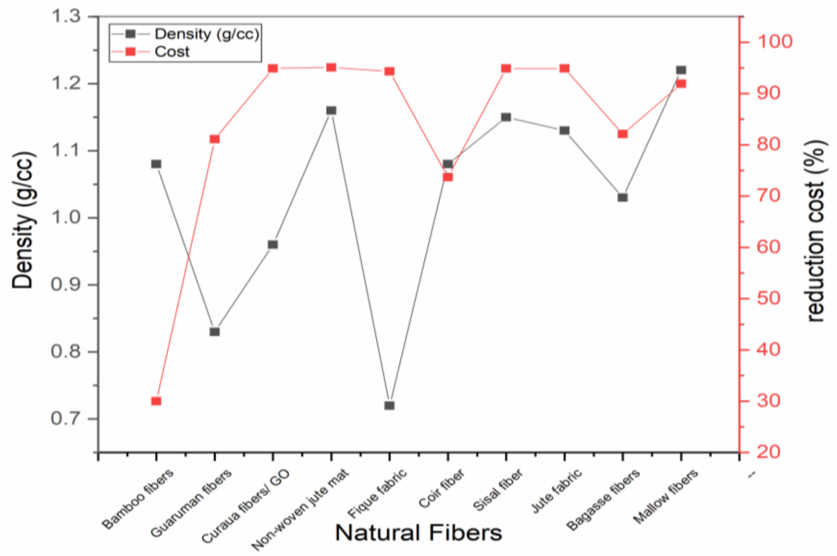

Fig. 15 Comparison of cost and density with existing Kevlar fiber

Table 4 Penetration depth and failure modes of different natural fibers

Intermediate layer	Penetration depth (mm)	Failure Modes	Ref
Pineapple leaf fiber/epoxy	26 ±2	Fiber bridging, delamination, matrix cracking	[14]
Mallow fiber (aligned)/epoxy	22 ±2	Fiber pullout, fiber stretching, matrix cracking, Fiber bridging	[182]
Sisal/Epoxy	12 ±2	Fiber pullout, fiber stretching, matrix crack	[10]
Ramie fiber/epoxy	18 ±2	delamination, fiber stretching, matrix crack	[13]
Coir fiber (aligned) epoxy	32 ±2	Fiber pullout, stretching, matrix crack	[12]
Jute fabric/polyester	17 ±3	Fiber pullout, stretching, matrix crack	[183]
Jute nonwoven mat/polyester	24 ±3	Fiber pullout, stretching, matrix crack	[184]
Curaua mat/epoxy	28 ±3	Fiber bridging, stretching, matrix crack	[14]
Piassava fiber/epoxy	15.6 ±3	Fiber bridging, stretching, matrix crack	[185]
Fique fiber/polyester	16 ±2	Fiber pullout, stretching, matrix crack	[186]
Epoxy-15% Fique fabric	20 ±1	Fiber bridging, stretching, matrix crack	[175]

Table 5 Application of natural fiber-reinforced polymer composites in ballistics thermoset

Natural fiber (intermediate layer)	Matrix type	Energy absorption (J)	Ballistic limit	Ref
Non-Woven kenaf and Kevlar (30, 50, 70%)	Epoxy	39-148		[187]
Jute fabric (10, 20, 30 vol. %)	polyester	200-260		[183]
Jute fabric (10, 20, 30 vol%)	Epoxy			[188]
Coir fiber (10, 20, 30%)	Epoxy			[12]
Sisal fiber (30%)	Epoxy	106		[9]
Fique fiber	Epoxy			[189]
Curaua fiber (10, 20, 30%)	Polyester			[190]
Kenaf/Kevlar (30/70)	Epoxy	148		[55]
Kenaf/Kevlar (Vf6/Vf47)	Epoxy	175		[55]
Coconut sheath/Kevlar (wt%5/25)	Epoxy	240		[6]
Curaua fiber (30vf)	Epoxy	197		[191]
Piassava fiber (vf)	Epoxy	272 ± 19J		[185]
Fique fiber	polyester	155 ± 7		[192]
Fique fabric	polyester	112 ± 7		[186]

Table 6 Application of natural fiber-reinforced polymer composites in ballistics thermo-propylene

Natural fiber	Matrix type	Energy absorption (J)	Ballistic limit	Ref
Flax, hemp and jute (46%)	Polypropylene			[193]
Kevalar/baslat	Polypropylene	112		[79]
Kenaf	Polyethylene	774		
Kenaf fabric/aramid	Polyvinylbuturyl		477-621	[57]
Chonta palm wood	High density polyethylene			[194]

6. FAILURE CRITERION

The use of natural fiber composites in the intermediate layer of a MAS has been studied by many researchers in recent years. The advantages of using natural fiber composites include their low cost, lightweight, and high specific energy absorption capacity. The intermediate composite layer of the MAS was fabricated using various natural fibers including guaruman, bagasse, mallow, fique, sisal, coir, ramie, bamboo and jute fibers and fabrics aligned in different orientations [195]. Emphasizes the importance of selecting the appropriate natural fibers, concentration, and manufacturing processes to develop an effective and durable intermediate layer for MAS. The development of MAS using natural fiber composites natural fiber composites in MAS has the potential to offer sustainable, cost-effective, and eco-friendly ballistic protection solutions. Additionally, jute, curaua, guaruman, and bagasse fibers exhibited improved matrix adhesion, resulting in reduced delamination and fiber breakage upon impact [181].

It was also observed from various experimental studies that the intermediate layer of MAS made of natural fiber hybrid composites had undergone failure by different modes including failure of matrix and fiber separately and delamination occurring at the interfacial region of matrix and the fiber and so on. These interlaminar failures significantly reduce the strength and stiffness of the natural finer composite material layers [196]. This type of failure can lead to significant material damage, compromising MAS effectiveness against ballistic impact. To address this, optimizing the intermediate layer design and natural fiber composite properties is crucial. Key considerations include selecting suitable fibers, matrix materials, fiber orientation, and manufacturing processes. Furthermore, post-treatments like surface and chemical treatments, along with interphase modification, enhance fiber-matrix adhesion, minimizing delamination and fiber breakage during impact. Fig. 16 presents the side view of impact regions and their energy absorption mechanisms.

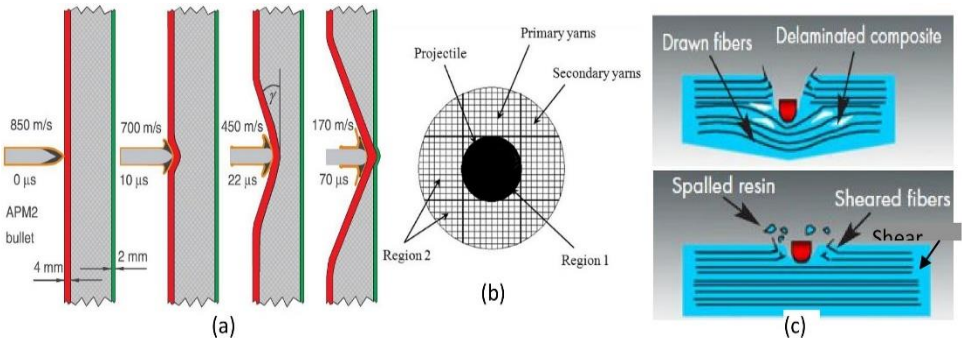

Fig. 16 2D schematic of a typical woven fabric composite laminate targets (a) Armor pierced by APM2 bullets – side view [196] (b) Elevation of impact zones and yarns [32], and (c) Mechanism of energy absorption in the layered woven fabric composites [32]

With natural fiber composites in the intermediate layer of MAS offer promising and sustainable ballistic protection, interlaminar failure must be addressed in design and manufacturing. Optimizing the intermediate layer's design and material properties can make natural fiber composites a viable solution for ballistic protection. Intralaminar failure occurs due to various modes like interfacial disbanding and fiber/matrix breaking, while interlaminar failure involves the failure of multiple plies. Intralaminar cracking in multi-directional laminates reduces load-bearing capacity and affects material thermoelastic characteristics, with delamination being a common consequence of in-plane matrix failure [197]. Accurately predicting and modeling the failure behavior of composite materials under ballistic impact requires addressing the interaction between parameters causing interlaminar and intralaminar failures. However, these failure modes are typically addressed individually and independently, allowing researchers and engineers to focus on developing specific failure criteria for each mechanism [198]. Fig. 17 shows different factors involving energy absorption in ballistic body armor.

