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# New Textile Composite Solutions for Armouring of Vehicles

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As a fibre reinforcement for composite materials, 3D woven structures like 3D warp interlock fabric have drawn a lot of attention in recent studies because they can have a greater impact than 2D laminated textiles with unlinked structures in the thickness. The projectile's shape and speed, the type of fibrous structure (geometry), the type and nature of the threads (raw material, linear density, and twisting value), and the type of impregnation of the composite material are all separate factors that affect the capacity to absorb impact energy. The attraction of textile composite structures, particularly those including 3D warp interlock textiles, has been discovered as part of our research on hard impact protection solutions. Based on the findings, protection solutions with this fabric structure had a higher dynamic deformation capacity for absorbing impact energy than those made with metallic materials when facing an FSP (diameter 20 mm, mass 54 g) at 630 m/s and 1600 m/s. This is in contrast to ceramic materials facing 12.7 mm ammunition (mass 43 g) at 610 m/s and solutions made with ceramic materials facing 12.7 mm ammunition (mass 43 g) at 610 There must be a specific kind of composite material employed for each of these hazards. The fundamental purpose of these composite material solutions is to react to the proper mode of impact behaviour.

## 1. Introduction

The modelling and simulation of the formation of 3D warp interlock fabrics has been the subject of numerous research works [1–5], as well as the characterization of geometrical and mechanical properties [6–12]. Several research investigations have also indicated that impact behaviour is where they are most interested [13–26]. In fact, the starting velocity of the projectile has a significant impact on the mode of dynamic behaviour of the fibrous structure in the composite material. The fabric offers essentially no projectile resistance when the material's deformation rate exceeds its reaction capacity for a brief period of time, and a shear-like failure mode in the thickness develops as a result.

Due to the various impact resistance influencing factors, including the projectile's shape and speed, the type of fibrous structure (geometry), the type and nature of the yarns (raw material, titration, and torsion), and the type of impregnation, it may be difficult to determine the velocity threshold of the fibrous material within a composite material subjected to an impact.

It is also noticed that the 3D warp interlock fabrics have technical and economic advantages over other reinforcements which could replace laminates in applications where they are no longer suitable [9, 10, 12, 14, 17, 23, 27–29].

However, the fabric has also exhibited some disadvantages while manufacturing and specific architecture designing [30–33].

Based on our and different research results, a dedicated section has been added in this paper in order to highlight all the advantages and disadvantages of the mentioned fabrics [8, 15, 16, 34, 35]. Based on the review, it is now possible to identify the advantages and disadvantages of not only the manufacturing process but also the architecture of the 3D warp interlock fabrics which correspond to a large number of possibilities of assembly of warp and weft yarns [36]. Moreover, detailed experimental observations on 3D woven composites have also indicated that the fabric geometry plays a dominant role on their mechanical properties and associated failure mechanisms [22]. Based on these observations, one of the most interesting characteristics of 3D warp interlock fabrics remains the modularity of their

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architectures and the precise location of stuffer warp yarns inside the structure which leads to an optimal value of the mechanical properties [20].

A targeted bibliographic analysis complemented by our research [8, 15, 16, 34, 35] allowed us to cross check and confirm the results obtained on the mechanical properties of the 3D warp interlock fabrics. Due to their specific consolidation mode in the thickness, these structures have also interesting mechanical properties [37]. Moreover, 3D warp interlock fabrics increase resistance to delamination [38] and impact resistance [39]. Some research studies have also revealed improved properties of resistance to crack propagation, damage tolerance, and dimensional stability [40].

## 2. Definition of 3D Warp Interlock Fabric

Recently, our research work has provided a general definition of 3D warp interlock fabric in order to take into account all the endogenous parameters of the 3D woven structure [41]. To better introduce our different research results based on these 3D warp interlock fabrics, a short description and general representation of the main parameters will be outlined.

*Description of 3D Warp Interlock Fabric.* In general, theweaving process creates surfaces which are obtained by theperpendicular cross-linking of warp yarns (*X* axis) and weftyarns (*Y* axis) [42, 43]. According to the definition given bythe standard AFNOR NF G 00-001, a 2D fabric is a planar structure formed by the perpendicular cross-linking of twoperpendicular yarns performed on a weaving loom [44–46].However, a 3D warp interlock fabric is composed of several layers, which are linked in the thickness by binding warp yarns as represented in Figure 1.

*Main Parameters of 3D Warp Interlock Fabric.* Several yarn arrangements can be made, and they provide a large amount of 3D structure [21]. Like 2D fabrics, a 3D warp interlock fabric is a woven reinforcement that contains binding warp yarns not only in both directions of the plane (warp and weft) but also a third type of yarn evolving in the thickness which brings cohesion to the whole reinforcement. Unlike 2D fabrics which vary based on only weave diagram, the 3D warp interlock fabrics could offer different woven architectures based on several parameters including the number of layers, type of binding warp yarns, type of stuffer warp yarns, etc. It can be also observed that the 3D warp interlock fabric is reinforced in 3 directions by which each group of threads ensures a precise function within the structure [35]. The schematic representation of a 3D warp interlock structure (Figure 2) illustrates the role of each yarninvolved in its architecture [47].

(1) The surface warp yarns (weaver surface) are integrated in the woven structure when it requires a different aspect of each face of the fabric with a more or less precise roughness. These threads have

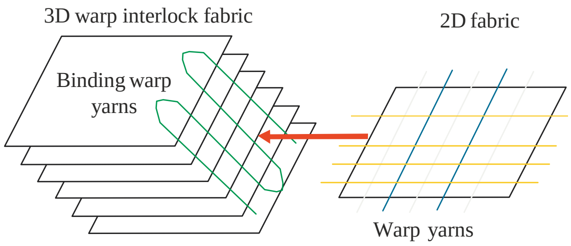


Figure 1: Geometric view of multilayer woven structures linkedinto the thickness by binding warp yarn.

