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NEW 3D TEXTILE COMPOSITE PROTECTION AGAINST ARMOUR PIERCING AMMUNITIONS

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Abstract: Weight and performance are the most important parameters in the ballistic Protection. A combination of ceramic tiles and textile composite shows good results as an anti-ballistic material against Armour Piercing (AP) threats. However, many textile structures can be used as a backing solution. 3D textile structure have already been used and have proven their efficiency. However, a combination of textile structures seems to increase the protection performance at the same weight. Thus, a new Textile composite protection has been designed, produced and tested with two different AP Ammunitions: 7,62mm and 12,7mm.
The armour was able to stop all the 7.62mm AP bullets but not the 12.7 mm AP threat. Ceramic tiles used for the armour appears to be not enough resistant for the 12,7mm AP ammunition. Concerning the 7,62mm AP threat, a new textile solution combining aramid and High Modulus Polyethylene yarns for the armour has been found, a bit lighter than the previous solutions, but above all; cheaper and faster than using only 3D warp interlock fabric.

1. Introduction

The dynamic behaviour of a target, composed of ceramic tiles on the top and composite structure on the bottom, impacted by a cylinder ammunition can be described with different steps. At the first stage, when the projectile is hitting the target, the jacket head of the ammunition is eroded and a wave stress is high speed propagate inside the ceramic without any penetration. During this mechanism, a cone is formed through the ceramic (Figure 1) due to the compressive wave resulted from the impact and reflected as a tension wave.

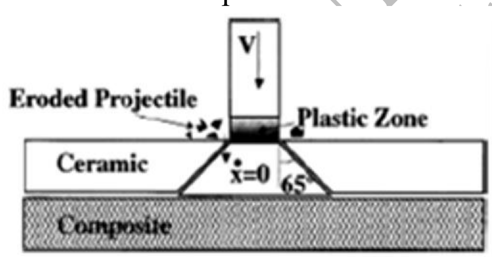

***Figure 1**: Configuration at the end of the first phase of the projectile penetration inside the ceramic structure*

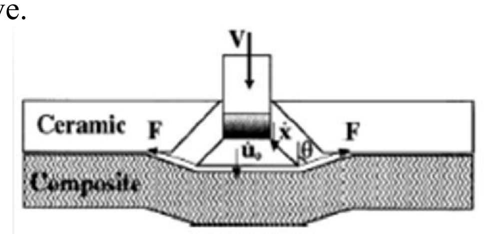

***Figure 2:** Phenomenological description of the second phase*

This tension wave induces the cracking of the brittle ceramic. Then during the second phase, the projectile penetrates (Figure 2) and the whole structure is involved to absorb the impact energy and reduce the projectile velocity. The fracture is spreading all around the cone and the projectile is eroded. This erosion is induced by the difference between the velocity at the rear of the projectile and the head which is the interface projectile/ceramic. This difference causes a pressure.

The goal of ceramics is to deform the threat in order to increase its surface which is in contact with the material(1). The best combination of ceramic/composite depends on the threatdimensions, mass and impact velocity. Taking into account different ballistic tests, a panel of different results is available to find which type of ceramic is recommended for a given threat (2).

During these two phases, the projectile loses some kinetic energy. The cone of deformation (Figure 2) allows to spread over a larger area the remaining energy. Thus, the backing structure may absorb the residual energy (3)(4).

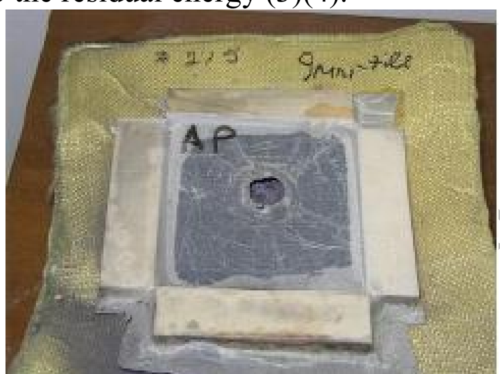

Figure 3:*Ballistic test results for SiC-based ceramics (tile 100x100 mm), 7.62 x 63 mm AP M2 at 880m/s NIJ 0101-04 type IV***(5)**