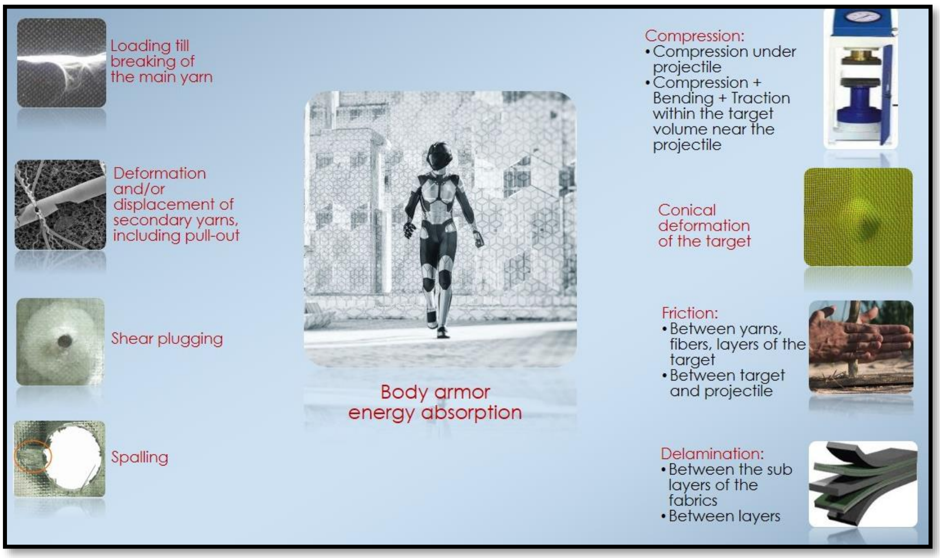

Fig. 17 Failure Criterion for packages based on fabrics

6.1. Intralaminar Failure Mechanisms

There are three main intralaminar failure mechanisms considered during composite material analysis which includes failure of the fiber, shear failure at fiber-matrix interface and matrix cracking. Failure modes are typically characterized by two in-plane modes, known as modes 1-2, and one out-of-plane shear mode, known as mode 2-3 [199]. These modes are used to describe the behavior of the material under different loading conditions and are crucial for understanding the failure mechanisms that occur during impact events. In most impact investigations, the most typical intra-laminar failure mechanisms include matrix out-of-plane and in-plane shear failure, fiber breakage and transverse tensile failure [200]. These mechanisms are all related to the deformation and damage that occurs within the composite layers during impact loading. Figs. 18 and 19 show failure modes of intra-laminar and inter-laminar and its transition.

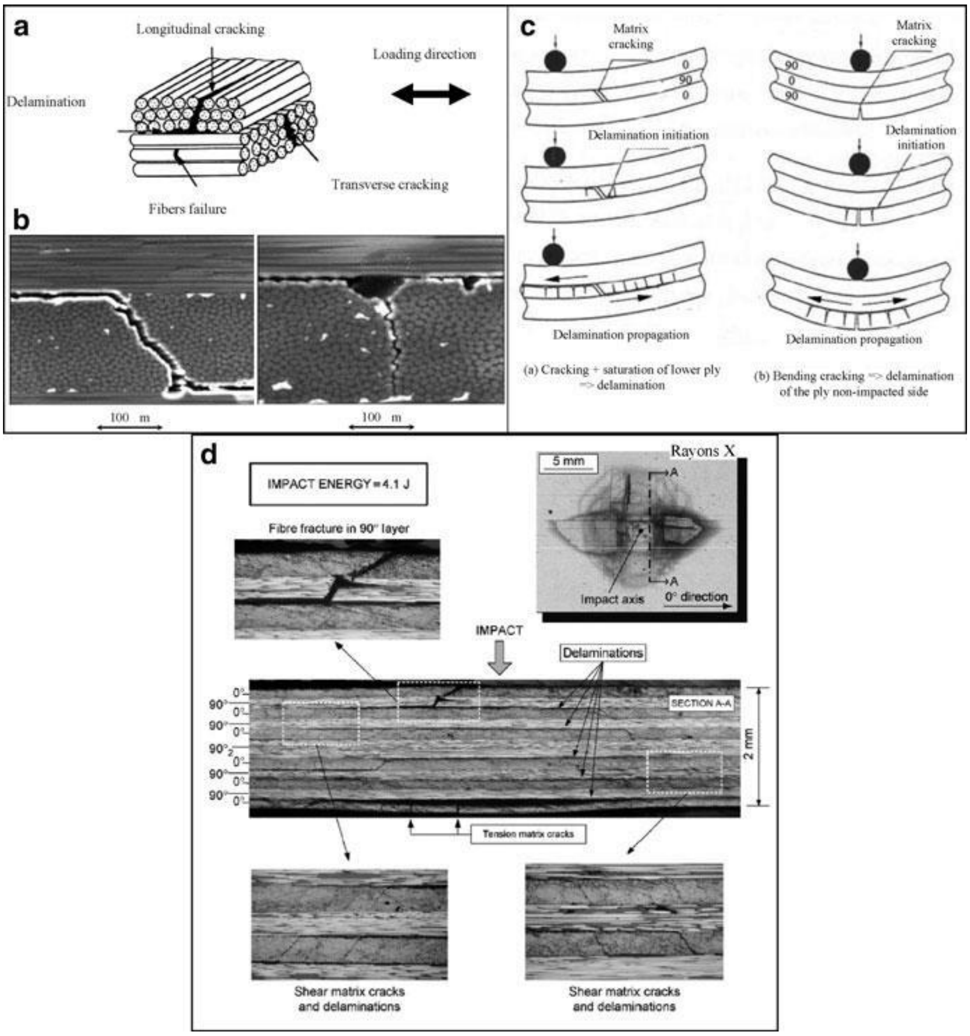

Fig. 18 Failure modes (a) intra-laminar failure modes (b) inter-laminar failure modes (c) transition from intra to inter-laminar failure modes [200]

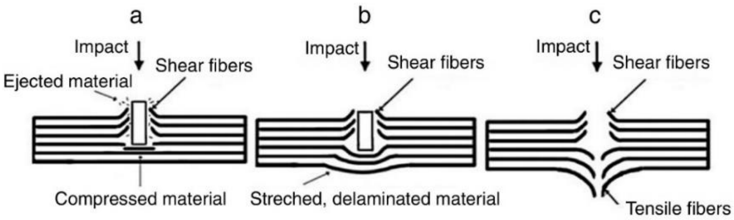

Fig. 19 Ballistic failure mechanism proposed after the impact: (a, b) partial penetration and (c) complete perforation [198]

Fiber breaking occurs when the fibers within the composite material fracture and break apart under tensile or compressive loading [19]. Transverse tensile failure happens when composite layers separate and delaminate perpendicular to fiber orientation. In-plane shear occurs when matrix material deforms within the composite under loading, while out-of-plane shear happens perpendicular to layer planes. Common failure modes in transversely loaded composite structures include transverse tensile failure, out-of-plane and in-plane shear, and fiber breakage in experimental studies [201]. Understanding these failure mechanisms is crucial for designing composite materials capable of withstanding impact loading. By characterizing these modes and creating predictive models, researchers and engineers can design lightweight composite structures that offer excellent resistance to impact damage [202, 203].

6.2. Interlaminar Failure Mechanisms

Linear elastic fracture mechanics (LEFM) is a widely used analysis technique for interlaminar failure or interfacial fracture in composite materials. Delamination failures, such as out-of-plane shear mode, in-plane shear mode, and peel mode (specified as Mode I, II, and III), are commonly observed, each with unique characteristics requiring specific analysis techniques. However, LEFM has limitations in analyzing these three common modes of failure [203]. Mode I failure, or peel, arises when a tensile load is applied perpendicular to the laminates' plane, causing delamination of the first layer. This process involves crack opening and separation, accurately described by Mode -I LEFM. Mode II failure, or in-plane shear, occurs when a shearing force is applied parallel to the laminates' plane, leading to sliding between layers. This mode involves crack sliding and shear displacement, also described by Mode -II LEFM [204]. Mode III failure or out-of-plane shear occurs when a shearing force is applied perpendicular to the plane of the laminates, causing the middle layer to slide with respect to the upper and lower layers [205]. The fracture process in mode III is characterized by crack sliding and out-of-plane shear displacement, and LEFM is not suitable for analyzing this mode because it assumes that the crack propagates in the plane of the laminates. LEFM is a useful tool for analyzing interlaminar failure or interfacial fracture in composites, but it has limitations when it comes to analyzing mode III failure [206].

7. CONCLUSIONS

The article demonstrates the potential of renewable resources in PMCs, the effectiveness of plant fibers as replacements for conventional fibers in ballistic protection and armor applications, and the possibility of using them as a suitable substitute for conventional fibers in such applications. Natural fiber materials are such kind of sustainable materials in hard body armor that have revolutionized the field of armor systems. Owing to their light-weight nature, they can be readily used as an alternative to heavy armor including metal body armor. The conclusions drawn from the above discussions can be summarized as follows:

- The impact behaviour of the multilayer armor systems was greatly influenced by the intrinsic parameters of the system including condition of use, target arrangements and its composition and material characteristics of the ballistic materials.
- To design and beget an environmentally friendly and sustainable ballistic protection made of natural fiber composites, numerical and experimental methods are to be combined in order to analyze and comprehend the ballistic impact mechanisms.