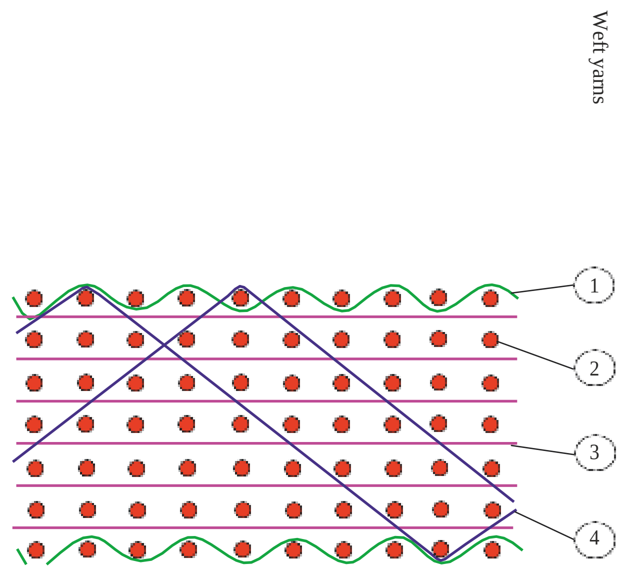


Figure 2: Schematic view of a 3D warp interlock fabric.

no great influence on the mechanical properties of the fabric; they have rather an “aesthetic” role.

(2) The weft yarns are perpendicular to the warp yarns and inserted at each shedding operation on a weaving machine. These yarns determine the number of layers of the 3D warp interlock structure and contribute essentially to the transverse me- chanical properties of the multilayered fabric.

(3) The binding warp yarns can bind the different layers of the fabric in the thickness. These yarns essentially contribute to maintain the cohesion of the whole woven structure with respect to their density in the multilayer structure and thus provide interlaminar resistance.

(4) The stuffer warp yarns are also positioned on the weaving machine and contribute to the longitudinal mechanical properties of the multilayer fabrics.

## 3. Advantages/Disadvantages of 3D WarpInterlock Fabrics

Based on the different parameters which define a 3D warp interlock fabric, several research papers have found some specific mechanical properties and highlight their advan- tages and disadvantages compared to other textile structures.

*Advantages of 3D Warp Interlock Fabrics.* As pointed out by Tong et al. [21], we also confirm that high perfor- mance yarns can be inserted into these multilayer woven structures without any major degradation using appropriate process parameters and loom devices. The insertion could also be made more easier as weft yarn and/or reinforcing warp yarn are straightly located into the textile structure and help increase the strength in the two directions of the 3D warp interlock fabric. These same authors also emphasize the ease of implementation of a 3D fibrous reinforcement to form a composite material inside a mould [21] due mainly to their monolithic, compacted, and integrated architecture [23, 48]. In 3D warp interlock fabrics, the layers are interconnected by binding warp yarns and thus provide a stronger cohesion, which allows to directly produce a thick reinforcement [22]. No set of fine reinforcements is then necessary to assemble together [49] while maintaining the ability to transit the resin more rapidly than in 2D fabrics of equivalent thickness [50]. In addition, several authors have also highlighted the possibility of making complex preforms close to the shapes of the final piece (near-net shape) [20] from 3D warp interlock fabrics, minimizing cutting and assembly needed for 2D fabric folds [21]. This helps to reduce the cost of materials and labour time [51] but also avoids using the vacuum resin impregnation process [29, 52] using thermoplastic yarns [53]. In addition, the possibility of making 3D warp interlocks fabrics using more or less adapted "traditional" weaving machines makes their production inexpensive compared to other technologies for manufacturing complex 3D structures [36].

According to several studies on 3D warp interlock architecture [10, 47, 54], the presence and control [23] of a binding warp yarn (from 1 to 30% by volume) [50] ensure better mechanical properties of the 3D woven structures compared to the 2D stitched fabrics not only in the plane of the structure but also by the increase of the rigidity properties and tenacity in the thickness [55].

Depending on the architecture and the evolution of binding warp yarns, different internal behaviours can be observed [56]. The surface warp yarns of the 3D warp interlock fabric provide a protective skin and play an important role in the evolution of the damage [57]; on the other hand, it makes them noticeably more sensible to damage compared to metal alloy laminates [58].

Similarly, the 3D warp interlock fabrics can be characterized by their greater ease and efficiency to apply within a mould because of their initial 3D shape and cohesion in thickness during draping, which will result a better surface quality of the woven preform [29]. The forming behaviour of the 3D warp interlock fabrics has been also measured during our moulding and folding research tests [59, 60]. Finally, a symmetrical armour in the thickness to stabilize the internal consumption of yarns between them has been recommended [34]. Such conclusions were also verified during the design of 3D warp interlock structures in terms of distribution of dynamic constraints resulting from a ballistic impact.

Binding in the thickness of the 3D warp interlock fabrics provides additional consolidation [61] to the different scales of the woven structure: at the local level, by interlacing the warp yarns with the reinforcing warp and weft threads of fabric layers together, and at the global level, by maintaining the cohesion between the layers of the 3D woven structure.

*Delamination Resistance Property*. In many studies [20–23], the delamination resistance of 3D woven structures is ensured by reinforcement in the thickness particularly through binding warp yarns.