The tiles size, when ceramics are used as at a strike face, is an important parameter. When a tile is impacted, it cracks due to the brittle behaviour of the ceramic. In case of multi-impacts, if there is only one tile, the first shot will act as described previously but the others will directly go through and the ceramic won't act efficiently. However, when armours are made with ceramic tiles, more than one tile is set up in order to limit the propagation of the tile fracture.

The tilesthickness is also very important. When a threat is penetrating the ceramic, if it happens next to the border, the thickness will be more important than if it was shot on the tile centre. Thus, the size needs to be increased to get a better ballistic performance. However, an optimum size exists for each material. The largest tile may not be the best for impact resistance (6).

To optimize the performance of the energy absorption during impact on ceramic material, a backing solution can be added. The backing is made with a textile structure as a fibrous reinforcement integrated in a composite material. This backing can be made by different textile solutions.

2. Textile solutions

The challenge for textilecomposite solution is to find the best combination of fibre and matrix to get the highest performance (7). Different fibres can be used to optimize the ballistic performance (8). For high performance fibres, they can be selected in a range of tow count or tenacity within the final use.

2.1. Uni-Directional(UD) structure

In UD, fibres are parallel between each other and located in the same plane. To get better performances, fibres plans are alternatively stacked together with respectively one direction and

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an orthogonal direction for the next layer. As a binder and to make a composite, a polymeric matrix is used. The whole fibre is engaged during the process of energy transfer and seems to be more efficient structure for anti-ballistic performance (9).

2.2. 2D and 3D Woven fabrics

2D woven structures are directly stacked together and more used in composite structure due to their mechanical properties. In ballistic application, they can be directly used for soft ballisticas a bullet proof vest(10).

When the projectile goes through the composite structure made with 2D fabrics, the fibres failed. When it happens, the ply is not stressed anymore to reduce the speed of the projectile. There is no bound between plies. Due to this lack of mechanical stress transfer, the structure doesn't react to the impact and a low amount of energy is consumed to stop the projectile.

With 3D woven structure, more plies are solicited whereas the projectile goes through (11). This kind of structure shows another advantage: it will have better performance for a multi-impact test. It shows better results for shear resistance and has a better behaviour at the delamination process (Figure 4) (12).

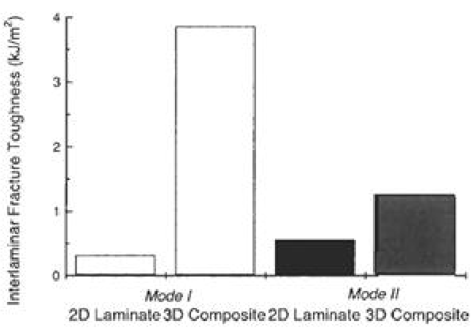

Figure 4: *Comparison of the delamination resistance of 2D and 3D composites for mode I (tension rupture) and mode II (shear rupture) loading*

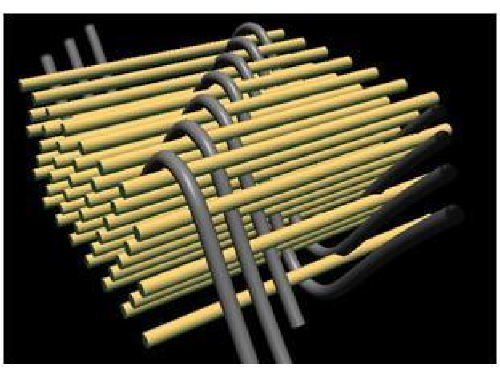

Figure 5: *Interlock through thickness structure* ***(13)***

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A 3D textile structure contains fibres in the three directions. These fibres are bound together through different process (14). The 3D warp interlock weaving technology allows to introduce yarns in the thickness of the material. According to the following scheme, warp yarns may have different orientations and can bind more than two layers (15). The structure geometry will change the mechanical properties (11). Once again, according to the final use, the 3D fibrous arrangement which lead to the final structure may be different (Figure 5).