- It could also be concluded that the intermediate natural fiber hybrid polymer composite layer fails majorly through fiber fracture, fiber pullout, delamination, fiber bridging and matrix cracking failure modes upon impact with a ballistic projectile. These materials possess high energy absorption capacity and allow for a more even load distribution through the varying fiber architecture, ply thickness and aerial density and different influential parameters.
- Utilization of natural fiber hybrid composites in multilayer armor systems minimizes the cost of raw materials and fabrication without compromising the ballistic performance much. Hybridization of the natural fibers with synthetic fibers enhances the ballistic performance of the materials system.
- The development of advanced body armor systems has been aided by recent advancements in the material science field. The evolution in the field of defense and aerospace sector led to further exploring these kinds of applications with aid of using additive manufacturing technologies for the fabrication of ballistic protection systems. This approach can lead to better-performing and lighter armor systems soon along with the optimal combination of advanced composites and hybrid materials.

Acknowledgement: *Authors sincerely acknowledge the necessary resources provided by the Centre for Machining and Materials Testing and Materials Characterization Laboratory, KPR Institute of Engineering and Technology, Coimbatore, India. This research budget was allocated by National Science, Research and Innovation Fund (NSRF) (Fundamental Fund 2024), and King Mongkut's University of Technology North Bangkok (Project no. KMUTNB-FF-67-A-03).*

REFERENCES

1. Nurazzi, NM., Asyraf, MRM., Khalina, A., 2021, *A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications*, Polymers (Basel), 13, 646.
2. Bhat, A., Naveen J., Jawaid M., 2021, *Advancement in fiber reinforced polymer, metal alloys and multi-layered armour systems for ballistic applications – A review*, Journal of Materials Research and Technology, 15, pp. 1300–1317.
3. Rakeshkumar C, R., Jayakumar, KS., 2023, *Ballistic impact assessment of Aluminium Alloy 7075 T6, Kevlar and basalt fiber reinforced composite laminate with different nano fillers*, Mater Res Express, 10, 025309.
4. Wu, S., Sikdar, P., Bhat, GS., 2022, *Recent progress in developing ballistic and anti-impact materials Nanotechnology and main approaches*, Defence Technology, 21, pp. 33-61.
5. Chang, BP., Mohanty, AK., Misra, M., 2020, *Studies on durability of sustainable biobased composites: a review*, RSC Advances, 10, pp. 17955–17999.
6. Naveen, J., Jawaid, M., Zainudin, E.S., Sultan, M.T., Yahaya, R., 2019, *Evaluation of ballistic performance of hybrid Kevlar ® / Cocos nucifera sheath reinforced epoxy composites*, The Journal of The Textile Institute, 110(8), pp. 1179–1189.
7. Pinheiro, M.A., Gomes, L.G., Silva, A.C.R.D., Candido, V.S., Reis, R.H.M., Monteiro, S.N., 2019, *Guaruman: A Natural Amazonian Fiber with Potential for Polymer Composite Reinforcement*, Materials Research, 22, e20190092.
8. Reis, R.H.M., Nunes, L.F., da Luz, F.S., Candido, V.S., da Silva, A.C.R., Monteiro, S.N., 2021, *Ballistic Performance of Guaruman Fiber Composites in Multilayered Armor System and as Single Target*, Polymers (Basel), 13(8), 1203.
9. Rohen, L.A., Margem, F.M., Monteiro, S.N., Vieira, C.M.F., Madeira de Araujo, B., Lima, E.S., 2015, *Ballistic Efficiency of an Individual Epoxy Composite Reinforced with Sisal Fibers in Multilayered Armor*, Materials Research, 18(2), pp. 55–62.
10. Braga, F.D.O., Bolzan, L.T., Ramos, F.J.H.T.V., Monteiro, S.N., Lima, É.P., Silva, L.C.D., 2018, *Ballistic Efficiency of Multilayered Armor Systems with Sisal Fiber Polyester Composites*, Materials Research, 20, pp. 767–774.

11. Garcia Filho, F.D.C., Oliveira, M.S., Pereira, A.C., Nascimento, L.F.C., Matheus, J.R.G., Monteiro, S.N., 2020, *Ballistic behavior of epoxy matrix composites reinforced with piassava fiber against high energy ammunition*, Journal of Materials Research and Technology, 9(2), pp. 1734–1741.
12. Luz, F.S.D., Monteiro, S.N., Lima, E.S., Lima, É.P., 2017, *Ballistic Application of Coir Fiber Reinforced Epoxy Composite in Multilayered Armor*, Materials Research, 20(2), pp. 23–28.
13. Monteiro, S.N., Milanezi, T.L., Louro, L.H.L., Lima Jr, E.P., Braga, F.O., Gomes, A.V., Drelich, J.W., 2016, *Novel ballistic ramie fabric composite competing with Kevlar™ fabric in multilayered armor*, Materials & Design, 96, pp. 263–269.
14. Monteiro, S.N., Louro, L.H.L., Trindade, W., Elias, C.N., Ferreira, C.L., de Sousa Lima, E., Weber, R.P., Miguez Suarez, J.C., Da Silva Figueiredo, A.B.H., Pinheiro, W.A., Da Silva, L.C., 2015, *Natural Curaua Fiber-Reinforced Composites in Multilayered Ballistic Armor*, Metallurgical and Materials Transactions A, 46, pp. 4567–4577.
15. da Silva, L.C., Oliveira, M.S., da Cruz Demosthenes, L.C., Bezerra, W.B.A., Monteiro, S.N.2019, *Ballistic Tests of Epoxy Matrix Composites Reinforced with Arapaima Fish Scales*, Green Materials Engineering- An EPD Symposium in Honor of Sergio Monteiro, The Minerals, Metals & Materials Series, Springer, Cham., pp. 169–175.
16. de Oliveira Braga, F., Bolzan, L.T., Lima Jr, É.P., Monteiro, S.N., 2017, *Performance of natural curaua fiber-reinforced polyester composites under 7.62 mm bullet impact as a stand-alone ballistic armor*, Journal of Materials Research and Technology, 6(4), pp. 323–328.
17. Luz, F.S.D., Garcia Filho, F.D.C., Oliveira, M.S., Nascimento, L.F.C., Monteiro, S.N., 2020, *Composites with Natural Fibers and Conventional Materials Applied in a Hard Armor: A Comparison*, Polymers (Basel), 12(9), 1920.
18. Naveen, J., Jayakrishna, K., Hameed Sultan, M.T.B., Amir, S.M.M., 2020, *Ballistic Performance of Natural Fiber Based Soft and Hard Body Armour- A Mini Review*, Frontiers in Materials, 7, 608139.
19. Doddamani, S., Kulkarni, S.M., Joladarashi, S., TS, M.K., Gurjar, A.K., 2023, *Analysis of light weight natural fiber composites against ballistic impact: A Review*, International Journal of Lightweight Materials and Manufacture, 6(3), pp. 450-468.
20. Dewangan, M.K., Panigrahi, S.K., 2021, *Factors influencing the ballistic impact mechanisms of textile composite materials: A review*, Polymers for Advanced Technologies, 32(5), pp. 1901–1923.
21. Goda, I., 2022, *Ballistic resistance and energy dissipation of woven-fabric composite targets: Insights on the effects of projectile shape and obliquity angle*, Defence Technology, 21, pp. 14-32.
22. Liu, H., Zhou, Y., Chen, L., Pan, X., Zhu, S., Liu, T., Li, W., 2023, *Drop-weight impact responses and energy absorption of lightweight glass fiber reinforced polypropylene composite hierarchical cylindrical structures*, Thin-Walled Structures, 184, p. 110468.
23. Aminudin, I.R., Aritonang, S., 2023, *Potential of natural fiber composite materials for bulletproof vest applications*, Defense and Security Studies, 4, pp. 8–14.
24. Abdollahiparsa, H., Shahmirzaloo, A., Teuffel, P., Blok, R.,2023, *A review of recent developments in structural applications of natural fiber-Reinforced composites (NFRCs)*, Composites and Advanced Materials, https://doi.org/10.1177/26349833221147540.
25. Ismail, SO., Akpan, E., Dhakal, HN., 2022, *Review on natural plant fibres and their hybrid composites for structural applications: Recent trends and future perspectives*, Composites Part C, 9, 100322.
26. Wang, L., Kanesalingam, S., Nayak, R., Padhye, R., 2014, *Recent Trends in Ballistic Protection*, Textiles and Light Industrial Science and Technology, 3, pp. 37-47.
27. Rajput, A., Sunny, M.R., Sarkar, A., 2023, *Optimization of honeycomb parameters of sandwich composites for energy and specific energy absorption using particle swarm optimization*, Marine Structures, 92,103498.
28. Gower, HL., Cronin, DS., Plumtree, A., 2008, *Ballistic impact response of laminated composite panels*, International Journal of Impact Engineering, 35(9), pp. 1000–1008.
29. Lim, B.H., Chu, J.M., Gao, J., Claus, B., Nie, Y., Chen, W., 2019, *The Effect of Projectile Nose Shape on the Critical Velocity of High-Performance Yarn*, Fibers, 7(4), p. 29.
30. Chen, X., Zhu, F., Wells, G., 2013, *An analytical model for ballistic impact on textile-based body armour*, Composites Part B: Engineering, 45(1), pp. 1508–1514.
31. Naik, N.K., Shrirao, P., Reddy, B.C.K., 2006, *Ballistic impact behaviour of woven fabric composites: Formulation*, International Journal of Impact Engineering, 32(9), pp. 1521–1552.
32. Abtew, M.A., Boussu, F., Bruniaux, P., Loghin, C., Cristian, I., 2019, *Ballistic impact mechanisms – A review on textiles and fibre-reinforced composites impact responses*, Composite structures, 223, 110966.
33. Talebi, H., Wong, S.V., Hamouda, A.M.S., 2009, *Finite element evaluation of projectile nose angle effects in ballistic perforation of high strength fabric*. Composite structures, 87(4), pp. 314–320.
34. Ghosh, A., Das, S., 2023, *Testing and evaluation of technical textiles*, In: Functional and Technical Textiles. Elsevier, USA, pp. 717–756.