The delamination resistance of the 3D warp interlock fabrics could be decomposed on a macroscopic scale for the woven structure and on a mesoscopic scale for the yarns. On the macroscopic scale, the failure mode can be decomposed into tension in the direction of the thickness (main stress of the binding warp yarns between the layers) and into type II mode shear between fabric layers (propagation of the main stress given by the binding warp yarns to the different fabric layers). At the mesoscopic scale, the local mode of rupture can be linked to plane shear at the cross-linking point where the binding warp yarns and the reinforcement warp threads of each fabric are interlaced (local loading of the warp and weft yarns of each fabric independently).

In the work of Tong et al. [21], the delamination of 3D fabrics is characterized by the failure modes I (tearing of the binding yarns) and II (shear failure) in comparison with stacked and unbonded 2D fabrics in the thickness (Figure 3).

In the research study of Tong et al. [21], it has been also shown that the mode I resistance of the 3D warp interlock fabric is greater than that of the 2D fabrics delamination resistance. It has been also influenced mainly by the fibre content in the structure, the elastic modulus of the fibres, and their resistance to fracture. Thus, when the de- lamination begins to propagate between the composite plies, different areas can be observed. The first corresponds to the breaking of the binding warp yarns and the sepa- ration of the woven layers, whereas the second only rep- resents the separation of the woven layers without breaking of the binding warp yarns. Finally, the third would initiate the propagation of the crack between layers at a speed given by the resistance parameters of the binding warp yarns (Figure 4) [21].

However, depending on the geometry of the woven structure, the interlaminar shear behaviour shows the effi- ciency of the 3D warp interlock fabrics with angle type bonding with respect to other binding types and the reduction of delamination in type II rupture mode (Figure 5) [54].

*Impact Resistance Property*. According to various studies [20–26], 3D warp interlock fabric reinforced com- posite has got a great emphasis compared to 2D fabriclaminates for the impact resistance.

Based on our investigations, it is also found that the damaged area of the impact zone increases with the initial velocity more significantly in a UD-based composite than 3D warp interlock fabric composite as indicated in Figure 6 [20]. The results also confirmed that weaker damaged area was observed in 3D warp interlock fabric reinforcements and unidirectional laminates as compared to stacked 2D fabric reinforcements [62]. This leads to a higher impact damage tolerance of 3D structural composites compared to 2D laminate composites [63].

Besides, the ability of limiting the damage area has provided the 3D warp interlock fabric a better ballistic performance when subjected to multiple impacts [64–66].

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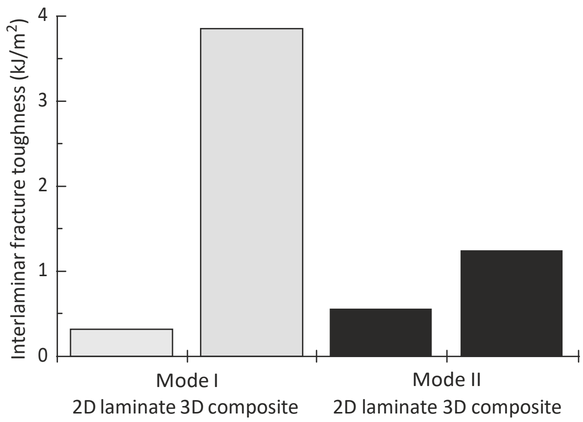



Figure 3: Interlaminar resistances at rupture modes I and II of composite materials made with stacked 2D fabrics and 3D warp interlock fabrics [21].

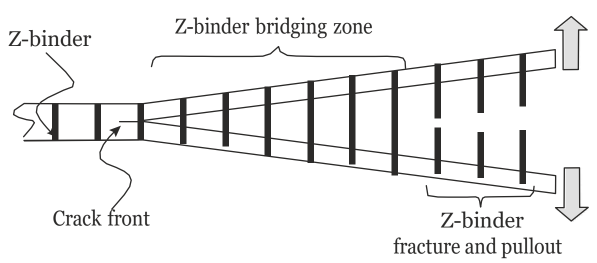



Figure 4: Yarn damage in the thickness during pull-out test of multilayer woven structure [21].

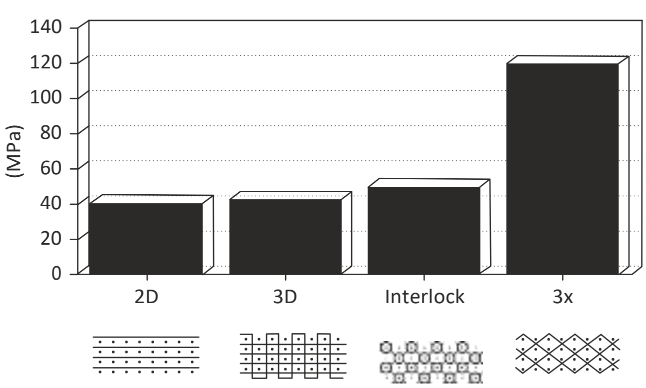



Figure 5: Influence of textile pattern on the interlaminar shearing tests for rupture mode type II [54].

This also confirms that the reinforcement in the thickness of a 3D material gives a better bending resistance after impact by decreasing the delamination and limiting the damage area due to the impact. Moreover, an increase of postimpact compressive strength has been observed for 3D warp interlock fabrics as compared to 2D fabrics (Figure 7) [21].