35. Khalili, S.M.R., Beigpour, R., Mahajan, P., 2023, *Strain rate dependency of lightweight hybrid green composite laminate-an experimental study*, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45, 283.
36. *Ballistic Resistance of Body Armor NIJ Standard-0101.06*. National Institute of Justice, U.S., Department of Justice, pp. 223054
37. Xu, S., Li, Y., Zhou, S., Jiang, X., Xie, W., Zhang, W., 2023, *Ballistic performance and damage analysis of CFRP laminates under uniaxial pretension and precompression*, International Journal of Impact Engineering, 178, 104620.
38. Rob Kinsler., *Comparison of V50 Shot Placement on Final Outcome,* Conference: Personal Armour Systems Symposium (PASS), 17 September 2012, Germany, pp. 1-10
39. Cavallaro, Paul V., 2011, *Soft Body Armor: An Overview of Materials, Manufacturing, Testing, and Ballistic Impact Dynamics*, NUWC-NPT Technical Report 12,057, Rhode Island, USA.
40. Ojoc, G.G., Pirvu, C., Sandu, S., Deleanu, L., 2020, *Standardization in testing ballistic protection systems*, IOP Conference Series: Materials Science and Engineering, 724(1), 012049.
41. Bandaru, A.K., Vetiyatil, L., Ahmad, S., 2015, *The effect of hybridization on the ballistic impact behavior of hybrid composite armors*, Composites Part B: Engineering, 76, pp. 300–319.
42. Swolfs, Y., Gorbatikh, L., Verpoest, I., 2014, *Fibre hybridisation in polymer composites: A review*, Composites Part A: Applied Science and Manufacturing, 67, pp. 181–200.
43. Sinan Üstün, H., Kaan Toksoy, A., Tanoğlu, M., 2022, *Investigation of hybridization effect on ballistic performance of multi-layered fiber reinforced composite structures*, Journal of Composite Materials, 56(15), pp. 2411–2431.
44. Vasudevan, A., Senthil Kumaran, S., Naresh, K., Velmurugan, R., Shankar, K. 2018, *Advanced 3D and 2D damage assessment of low velocity impact response of glass and Kevlar fiber reinforced epoxy hybrid composites*, Advances in Materials and Processing Technologies, 4(3), pp. 493–510.
45. Yang, Z., Liu, J., Wang, F., Li, S., Feng, X., 2019, *Effect of fiber hybridization on mechanical performances and impact behaviors of basalt fiber/UHMWPE fiber reinforced epoxy composite,* Composite Structures, 229, 111434.
46. Al-Kinani, R., Najim, F. and De Moura, M.F.S.F., 2014, *The Effect of Hybridization on the GFRP Behavior under Quasi-Static Penetration*, Mechanics of Advanced Materials and Structures, 21(2), pp. 81–87.
47. Park, R., Jang, J., 2001, *Impact behavior of aramid fiber/glass fiber hybrid composites: The effect of stacking sequence*, Polymer Composites, 22(1), pp. 80–89.
48. Wan, Y.Z., Lian, J.J., Huang, Y., He, F., Wang, Y.L., Jiang, H.J., Xin, J.Y. 2007, *Preparation and characterization of three-dimensional braided carbon/Kevlar/epoxy hybrid composites*, Journal of materials science, 42, pp. 1343–1350.
49. Korkmaz, M., Okur, A., Labanieh, A.R. and Boussu, F., 2022, *Investigation of the mechanical and forming behaviour of 3D warp interlock carbon woven fabrics for complex shape of composite material*, Journal of Industrial Textiles, 51(3 suppl), pp. 5427S-5465S.
50. El Messiry, M., Eltahan, E., 2016, *Stab resistance of triaxial woven fabrics for soft body armor*, Journal of Industrial Textiles, 45(5), pp. 1062–1082.
51. Sun, B., Liu, Y., Gu, B., 2009, *A unit cell approach of finite element calculation of ballistic impact damage of 3-D orthogonal woven composite*, Composites Part B: Engineering, 40(6), pp. 552–560.
52. Luo, Y., Lv, L., Sun, B., Qiu, Y., Gu, B., 2007, *Transverse impact behavior and energy absorption of three-dimensional orthogonal hybrid woven composites*, Composite Structures, 81(2), pp. 202–209.
53. Kumaresan Gladys, A., Muthuvelu, V.S., Kumar, K., Ganesh, K., 2022, *Energy absorption performance of Kevlar/snake grass fiber composites under ballistic impact test with nano Al_2O_3 inclusion*, Polymer Composites, 43(9), pp. 6082–6095.
54. Nugroho, A., Sufiandi, S., Syahrial, A.Z. 2022, *Energy absorption of densified veneer-aramid hybrid composites subjected to ballistic impact*, Heliyon, 8(8), e10271.
55. Yahaya, R., Sapuan, S.M., Jawaid, M., Leman, Z., Zainudin, E.S., 2016, *Investigating ballistic impact properties of woven kenaf-aramid hybrid composites*, Fibers and Polymers, 17, pp. 275–281.
56. Pagnoncelli, M., Piroli, V., Romanzini, D., Pereira, I.M., Rodrigues Dias, R., Amico, S.C., Zattera, A.J., 2018, *Mechanical and ballistic analysis of aramid/vinyl ester composites*, Journal of Composite Materials, 52(3), pp. 289–299.
57. Salman, S.D., Leman, Z., Sultan, M.T., Ishak, M.R., Cardona, F., 2016, *Ballistic Impact Resistance of Plain Woven Kenaf/Aramid Reinforced Polyvinyl Butyral Laminated Hybrid Composite*, Bioresources, 11(3), pp.7282-7295.
58. Yahaya, R., Sapuan, S.M., Jawaid, M., Leman, Z., Zainudin, E.S., 2016, *Measurement of ballistic impact properties of woven kenaf–aramid hybrid composites*, Measurement, 77, pp. 335–343.

59. Bulut, M., Erkliğ, A., Yeter, E., 2016, *Hybridization effects on quasi-static penetration resistance in fiber reinforced hybrid composite laminates*, Composites Part B: Engineering, 98, pp. 9–22.
60. Roylance, D., 2020, *Impact of Textile Structures*, In Encyclopedia of Continuum Mechanics, Springer Berlin Heidelberg, pp. 1288–1297.
61. Bilisik, K., Karaduman, N.S., Bilisik, NE., 2016, *Fiber Architectures for Composite Applications*, In: Rana, S., Fangueiro, R. (eds) Fibrous and Textile Materials for Composite Applications. Textile Science and Clothing Technology. Springer-Singapore, pp. 75–134.
62. Kordani, N., 2023, *Materials, design, and technology of body armor*, In: Advances in Healthcare and Protective Textiles. Woodhead publishing, USA, pp. 259–301.
63. Shi, X., Sun, Y., Xu, J., Chen, L., Zhang, C., Zhang, G., 2023, *Effect of Fiber Fraction on Ballistic Impact Behavior of 3D Woven Composites*, Polymers (Basel), 15(5), 1170.
64. Biradar, A., Arulvel, S., Kandasamy, J., 2023, *Significance of ballistic parameters and nanohybridization in the development of textile-based body armor: A review*, International Journal of Impact Engineering, 180, 104700.
65. Lin, C.C., Lin, C.M., Huang, C.C., Lou, C.W., Meng, H.H., Hsu, C.H., Lin, J.H., 2009, *Elucidating the Design and Impact Properties of Composite Nonwoven Fabrics with Various Filaments in Bulletproof Vest Cushion Layer*, Textile Research Journal, 79(3), pp. 268–274.
66. Erol, O., Powers, BM., Keefe, M., 2017, *Effects of weave architecture and mesoscale material properties on the macroscale mechanical response of advanced woven fabrics*, Composites Part A: Applied Science and Manufacturing, 101, pp. 554–566.
67. Vasudevan, A., Kumaran, S.S., Naresh, K., Velmurugan, R., 2020, *Layer-wise damage prediction in carbon/Kevlar/S-glass/E-glass fibre reinforced epoxy hybrid composites under low-velocity impact loading using advanced 3D computed tomography*, International Journal of Crashworthiness, 25(1), pp. 9–23.
68. Wang, Y., Chen, X., Young, R., Kinloch, I., Garry, W., 2016, *An experimental study of the effect of ply orientation on ballistic impact performance of multi-ply fabric panels*, Textile Research Journal, 86(1), pp. 34–43.
69. Min, S., Chu, Y., Chen, X., 2016, *Numerical study on mechanisms of angle-plied panels for ballistic protection*, Materials & Design, 90, pp. 896–905.
70. Nilakantan, G., Nutt, S., 2018, *Effects of ply orientation and material on the ballistic impact behavior of multilayer plain-weave aramid fabric targets*, Defence Technology, 14(3), pp. 165–178.
71. Dewangan, MK., Panigrahi, SK., 2020, *Multi-scale modeling of three-dimensional angle interlock woven composite subjected to ballistic impact using FEM*, Polymers for Advanced Technologies, 31(12), pp. 3079–3094.
72. Sayer, M., Bektaş, N.B., Sayman, O., 2010, *An experimental investigation on the impact behavior of hybrid composite plates*, Composite Structures, 92(5), pp. 1256–1262.
73. Porwal, P.K., Phoenix, S.L., 2005, *Modeling System Effects in Ballistic Impact into Multi-layered Fibrous Materials for Soft Body Armor*, International journal of fracture, 135, pp. 217–249.
74. Jordan, J.B., Naito, C.J., 2014, *An experimental investigation of the effect of nose shape on fragments penetrating GFRP*, International Journal of Impact Engineering, 63, pp. 63–71.
75. Dogan, S., Arman, Y., Dogan, A., 2023, *Effect of impactor nose form on the impact behavior of reinforced composite materials*, Materials Testing, 65(8), pp. 1254–1262.
76. Zhou, Y., Chen, X., 2015, *A numerical investigation into the influence of fabric construction on ballistic performance*, Composites Part B: Engineering, 76, pp. 209–217.
77. Stopforth, R., Adali, S., 2019, *Experimental study of bullet-proofing capabilities of Kevlar, of different weights and number of layers, with 9 mm projectiles*, Defence Technology, 15(2), pp. 186–192.
78. Shaktivesh, Nair N., Naik, N., 2015, *Ballistic impact behavior of 2D plain weave fabric targets with multiple layers: Analytical formulation*, International Journal of Damage Mechanics, 24(1), pp. 116–150.
79. Bandaru, A.K., Patel, S., Sachan, Y., Alagirusamy, R., Bhatnagar, N., Ahmad, S., 2016, *Low velocity impact response of 3D angle-interlock Kevlar/basalt reinforced polypropylene composites*, Materials & Design, 105, pp. 323–332.
80. Bandaru, A.K., Chavan, V.V., Ahmad, S., Alagirusamy, R., Bhatnagar, N., 2016, *Low velocity impact response of 2D and 3D Kevlar/polypropylene composites*, International Journal of Impact Engineering, 93, pp. 136–143.
81. Jia, X., Sun, B., Gu, B., 2011, *Ballistic penetration of conically cylindrical steel projectile into 3D orthogonal woven composite: a finite element study at microstructure level*, Journal of Composite Materials, 45(9), pp. 965–987.
82. Sabet, A., Fagih, N., Beheshty, M.H., 2011, *Effect of reinforcement type on high velocity impact response of GRP plates using a sharp tip projectile*, International Journal of Impact Engineering, 38(8-9), pp. 715–722.
83. Lee, B.L., Song, J.W., Ward, J.E., 1994, *Failure of Spectra® Polyethylene Fiber-Reinforced Composites under Ballistic Impact Loading*, Journal of Composite Materials, 28(13), pp. 1202–1226.

84. Flanagan, M.P., Zikry, M.A., Wall, J.W., El-Shiekh, A., 1999, *An Experimental Investigation of High Velocity Impact and Penetration Failure Modes in Textile Composites*, Journal of Composite Materials, 33(12), pp. 1080–1103.
85. Mines, R.A.W., Roach, A.M., Jones, N., 1999, *High velocity perforation behaviour of polymer composite laminates*, International Journal of Impact Engineering, 22(6), pp. 561–588.
86. Chu, C.K., Chen, Y.L., Hseu, G.C., Hwang, D.G., 2007, *The Study of Obliquity on the Ballistic Performance of Basket Fabric Composite Materials*, Journal of Composite Materials, 41(13), pp. 1539–1558.
87. Arora, S., Majumdar, A., Butola, B.S., 2020, *Soft armour design by angular stacking of shear thickening fluid impregnated high-performance fabrics for quasi-isotropic ballistic response*, Composite Structures, 233, 111720.
88. Zhao, L., Qian, X., Sun, Y., Yuan, M., Tang, F., Zhao, Y., Zhang, Q., Chen, Y., 2018, *Ballistic behaviors of injection-molded honeycomb composite*, Journal of Materials Science, 53(20), pp. 14287–14298.
89. Latif, R., Wakeel, S., Zaman Khan, N., Noor Siddiquee, A., Lal Verma, S., Akhtar Khan, Z.,2019, *Surface treatments of plant fibers and their effects on mechanical properties of fiber-reinforced composites: A review*, Journal of Reinforced Plastics and Composites, 38(1), pp. 15–30.
90. Mohammed, M., Rahman, R., Mohammed, A.M., Betar, B.O., Osman, A.F., Adam, T., Dahham, O.S., Gopinath, S.C., 2022, *Improving hydrophobicity and compatibility between kenaf fiber and polymer composite by surface treatment with inorganic nanoparticles*, Arabian Journal of Chemistry, 15(11), 104233.
91. Birniwa, A.H., Abdullahi, S.S.A., Ali, M., Mohammad, R.E.A., Jagaba, A.H., Amran, M., Avudaiappan, S., Maureira-Carsalade, N., Flores, E.I.S., 2023, *Recent trends in treatment and fabrication of plant-based fiber-reinforced epoxy composite: A review*, Journal of Composites Science, 7(3), 120.
92. Chen, S., Bourham, M., Rabiei, *A.*, 2014, *Novel light-weight materials for shielding gamma ray*, Radiation Physics and Chemistry, 96, pp. 27–37.
93. Rajeshkumar, L., Kumar, PS., Ramesh, M., 2023, *Assessment of biodegradation of lignocellulosic fiber-based composites – A systematic review*, International Journal of Biological Macromolecules, 253, 127237.
94. Phiri, R., Rangappa, S., Siengchin, S., Marinkovic, D., 2023, *Agro-waste natural fiber sample preparation techniques for bio-composites development: methodological insights*, Facta Universitatis-Series Mechanical Engineering, 21(4), pp. 631-656.
95. Salman, S.D., Leman, Z., Sultan, M.T.H., Ishak, M.R., Cardona, F., 2017, *Effect of kenaf fibers on trauma penetration depth and ballistic impact resistance for laminated composites*, Textile Research Journal, 87(17), pp. 2051–2065.
96. dos Santos Alves, A.L., Nascimento, L.F.C., Suarez, J.C.M., 2005, *Influence of weathering and gamma irradiation on the mechanical and ballistic behavior of UHMWPE composite armor*, Polymer Testing, 24(1), pp. 104–113.
97. Figueiredo, A.B.H.D.S., Vital, H.D.C., Weber, R.P., Lima Júnior, É.P., Rodrigues, J.G.P., Aguilera, L.D.S., Biasi, R.S.D., 2019, *Ballistic Tests of Alumina-UHMWPE Composites Submitted to Gamma Radiation*, Materials Research, 22, e20190251.
98. Li, Y., Mai, Y-W., Ye, L., 2005, *Effects of fibre surface treatment on mechanical properties of sisal-fiber composites*, Composite Interfaces, 12(1-2), pp. 141–163.
99. Chen, G., Luo, H., 2020, *Effects of node with discontinuous hierarchical fibers on the tensile fracture behaviors of natural bamboo*, Sustainable Materials and Technologies, 26, e00228.
100. Akhavan-Safar, A., Salamat-Talab, M., Delzendehrooy, F., Barbosa, A.Q., da Silva, L.F.M., 2021, *Mode II fracture energy of laminated composites enhanced with micro-cork particles*, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 43, 490.
101. Ko, S., Davey, J., Douglass, S., Yang, J., Tuttle, M.E., Salviato, M., 2019, *Effect of the thickness on the fracturing behavior of discontinuous fiber composite structures*, Composites Part A: Applied Science and Manufacturing, 125, 105520.
102. Khalid, M.Y., Al Rashid, A., Arif, Z.U., Ahmed, W., Arshad, H., Zaidi, A.A., 2021, *Natural fiber reinforced composites: Sustainable materials for emerging applications*, Results in Engineering, 11, 100263.
103. Xu, L.Z., Ren, W.K., Wang, J.B., Wang, X.D., Gao, G.F., 2023, *An experimental investigation into ballistic performance of woven fabrics with single and multiple layers*, Textile Research Journal, 93(9-10), pp. 2394–2408.
104. Li, Z., Xue, Y., Sun, B., Gu, B., 2023, *Hybrid ratio optimizations on ballistic penetration of carbon Kevlar UHMWPE fiber laminates*, International Journal of Mechanical Sciences, 258, 108585.
105. Chen, L., Cao, M., Fang, Q., 2021, *Ballistic performance of ultra-high molecular weight polyethylene laminate with different thickness*, International Journal of Impact Engineering, 156, 103931.
106. Zhang, R., Han, B., Zhong, J.Y., Qiang, L.S., Ni, C.Y., Zhang, Q., Zhang, Q.C., Li, B.C., Lu, T.J., 2022, *Enhanced ballistic resistance of multilayered UHMWPE laminated plates*, International Journal of Impact Engineering, 159, 104035.