Textile composites are one of the current solutions used not only to respond to high-speed impact of vehicles from various types of projectiles, conventional or improvised, but also to minimize the total weight of the armour [67, 68]. The fibrous materials used in composite material must absorb

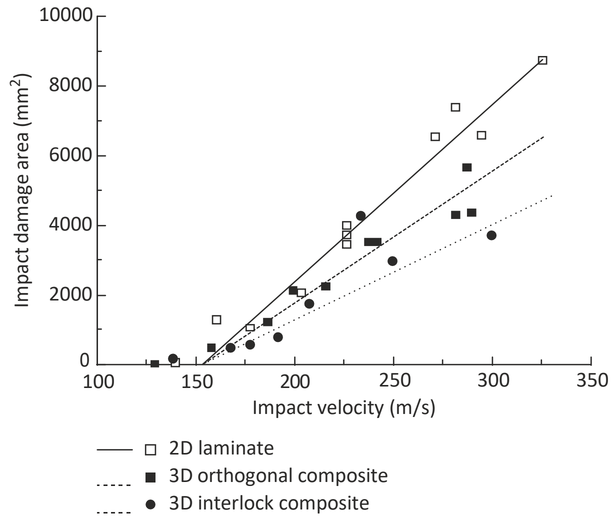



Figure 6: Influence of impact velocity on the damage surface of composite materials made with UD laminates and 3D warp interlock fabrics [20].

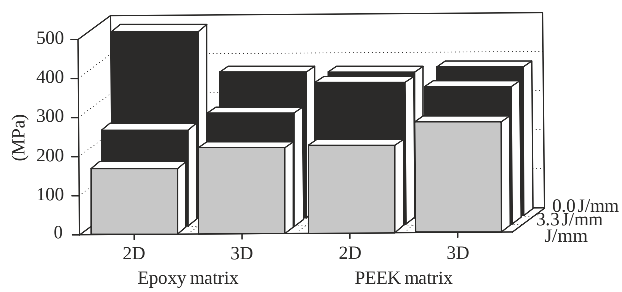



Figure 7: Influence of textile pattern and resin type on the compression stress before and after impact [54].

the integrity of the shielding protection solution through their damage.

In the prospective study of Madhu Bhat [69], the future combat tank armouring solutions will be composed of multimaterials including passive and/or active defence functions in front of various high-speed fragment and/or shock wave threats.

Thus, as part of our research, various composite textile some of the kinetic impact energy and allow and maintain solutions alone or along with ceramics or armoured steels have been proposed to high-speed perforating bullets or fragments (FSP) to impact response, such as perforating bullets or fragments at high speed.

Various research studies have also shown the interest of coupling different types of materials with different impact behaviours to provide a hard protection solution. For ex- ample, in the work of Naik et al. [70], an analytical model helps to understand the four different stages of a cylindrical projectile impact on a target composed from its front face to its rear face of the following:

(i) An E-glass fabric/epoxy composite layer to contain the ceramic debris generated during the impact

(ii) A layer of alumina ceramic tiles to absorb the kinetic energy of the projectile by its high value of stiffness

(iii) An ethylene propylene-diene elastomer layer for absorbing the shock wave transmitted during the contact between the projectile and the ceramic material

(iv) A layer of E-glass fabric/epoxy composite to permanently absorb the remaining kinetic energy of the projectile by its ability to deform upon impact

According to the study, the mechanisms of absorption of the kinetic energy of the projectile are mainly due to the punching resistance of the ceramic material and the dynamic tensile resistance of the composite material, located on the rear face. The insertion of an elastomer-type absorber material makes it possible to reduce the concentration of localized stresses at the impact point but induces non-homogeneous propagation of these stresses at the material interface [71].

Nayak et al. [72] have also studied the influence of additional layer located on the rear face of UD composite material, preimpregnated with para-aramid Twaron, on the very clear improvement of the ballistic performance of the 7.62 mm perforating ammunition (AP) to a layer of alumina ceramic reinforced with zirconium. The polypropylene resin-based para-aramid UD composite structure has resulted higher ballistic limit velocity values than for the same epoxy resin composite structure, mainly due to its more important elongation and delamination abilities.

In addition to previous work, Grogan et al. [17] showed the interest of 3D warp interlock woven structures, based on S2-glass yarns, inserted between layers of 2D fabrics, and positioned on the rear face of alumina ceramic tiles, submitted to the impact of armour-piercing ammunition type M2 AP at 925 m/s. Based on the postimpact target analyses, the control of delamination and the resulted lower penetrations have given better results for 3D warp interlock fabrics as compared to 2D woven structures alone.

The intradelamination of Dyneema HB26 high modulus polyethylene laminates which is consolidated at two pressure values (165 and 300 bars) was tested against a FSP with 20 mm diameter at 950 m/s according to the STANAG standard 2920 [73]. Based on these observations, the influence of the thickness of the adhesive ply between the two laminate layers on target performance shows a great effect, and the result leads to protection for a small thickness value and perforation for a higher value [74]. Similarly, Cheeseman and Bogetti [75] have also studied the postimpact behaviours of composite laminates. Based on their observations, the impact energy absorption mode is mainly composed of a shear behaviour in the thickness, localized in the direct contact zone between cylindrical projectile surface and laminated structure as well as a mode of intraply delamination type of laminates which is located outside the zone of contact with the projectile.

*Disadvantages of 3D Warp Interlock Fabrics.* During our research works [15, 34], the yarn damages mainly occurred not only during weaving [76] because of their yarn-to-yarn abrasion [58] and the high value of yarn's density but also during contacts between the yarn and other elements of the weaving loom due to their misalignment with warp yarns [31, 77]. This has been quantified by a criterion based on the loss of weight of material [78] throughout the manufacturing process [79]. Moreover, the main causes of this degradation [80] have also been identified. These control and evaluation methods allowed us not only to adapt our existing production tool and focus on design of our new production tools but also to minimize the effect of the manufacturing process on the degradation of yarns during weaving process.