107. Kumar, S.D., Samvel, R., Aravindh, M., Vibin, R.A., Poovarasu, E., Prasad, M.S., 2023, *Ballistic studies on synthetic fibre reinforced polymer composites and it's applications –A brief review*, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2023.03.679.
108. Gloger, M., Stempien, Z., Pinkos, J., 2023, *Numerical and experimental investigation of the ballistic performance of hybrid woven and embroidered-based soft armour under ballistic impact*, Composite Structures, 322, 117420.
109. Moure, M.M., Rubio, I., Aranda-Ruiz, J., Loya, J.A., Rodríguez-Millán, M., 2018, *Analysis of impact energy absorption by lightweight aramid structure*, Composite Structures, 203, pp. 917–926.
110. Min, S., Chen, X., Chai, Y., Lowe, T.,2016, *Effect of reinforcement continuity on the ballistic performance of composites reinforced with multiply plain weave fabric*, Composites Part B: Engineering, 90, pp. 30–36.
111. Karthikeyan, K., Russell, BP., 2014, *Polyethylene ballistic laminates: Failure mechanics and interface effect*, Materials & Design, 63, pp. 115–125.
112. Chen, X., Zhou, Y., Wells, G., 2014, *Numerical and experimental investigations into ballistic performance of hybrid fabric panels*, Composites Part B: Engineering, 58, pp. 35–42.
113. Claus, J., Santos, R.A., Gorbatikh, L., Swolfs, Y., 2020, *Effect of matrix and fibre type on the impact resistance of woven composites*, Composites Part B: Engineering, 183, 107736.
114. da Silva Chagas, N.P., de Oliveira Aguiar, V., da Costa Garcia Filho, F., da Silva Figueiredo, A.B.H., Monteiro, S.N., Huaman, N.R.C., Marques, M.D.F.V., 2022, *Ballistic performance of boron carbide nanoparticles reinforced ultra-high molecular weight polyethylene (UHMWPE),* Journal of Materials Research and Technology, 17, pp. 1799–1811.
115. Sharma, S., Dhakate, S.R., Majumdar, A., Singh, B.P., 2019, *Improved static and dynamic mechanical properties of multiscale bucky paper interleaved Kevlar fiber composites*, Carbon, 152, pp. 631–642.
116. Arora, S., Majumdar, A., Butola, B.S., 2020, *Deciphering the structure-induced impact response of ZnO nanorod grafted UHMWPE woven fabrics*, Thin-Walled Structures, 156, pp. 106991.
117. Chatterjee, V.A., Verma, S.K., Bhattacharjee, D., Biswas, I., Neogi, S.,2019, *Enhancement of energy absorption by incorporation of shear thickening fluids in 3D-mat sandwich composite panels upon ballistic impact*, Composite Structures, 225, 111148.
118. Gopinath, G., Zheng, J.Q., Batra, R.C., 2012, *Effect of matrix on ballistic performance of soft body armor,* Compos Struct, 94(9), pp. 2690–2696.
119. Sapozhnikov, S., Kudryavtsev, O., 2015, *Modeling of Thermoplastic Composites in Protective Structures*, Mechanics of Composite Materials, 51, pp. 419–426.
120. Oladele, I.O., Onuh, L.N., Siengchin, S., Sanjay, M.R., Adelani, S.O., 2023, *Modern Applications of Polymer Composites in Structural Industries:A Review of Philosophies, Product Development, and Graphical Applications*, Applied Science and Engineering Progress, 17(1), 6884.
121. Han, F., Zhang, Y., Wang, C., Wang, Z., Yue, H., Zong, L., Wang, J., Jian, X., 2023, *Analysis of ballistic performance and penetration damage mechanisms of aramid woven fabric reinforced polycarbonate composites with different matrix content,* Chemical Engineering Journal, 453, 139470.
122. Mahesh, V., Joladarashi, S., Kulkarni, S.M., 2021, *A comprehensive review on material selection for polymer matrix composites subjected to impact load*, Defence Technology, 17(1), pp. 257–277.
123. Evci, C., 2015, *Thickness-dependent energy dissipation of laminated composites subjected to low velocity impact*, Composite Structures, 133, pp. 508–521.
124. Mulage, K.S., Mishra, A.K., Patkar, R.N., Kharat, S.H., Khanna, P.K., Kakade, S.D., 2012, *Effect of Ballistic Modifiers on the burn rate of extruded composite propellant formulations based on Thermoplastic elastomeric binder*, International Journal of Energetic Materials and Chemical Propulsion, 11(4), pp. 375–388.
125. Khaire, N., Tiwari, G., 2023, *Ballistic response of sandwich shell panels: A comparative study,* International Journal of Impact Engineering, 176, 104548.
126. Mohan Kumar, T.S., Joladarashi, S., Kulkarni, S.M., Doddamani, S. 2023, *Optimization of process parameters for ballistic impact response of hybrid sandwich composites,* International Journal on Interactive Design and Manufacturing (IJIDeM), 17(3), pp. 1099–1111.
127. Ding, Y., Liu, J., Hall, Z.E., Brooks, R.A., Liu, H., Kinloch, A.J., Dear, J.P., 2023, *Damage and energy absorption behaviour of composite laminates under impact loading using different impactor geometries*, Composite Structures, 321, 117259.
128. Dundi, R.K., Amin, P.N., Mathivanan, N.R., 2023, *Analysis of factors influencing absorbed energy in CFRP and Kevlar hybrid laminate subjected to low-velocity impact*, Australian Journal of Multi-Disciplinary Engineering, 19(1), pp. 1–9.
129. Reddy, T.S., Mogulanna, K., Reddy, K.G., Reddy, P.R.S., Madhu, V., 2019, *Effect of thickness on behaviour of E-glass/epoxy composite laminates under low velocity impact*, Procedia Structural Integrity, 14, pp. 265–272.
130. Deng, Y., Wang, Y., Cai, X., Du, J., Wei, G., 2023, *Influence of thickness on impact resistance of glass fiber woven composite laminates*, Journal of Applied Polymer Science, 140(27), e53791.

131. Nunes, S.G., Scazzosi, R., Manes, A., Amico, S.C., de Amorim Júnior, W.F., Giglio, M., 2019, *Influence of projectile and thickness on the ballistic behavior of aramid composites: Experimental and numerical study*, International Journal of Impact Engineering, 132, 103307.

132. Senthil Kumar, M.S., Rajeshkumar, L., Rangappa, S.M., Siengchin, S., 2024, *Mechanical behaviour analysis for banana/coir natural fiber hybrid epoxy composites through experimental modelling*, Journal of Polymer Research, *31*(6), 163.

133. Quaresimin, M., Ricotta, M., Martello, L., Mian, S., 2013, *Energy absorption in composite laminates under impact loading*, Composites Part B: Engineering, 44(1), pp. 133–140.

134. De Morais, W.A., Monteiro, S.N., d'Almeida, J.R.M., 2005, *Evaluation of repeated low energy impact damage in carbon–epoxy composite materials*, Composite Structures, 67(3), pp. 307–315.

135. Braga, F.D.O., Lima, É.P., Lima, E.D.S., Monteiro, S.N.,2017, *The effect of thickness on aramid fabric laminates subjected to 7.62 mm ammunition ballistic impact,* Materials Research, 20, pp. 676–680.

136. Nguyen, L.H., Ryan, S., Cimpoeru, S.J., Mouritz, A.P., Orifici, A.C., 2015, *The effect of target thickness on the ballistic performance of ultra-high molecular weight polyethylene composite*, International Journal of Impact Engineering, 75, pp. 174–183.

137. Naik, N.K., Doshi, A.V., 2008, *Ballistic impact behaviour of thick composites: Parametric studies*, Composite structures, 82(3), pp. 447–464.

138. Naik, N.K., Shrirao, P., Reddy, B.C.K., 2005, *Ballistic impact behaviour of woven fabric composites: Parametric studies*, Materials Science and Engineering: A, 412(1-2), pp. 104–116.

139. Chen, W., Hudspeth, M., Guo, Z., Lim, B.H., Horner, S., Zheng, J.Q., 2017. *Multi-scale experiments on soft body armors under projectile normal impact,* International Journal of Impact Engineering, 108, pp.63-72.

140. Garcia-Castillo, S.K., Sánchez-Sáez, S., Barbero, E., 2012, *Influence of areal density on the energy absorbed by thin composite plates subjected to high-velocity impacts*, Journal of Strain Analysis for Engineering Design, 47(7), pp. 444–452.

141. Alonso, L., Navarro, C., García-Castillo, S.K., 2019, *Experimental study of woven-laminates structures subjected to high-velocity impact*, Mechanics of Advanced Materials and Structures, 26(12), pp. 1001–1007.

142. Cantwell, WJ., Morton, J., 1990, *Impact perforation of carbon fibre reinforced plastic*, Composites science and technology, 38(2), pp. 119–141.

143. Ulven, C., Vaidya, U.K., Hosur, M.V., 2003, *Effect of projectile shape during ballistic perforation of VARTM carbon/epoxy composite panels*, Composite structures, 61(1-2), pp. 143–150.

144. Reddy, P.R.S., Reddy, T.S., Srikanth, I., Kushwaha, J., Madhu, V., 2020, *Development of cost-effective personnel armour through structural hybridization,* Defence Technology, 16(6), pp. 1089–1097.

145. Ali, A., Adawiyah, R., Rassiah, K., Ng, W.K., Arifin, F., Othman, F., Hazin, M.S., Faidzi, M.K., Abdullah, M.F., Ahmad, M.M.,2019, *Ballistic impact properties of woven bamboo- woven E-glass- unsaturated polyester hybrid composites,* Defence Technology, 15(3), pp. 282–294.

146. Zhu, L., Gao, W., Dikin, D.A., Percec, S., Ren, F., 2023, *Anti-Ballistic Performance of PPTA/UHMWPE Laminates*, Polymers (Basel), 15(10), 2281.

147. Yang, Y., Ling, T., Liu, Y., Xue, S., 2021, *Synergistic effect of hybrid ballistic soft armour panels*, Composite Structures, 272, 114211.

148. Barhoumi, H., Bhouri, N., Feki, I., Baffoun, A., Hamdaoui, M., Ben Abdessalem, S., 2023, *Review of ballistic protection materials: Properties and performances*, Journal of Reinforced Plastics and Composites, 42(13-14), pp. 685–699.

149. He, Y., Min, S., Chen, S., Wang, J., Wang, Z., Zhou, Y., 2023, *Effect of Z-binding depths on the ballistic performance of 3D woven through-the-thickness angle-interlock fabrics*, Journal of Industrial Textiles, 53, https://doi.org/10.1177/15280837231188528.

150. Yang, Y., Chen, X., 2017, *Investigation of failure modes and influence on ballistic performance of Ultra-High Molecular Weight Polyethylene (UHMWPE) uni-directional laminate for hybrid design*, Composite Structures, 174, pp. 233–243.

151. *Ballistic Resistance of Body Armor NIJ Standard-0101.06,* National Institute of Justice, https, pp.//nij.ojp.gov/library/publications/ballistic-resistance-body-armor-nij-standard-010106 (Last access 7 August 2023).

152. Berrouane, A., Derradji, M., Khiari, K., Amri, B., Mehelli, O., Abdous, S., Zegaoui, A., Ramdani, N., Belgacemi, R., Liu, W., 2023, *New strategy for the development of lightweight ballistic armors with limited backface signature*, High Performance Polymers, 35(5), pp. 533–544.

153. Xie, Y.C., Zhang, H., Zhu, W., Huang, G.Y., 2022, *Effects of textile structure and projectile geometry on ballistic performance of UHMWPE textiles*, Composite Structures, 279, 114785.

154. Abtew, M.A., Boussu, F., Bruniaux, P., Loghin, C., Cristian, I., 2019, *Engineering of 3D warp interlock p-aramid fabric structure and its energy absorption capabilities against ballistic impact for body armour applications*, Composite Structures, 225, 111179.

155. Carrillo, J.G., Gamboa, R.A., Flores-Johnson, E.A., Gonzalez-Chi, P.I., 2012, *Ballistic performance of thermoplastic composite laminates made from aramid woven fabric and polypropylene matrix*, Polymer Testing, 31(4), pp. 512–519.
156. Karahan, M., Jabbar, A., Karahan, N., 2015, *Ballistic impact behavior of the aramid and ultra-high molecular weight polyethylene composites*, Journal of Reinforced Plastics and Composites, 34(1), pp. 37–48.
157. Haris, A., Tan, V.B.C., 2021, *Effects of spacing and ply blocking on the ballistic resistance of UHMWPE laminates*, International Journal of Impact Engineering, 151, 103824.
158. Tan, V.B.C., Lim, C.T., Cheong, C.H., 2003, *Perforation of high-strength fabric by projectiles of different geometry*, International Journal of Impact Engineering, 28(2), pp. 207–222.
159. Ma, Y., Dippolito, M., Miao, Y., Wang, Y., 2021. *A filament-level analysis on failure mechanism and ballistic limit of real-size multi-layer 2D woven fabrics under FSP impact*, Textile Research Journal, 91(23-24), pp.2896-2910.
160. Gu, B., 2003, *Analytical modeling for the ballistic perforation of planar plain-woven fabric target by projectile*, Composites Part B: Engineering, 34(4), pp. 361–371.
161. Pasquali, M., Terra, C., Gaudenzi, P., 2015, *Analytical modelling of high-velocity impacts on thin woven fabric composite targets*, Composite Structures, 131, pp. 951–965.
162. Naik, N.K., Doshi, A.V., 2005, *Ballistic Impact Behavior of Thick Composites: Analytical Formulation*, AIAA Journal, 43(7), pp. 1525–1536.
163. Naik, N.K., Shrirao, P., Reddy, B.C.K., 2006, *Ballistic impact behaviour of woven fabric composites: Formulation*, International Journal of Impact Engineering, 32(9), pp. 1521–1552.
164. Langston, T., 2017, *An analytical model for the ballistic performance of ultra-high molecular weight polyethylene composites*, Composite Structures, 179, pp. 245–257.
165. Shanazari, H., Liaghat, G.H., Hadavinia, H., Aboutorabi, A., 2017, *Analytical investigation of high-velocity impact on hybrid unidirectional/woven composite panels*, Journal of Thermoplastic Composite Materials, 30(4), pp. 545–563.
166. Alonso, L., Navarro, C., García-Castillo, S.K.,2018, *Analytical models for the perforation of thick and thin thickness woven-laminates subjected to high-velocity impact*, Composites Part B: Engineering, 143, pp. 292–300.
167. Bresciani, L.M., Manes, A., Giglio, M., 2015, *An analytical model for ballistic impacts against plain-woven fabrics with a polymeric matrix*, International Journal of Impact Engineering, 78, pp. 138–149.
168. Choudhury, S., Yerramalli, C.S., Guha, A., 2023, *Analytical modeling of the ballistic impact performance of glass fabric - epoxy composites at low temperatures*, International Journal of Impact Engineering, 176, pp. 104565.
169. Pirvu, C., Musteata, A.E., Ojoc, G.G., Sandu, S., Deleanu, L., 2019, *A Meso Level FE Model for the Impact Bullet – Yarn*, Materiale Plastice, 56(1), pp. 22–31.
170. Ma, P., Jin, L., Wu, L., 2019, *Experimental and numerical comparisons of ballistic impact behaviors between 3D angle-interlock woven fabric and its reinforced composite*, Journal of Industrial Textiles, 48(6), pp. 1044–1058.
171. Ul Haq, A., Kumar Reddy Narala, S., 2023, *Dynamic response of honeycomb cored sandwich panels under high velocity impact: A numerical study*, Materials Today Proceedings, https://doi.org/10.1016/j.matpr.2023.03.106.
172. Nilakantan, G., Keefe, M., Bogetti, T.A., Adkinson, R., Gillespie Jr, J.W., 2010, *On the finite element analysis of woven fabric impact using multiscale modeling techniques*, International Journal of Solids and Structures, 47(17), pp. 2300–2315.
173. Nilakantan, G., Keefe, M., Bogetti, T.A., Gillespie Jr, J.W., 2010, *Multiscale modeling of the impact of textile fabrics based on hybrid element analysis*, International Journal of Impact Engineering, 37(10), pp. 1056–1071.
174. Grujicic, M., Hariharan, A., Pandurangan, B., Yen, C.F., Cheeseman, B.A., Wang, Y., Miao, Y., Zheng, J.Q., 2012, *Fiber-Level Modeling of Dynamic Strength of Kevlar® KM2 Ballistic Fabric*, Journal of Materials Engineering and Performance, 21, pp. 1107–1119.
175. Oliveira, M.S., da Costa Garcia Filho, F., Pereira, A.C., Nunes, L.F., da Luz, F.S., de Oliveira Braga, F., Colorado, H.A., Monteiro, S.N., 2019, *Ballistic performance and statistical evaluation of multilayered armor with epoxy-fique fabric composites using the Weibull analysis*, Journal of Materials Research and Technology, 8(6), pp. 5899-5908.
176. Nilakantan, G., 2013, *Filament-level modeling of Kevlar KM2 yarns for ballistic impact studies*, Composite Structures, 104, pp. 1–13.
177. Gopinath, G., Batra, R.C., 2022, *Finite element method based micromechanical methodology for homogenizing fiber/fabrics-reinforced composites and their progressive failure*, Composite Structures, 286, 115279.
178. Zhu, W., Liu, J., Wei, X., 2021, *A multiscale model for the prediction of ballistic performance of fiber-reinforced composites*, International Journal of Impact Engineering, 154, 103889.
179. Kędzierski, P., Popławski, A., Gieleta, R., Morka, A., Sławiński, G., 2015, *Experimental and numerical investigation of fabric impact behavior*, Composites Part B: Engineering, 69, pp. 452–459.
180. Bao, J.W., Wang, Y.W., An, R., Cheng, H.W., Wang, F.C., 2022, *Investigation of the mechanical and ballistic properties of hybrid carbon/ aramid woven laminates*, Defence Technology, 18(10), pp. 1822–1833.