The main disadvantages of the 3D warp interlock woven structures lie in their lack of production and especially not in sufficient quantities. Thus, it does not help to reduce the cost of manufacturing, and more precisely it wastes time during preparation and assembly on a weaving machine. This makes the 2D fabrics to be mainly used because of their lower cost for large quantities to produce as compared to the 3D warp interlock woven structures [34].

3D warp interlock fabrics have a lower value of fibre volume fraction than for 2D fabrics or UDs, this fraction does not exceed 55% [32], rarely reaching 60% [33]. Indeed, the vacuum zones, caused by the presence of binding warp yarns in the thickness, will be filled by the insertion of the resin during the manufacture of the composite.

The value of Young’s modulus can be reduced by 10 to 35% for some 3D preforms compared to 2D fabrics with a similar fibre ratio [21]. This reduction mainly comes from both warp yarns crimp and yarn damages during weaving process. However, these results cannot be generalized for all 3D structures. In fact, Young’s modulus can vary and surpass those of 2D fabrics by increasing the level of fibres in the woven structure (Figure 8) [21].

The compressive strength value before impact is lower for 3D warp interlock fabrics based composites than unidirectional laminate-based composites (Figure 9) [21]. Such decline comes from the yarns crimp and applied load on yarns in the thickness direction. The 3D warp interlock fabrics have a weak axial compression resistance due to the cross links between warp and weft yarns and the applied loads on yarns. The yarns then rotate under the action of the load until they become unstable and break. It is in- teresting to note that composites based on 3D warp in- terlock fabrics have a more important elastic behaviour in compression but withstand a lower load than composites based on 2D fabrics [21].

Thus, the fibre ratio in the direction of the thickness does not influence neither the tensile properties of the different 3D warp interlock fabrics nor compression and shear properties. For an equivalent fibre ratio, only the structural geometry seems to have an influence on the compression and shear properties. In addition, for different fibre levels (4 and 9%), the difference in mechanical properties was not significant [23].

The study of stacked 2D fabrics and two orthogonal binding types of 3D warp interlock fabrics demonstrated that the modulus and shear strength in the plane of the fabric have larger values for the stacked 2D fabric material and consequently for any other types of binding warp yarns inside the 3D warp interlock fabrics [81].

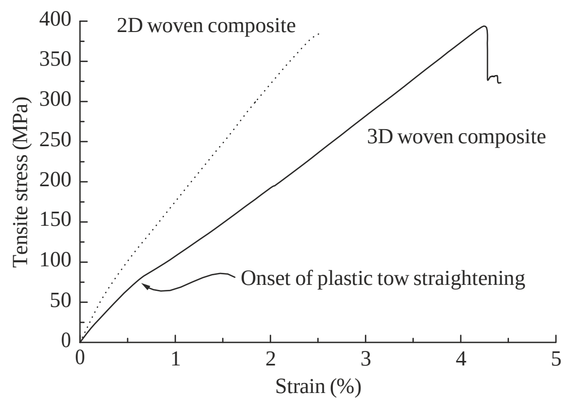



Figure 8: Comparison of tensile stress values versus elongation for composite materials made with 2D fabrics and 3D warp interlock fabrics [21].

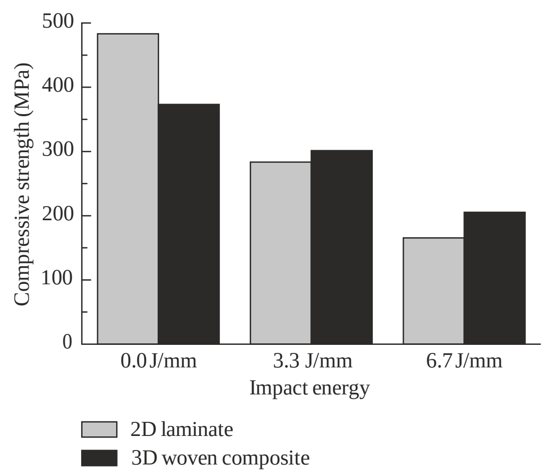



Figure 9: Comparison of compression resistance values before and after impacts of composite materials made with UD laminates and 3D warp interlock fabrics [21].

Thus, the introduction of binding warp yarn into the thickness of the multilayer woven structure provides strong anisotropic properties [23] and can reduce certain properties of the material, such as in-plane hardness, fatigue strength, in-plane Young's modulus, and tensile strength. The introduction of the binding warp yarn into the thickness must be done appropriately in order to limit the undulations [56], interfibre friction [58], and the applied tensions during weaving [82] as well as the loss of strength of the composite to fatigue [20].

## 4. Experimental Results on Protective Solutions

Taking into account all these main advantages and drawbacks of the 3D warp interlock fabrics, we have highlighted their interesting properties against impact and especially 12.7 mm ammunition [83, 84] and fragment simulating projectile (FSP) at different velocities [34, 35].

*Protective Solution against 12.7 mm Ammunition at 610 m/s.* Laminated structures, used as a backing solution of a high-resistance ceramic material in order to absorb the impact energy of a high-speed fragment (FSP) projectile, have been proposed by Hazell and Appleby-Thomas [85] and by Appleby-Thomas and Hazell [86]. In addition, they recommended paying particular attention to laminated structures bound in thickness whose impact behaviour can provide significant responses in terms of resistance to de- lamination. Thus, as part of our research [87–92], we used a 3D warp interlock fabric, as a fibrous reinforcement [93–95] to form successive layers of thermoplastic composite ma- terial and to substitute them for unidirectional laminates based on high modulus polyethylene films. This solution hasbeen successively patented [83, 84].