181. Nayak, S.Y., Sultan, M.T.H., Shenoy, S.B., Kini, C.R., Samant, R., Shah, A.U.M., Amuthakkannan, P., 2020, *Potential of Natural Fibers in Composites for Ballistic Applications–A Review,* Journal of Natural Fibers, 19(5), pp. 1648-1658.
182. Nascimento, L.F.C., Louro, L.H.L., Monteiro, S.N., Gomes, A.V., Júnior, É.P.L., Marçal, R.L.S.B., 2017, *Ballistic Performance in Multilayer Armor with Epoxy Composite Reinforced with Malva Fibers,* Proceedings of the 3rd Pan American materials congress, The Minerals, Metals & Materials Series. Springer-Cham., pp. 331–338.
183. Monteiro, S.N., Pereira, A.C., Ferreira, C.L., Pereira Júnior, É., Weber, R.P., Assis, F.S.D., 2018, *Performance of Plain-Woven Jute Fabric-Reinforced Polyester Matrix Composite in Multilayered Ballistic System,* Polymers (Basel), 10(3), 230.
184. de Assis, F.S., Pereira, A.C., da Costa Garcia Filho, F., Lima Jr, E.P., Monteiro, S.N., Weber, R.P., 2018, *Performance of jute non-woven mat reinforced polyester matrix composite in multilayered armor,* Journal of Materials Research and Technology, 7(4), pp.535-540.
185. Garcia, Filho F.D.C., Monteiro, S.N., 2019, *Piassava Fiber as an Epoxy Matrix Composite Reinforcement for Ballistic Armor Applications,* JOM, 71, pp. 801–808.
186. Pereira, A.C., de Assis, F.S., da Costa Garcia Filho, F., Oliveira, M.S., da Cruz Demosthenes, L.C., Lopera, H.A.C., Monteiro, S.N., 2019, *Ballistic performance of multilayered armor with intermediate polyester composite reinforced with fique natural fabric and fibers*, Journal of Materials Research and Technology, 8(5), pp.4221-4226.
187. Jambari, S., Yahya, M.Y., Abdullah, M.R., Jawaid, M., 2017, *Woven Kenaf/Kevlar Hybrid Yarn as potential fiber reinforced for anti-ballistic composite material,* Fibers and Polymers, 18, pp. 563–568.
188. Pereira, A.C., Monteiro, S.N., de Assis, F.S., Margem, F.M., da Luz, F.S., de Oliveira Braga, F., 2017, *Charpy impact tenacity of epoxy matrix composites with aligned jute fibers,* Journal of Materials Research and Technology, 6(4), pp. 312–316.
189. Oliveira, M.S., Pereira, A.C., da Costa Garcia Filho, F., da Luz, F.S., de Oliveira Braga, F., Nascimento, L.F.C., Lima, É.P., da Cruz Demosthenes, L.C., Monteiro, S.N., 2019, *Fique Fiber-Reinforced Epoxy Composite for Ballistic Armor Against 7.62 mm Ammunition,* Green Materials Engineering: An EPD Symposium in Honor of Sergio Monteiro, Springer-Cham., pp. 193–199.
190. Neves Monteiro, S., de Oliveira Braga, F., Pereira Lima, E., Henrique Leme Louro, L., Wieslaw Drelich, J., 2017, *Promising curaua fiber-reinforced polyester composite for high-impact ballistic multilayered armor,* Polymer Engineering & Science, 57(9), pp.947-954.
191. de Oliveira Braga, F., Bolzan, L.T., da Luz, F.S., Lopes, P.H.L.M., Lima Jr, É.P. and Monteiro, S.N., 2017, *High energy ballistic and fracture comparison between multilayered armor systems using non-woven curaua fabric composites and aramid laminates,* Journal of Materials Research and Technology, 6(4), pp.417-422.
192. Pereira, A.C., Assis, F.S.D., Garcia Filho, F.D.C., Oliveira, M.S., Lima, E.S., Lopera, H.A.C., Monteiro, S.N., 2019, *Evaluation of the Projectile's loss of Energy in Polyester Composite Reinforced with Fique Fiber and Fabric,* Materials Research, 22, e20190146.
193. Wambua, P., Vangrimde, B., Lomov, S., Verpoest, I., 2007, *The response of natural fiber composites to ballistic impact by fragment simulating projectiles,* Composite Structures, 77(2), pp. 232–240.
194. Haro, EE., Szpunar, JA., Odeshi, AG., 2018, *Dynamic and ballistic impact behavior of biocomposite armors made of HDPE reinforced with chonta palm wood (Bactris gasipaes) microparticles,* Defence Technology, 14(3), pp. 238–249.
195. Batra, R.C., Gopinath, G., Zheng, J.Q., 2012, *Damage and failure in low energy impact of fiber-reinforced polymeric composite laminates,* Composite Structures, 94(2), pp. 540–547.
196. Pham, Q.H., Ha-Minh, C., Chu, T.L., Kanit, T., Imad, A., 2022, *Numerical investigation of fibre failure mechanisms of one single Kevlar yarn under ballistic impact,* International Journal of Solids and Structures, *239*, 111436.
197. Pandya, K.S., Kumar, C.V.S., Nair, N.S., Patil, P.S., Naik, N.K., 2015, *Analytical and experimental studies on ballistic impact behavior of 2D woven fabric composites,* International Journal of Damage Mechanics, 24(4), pp. 471-511.
198. da Silva, A.O., de Castro Monsores, K.G., Oliveira, S.D.S.A., Weber, R.P., Monteiro, S.N., 2018, *Ballistic behavior of a hybrid composite reinforced with curaua and aramid fabric subjected to ultraviolet radiation,* Journal of Materials Research and Technology, 7(4), pp.584-591.
199. Goda, I., Girardot, J., 2021, *A computational framework for energy absorption and damage assessment of laminated composites under ballistic impact and new insights into target parameters,* Aerospace Science and Technology, 115, 106835.
200. Bouvet, C., Hongkarnjanakul, N., Rivallant, S., Barrau, J.J., 2013. *Discrete impact modeling of inter-and intra-laminar failure in composites,* In: Abrate, S., Castanié, B., Rajapakse, Y. (eds), Dynamic failure of composite and sandwich structures, Springer, Dordrecht, 192, pp. 339-392.

201. Tiwari, G., Khaire, N., 2022, *Ballistic performance and energy dissipation characteristics of cylindrical honeycomb sandwich structure*, International Journal of Impact Engineering, 160, 104065.
202. Wu, W., 2023, *Tensile Failure Behaviors and Theories of Carbon/Glass Hybrid Interlayer and Intralayer Composites,* Coatings, 13(4), 774.
203. Li, Y., Fan, H., Gao, X.L., 2022, *Ballistic helmets:Recent advances in materials, protection mechanisms, performance, and head injury mitigation*, Composites Part B: Engineering, 238, 109890.
204. Bogetti, T.A., Walter, M., Staniszewski, J., Cline, J., 2017, *Interlaminar shear characterization of ultra-high molecular weight polyethylene (UHMWPE) composite laminates*, Composites Part A: Applied Science and Manufacturing, 98, pp. 105–115.
205. Xiang, Y., Zhang, Z., Yang, X., Lin, Y., Zhang, G., Sun, M., Yan, F., Wang, M., 2022, *Failure mechanism of carbon/ultra-high molecular weight polyethylene twill fiber reinforced hybrid laminates under ballistic impact*, Materials & Design, 216, pp. 110578.
206. Nitin, MS., Suresh Kumar, S., 2022, *Ballistic performance of synergistically toughened Kevlar/epoxy composite targets reinforced with multiwalled carbon nanotubes/graphene nanofillers,* Polymer Composites, 43(2), pp. 782-797.