The impact behaviour of successive layers of composite materials can be decomposed into three stages (Figure 10) [96, 97], as already pointed out in various research works [98–101]. At first, the projectile perforates the target and causes a mode of fracture by punching and transverse shearing of the first ply A of the 3D warp interlock fabric composite, which initiates an overall deformation trans- mitted by a shock wave within the multilayer structure [102]. In the second step, the second ply B of the composite

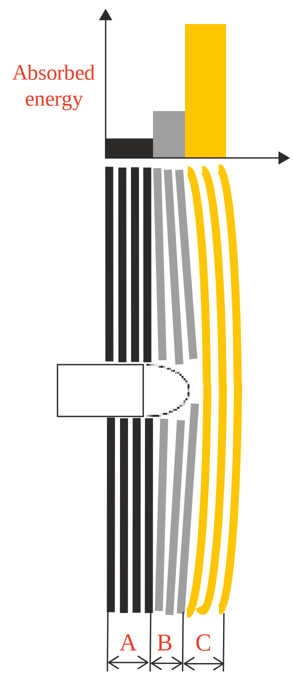



Figure 10: Decomposition of impact behaviour of the 3 plies A, B, and C of 3D warp interlock fabrics [93].

separates from the first ply A by delamination [103, 104] and thus consumes part of the impact energy of the projectile. The mode of rupture becomes a combination between the transverse shear and the dynamic tensile rupture of the inserted yarns in the different layers of the 3D warp interlock fabric. This generates a transmission of resulted impact waves in the direction perpendicular to the impact direction of the projectile, thereby promoting the dispersion zone in the direction of the warp and weft yarns, which increases the dynamic deformation value of the second composite ply B. Finally, the third and final ply C of the composite absorbs the remaining amount of projectile energy through its dynamic deformation, mainly due to the dynamic tensile strength and the elongation capacity of the warp and weft yarns inserted in the 3D warp interlock fabric [105].

Considering this impact behaviour mode, three composite targets have been made with $Al_2O_3$ alumina ceramic tiles coupled to three layers of textile composite based on 3D warp interlock fabric made with high modulus polyethylene yarns (Spectra 900) and low-density polyethylene yarns (Figure 11) [107, 108]. Each of these targets was subjected to a single impact of armour-piercing ammunition 12.7 mm (43 g) at 610 m/s according to MIL-PRF-46103-E Type III standard [106]. None of the impacted targets were perforated, and a maximum deformation depth of 25 mm in height was measured postmortem.

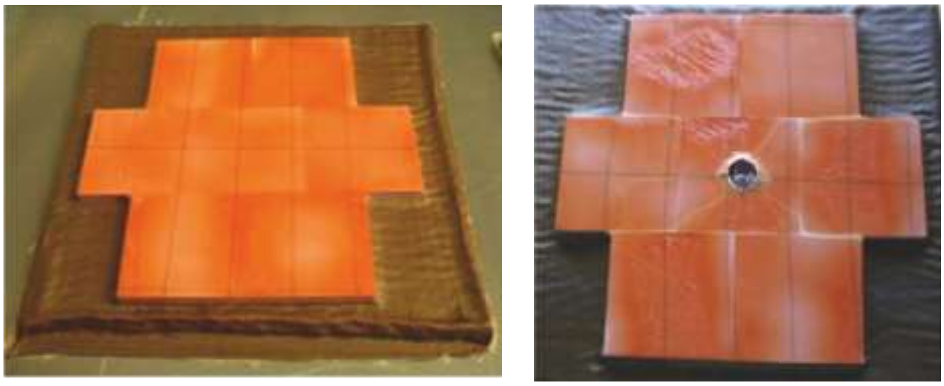
The cross-sectional comparison of the composite targets allowed us to observe their mode of deformation after impact. Thus, the delamination of the composite plies based on 3D warp interlock fabric (Figure 12(a)) [94, 95] and a resulted weight reduction of the target by 10%, for the same type of impact, compared to the highly degraded target based on high modulus polyethylene films can be shown (Figure 12(b)) [93].

*Protective Solution against FSP at 630°m/s.* Subsequently, as part of Lefebvre's research [34, 109, 110], we have studied the impact behaviour of different 3D woven patterns submitted to a FSP impact at 630 m/s according to standard STANAG 4569 [111]. The pro- tective solution was based on metallic material on the front side coupled with 3D warp interlock fabrics (made with para-aramid Kevlar yarns 29 (3,300 dtex) or Vectran Ar- omatic Polyester Yarn (2 1,650 dtex)) at the back side as shown in Figure 13.

In this study, three different combinations of composite materials based on two types of yarns, such as para-aramid Kevlar 29 (3,300 dtex) yarns and Vectran (2 1,650 dtex) aromatic polyester yarns, were produced. Two different infusion processes, namely, epoxy resin at 0.5 bar pressure for 3D warp interlock fabrics based on para-aramid thread Kevlar 29 (3,300 dtex) and at 1 bar pressure for 3D warp interlock fabrics made with Vectran aromatic polyester yarn (2 1,650 dtex), have been also applied as indicated in Figure 14 [112].

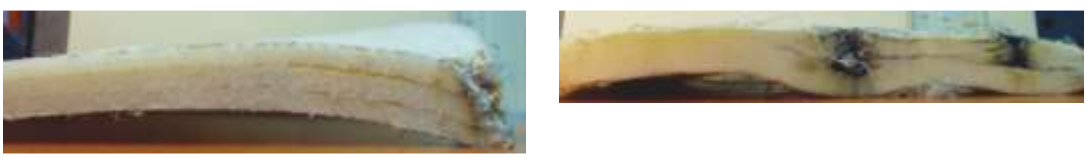
Combinations of composite materials based on 3D warp fabric interlock have provided 13 different coupons, each declined in 3 targets of dimensions 40 40 cm. The pro- tective solutions subjected to the impact of a FSP made it possible to identify 4 main types of failure (Figure 15).

We have identified protective solutions to FSP impact for speed limits greater than 630 m/s. The most successful fi- brous reinforcement of the composite part seems to be an orthogonal architecture of 3D warp interlock fabric with a layer-to-layer binding and with a high number of layers of weft yarns within the structure. We have also observed that the high volume resin content within the composite structure limits the deformation of the fibrous reinforcement and therefore decreases its impact energy absorption



(a) (b)

Figure 11: Ceramic and textile composite target made with 3D warp interlock fabric before impact (a) and after impact (b) with 12.7 mm AP at 610 m/s according to standard MIL-PRF-46103E type III [106].



(a) (b)

Figure 12: (a) Cross-sectional view of 3 plies of composite structures after impact; (b) Cross-sectional view of the laminated composite structure after impact.

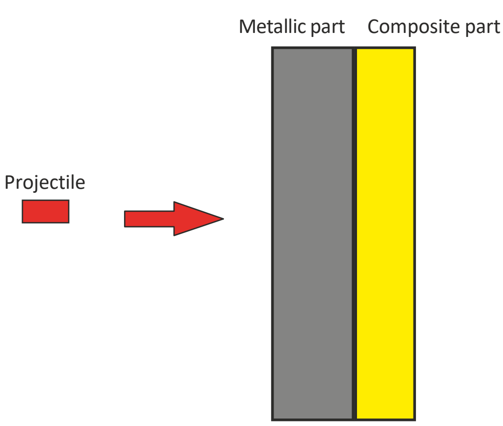



Figure 13: Schematic view of the target made with metallic and composite parts submitted to FSP impact at 630 m/s according to STANAG 4569 standard [111].

capacity [113]. This type of resin also appears to influence the pattern of impact behaviour of composite structures, as pointed out by Lee et al. [114]. They have also demonstrated, both for ballistic and fatigue tests, some significant difference of behaviour for high modulus polyethylene fibres infused with vinyl-ester resin than with polyurethane resin.

*Protective Solution against FSP at 1600 m/s.* In the research work of Nayak et al. [115], image analyses

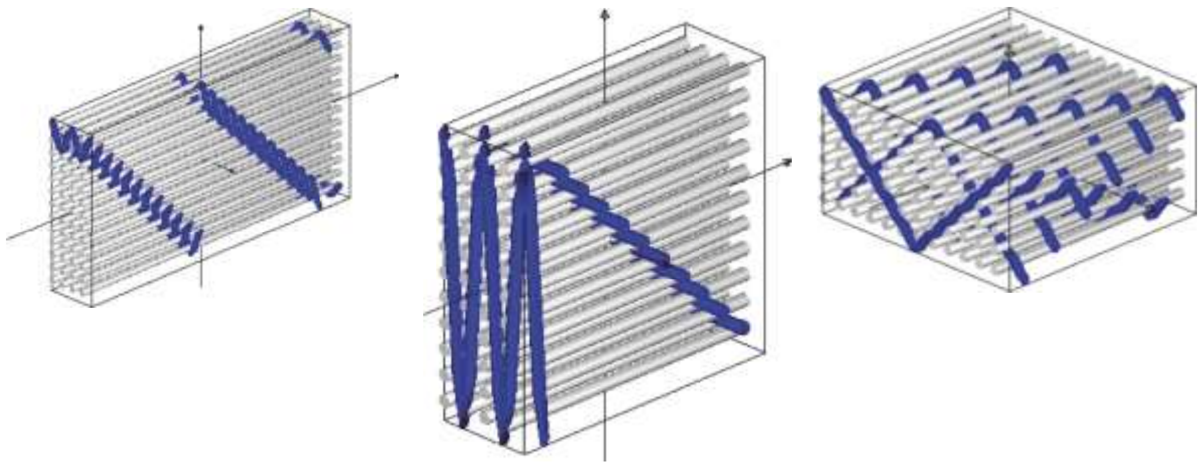
deformation zones for polypropylene resin and epoxy resin composite materials, while the same type of fibrous reinforcement, such as a para-aramid yarn-based fabric submitted to different ranges of impact speed of a 7.62 mm AP perforating ammunition. This tends to reveal a greater ballistic impact energy absorption capacity for thermoplastic resin-based composite materials than thermosetting resin.

Thus, in the context of Provost's research [116, 117], we studied the FSP impact behaviour at 1600 m/s according to the standard STANAG 4569 [111] of a protective solution based on metallic parts located on the front with different composite materials located at the opposite back. These composite materials have been made with 3D warp in-

from an ultrasonic measurement process revealed larger terlock fabrics, based on para-aramid yarns Twaron (3360 dtex) and impregnated with thermoplastic or thermoset- ting resins.

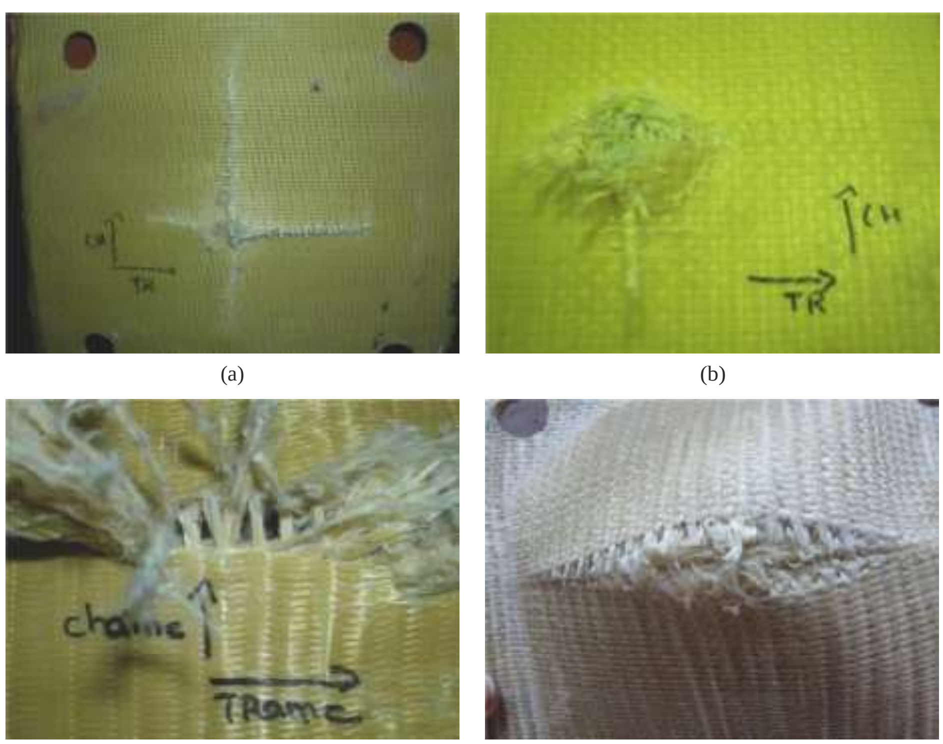
In the continuity of the work of Lefebvre [34, 118], the front face of the protection solution was decomposed into two metallic materials of different thicknesses to maintain a re- sidual velocity of the projectile at the output of the armoured metal estimated at 431 m/s by numerical simulations [116] (Figure 16). During the various impact tests by FSP at dif- ferent speeds, we observed the same impact behaviours of the metallic parts leading to nonperforation of the composite backing or a perforation.

By considering the architecture parameters mentioned in our patents [83, 84], three types of composite backing were realized, each declined in 3 targets subjected to a FSP impact to determine the speed limit of perforation. Based on



(a) (b) (c)

Figure 14: Geometric models of 3D warp interlock fabrics used as fibrous reinforcements for composite part of the impacted target.




(a) (b)

(c) (d)

Figure 15: Different failure types of 3D interlock fabrics submitted to FSP impact. (a) Bidirectional failure type. (b) Localized failure type. (c) Unidirectional failure type without yarn rupture. (d) Unidirectional failure type with yarn rupture.

these observations, the 3D warp interlock fabric architecture [119] and the thermoplastic resin impregnation show a great influence on the impact energy absorption capacity of the final solutions [120].

Moreover, we have also observed different postimpact deformations of the 3D warp interlock fabric composite target backing subjected to the different speeds of a FSP leading to perforations or nonperforations as shown in Figure 17 [121].

## 5. Conclusion

We have presented a description of the impact phenomenon on composite structures as part of the research on hard impact protection solutions based on our own observations and literature reviews. As a result of literature research, we were able to clearly define the impact behaviour of 3D warp interlock textiles as fibrous reinforcement of a composite material.

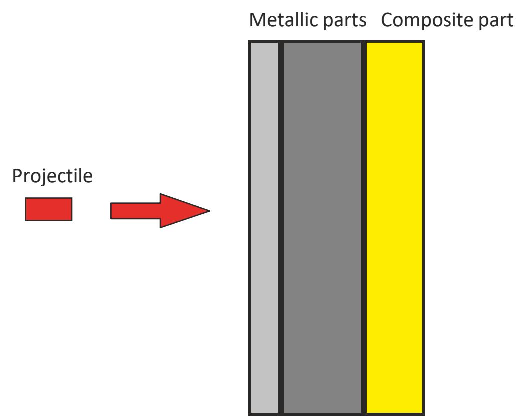



Figure 16: Schematic view of the target made with metallic parts and composite material made with 3D warp interlock fabric.

(a) (b) (c)

Figure 17: Representations of the different tested solutions of 3D warp interlock fabric submitted to high-speed FSP impact.

Several criteria, including the kind and nature of yarns, the type of resin and its application process, the type of architecture, the number of layers, and the densities of the warp and weft yarns, have all been identified. In order to counteract various dangers and their corresponding impact speeds, we have also evaluated a variety of two-part hard protection options, one composed of metallic or ceramic and the other of composite material.

The first protective solution, made with alumina $Al_2O_3$ type ceramic material and fibrous reinforcement impreg- nated with low density polyethylene resin reinforced with 3D warp interlock fabrics made with high modulus poly- ethylene yarns (Spectra 900), has responded to the impact of

12.7 mm armour-piercing ammunition at 610 m/s. The second hard protection solution, combining metallic and composite materials, with fibrous reinforcement impreg- nated with low density polyethylene resin and based on 3D warp interlock fabric with para-aramid Kevlar 29 (3300 dtex) yarns was used to respond to the impact of a FSP up to 660 m/s. Another protective solution made with several metallic parts and composite material, using two fibrous reinforcements impregnated with low density polyethylene resin and based on 3D warp interlock fabric made with para- aramid Twaron (3360 dtex) yarns, has also responded to a FSP impact up to 1742 m/s.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.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