Compared to UD, woven structure seems to have less energy absorption due to the crossover points of the fabrics. Due to these points, the mechanical properties are reduced for 3D woven structure than UD sheets (12). However, during the weaving process, fibres are less damaged (16)and their mechanical performances slightly decrease compared to initial value taken from the bobbin. Thus, 3D woven structures can be as resistant as UD laminates under high dynamic stress.

3. Energy absorption in a composite structure under ballistic impact

In composite structure the absorption of energy depends on a lot of parameters such as: fibre material, matrix, fibre/matrix interface, fibres orientation, textile structure geometry(17). Whereas the first layers are impacted, the whole composite is stressed (*Figure 6*) and the energy transfer is operated by the fibre absorption (18).

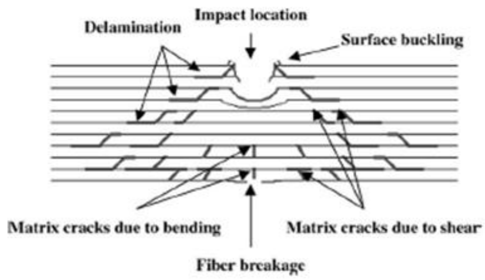

Figure 6: *Schematic representation shows a typical impact damage mode for composite laminate*

The delamination phenomenon is induced by the plies sliding between each other. The effect of cracking matrix may be the cause of internal stress(19). This phenomenon is important to get a better energy absorption (20)(21).

Three main stresses occur during a ballistic impact: the tensile failure of the first yarns, the elastic deformation of the structure and the intra-ply delamination induced by the projectile (22). The last one is the most important, as soon as kinetic energy remained important, the projectile goes through the structure.

The edge effect is very important in ballistic test. The closer the initial impact is, the faster the shockwave is reflected. Due to this reflection, the stress on the yarn will considerably increase (23).

After defeating the threat, the bulge in the UD structure will go back due to the elastic answer of the material (9). This deformation can solely exist once the energy is absorbed. Considering the composite material made with woven fabric, the velocity of both bulge and projectile has been measured. As far as the projectile velocity is decreasing, the bulge is growing and its velocity is increasing up to a maximum (24). A hybrid composite composed of different tow counts inside different textile structures seems to give better results as an anti-ballistic solution (25).

Composite material models have been studied and experimented with impact simulation (26) (27)(28). They can be used to first validate an analytical model and provide main trends of yarns orientations.

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4. A new ballistic proof structure

According to all of the previous models, at least two stages need to be taken into account: the energy absorption and the "catching bullet" process. In the structure used in the patent(29), this aspect of the penetration mechanism is forgotten. To optimize this anti-ballistic structure, a hybrid solution including different textile structures may be necessary.

To design this new ballistic protection, different plies of textile materialswill be used to obtain different behaviour during the impact :

- the first layer needs a high resistant material to destroy the jacket and deform the core of the bullet. This material needs to be as hard as possible to avoid a perforation. Ceramic tiles will be used as a strike face.
- the second layer implies an energy absorption mechanism by delamination and shearing. The chosen and suitedstructure will be UD sheets inside a composite.
- the third layer involves an energy absorption by deformation of the whole structure. The chosen structure for this performance will be a 3D fabric, especially a warp interlock fabric.

Two plies of warp interlock fabric made with high modulus polyethylene yarns (Spectra®) will be used. The UD sheets of para-aramid material (Twaron®) will be used for the structure.

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5. Ballistic tests

The ballistic tests are based on the standards NIJ IV 0101 04 for the AP M2 7.62mm and MILPRF 46-103E for the AP M8 12.7mm. Velocities and distance are from the standard norm.

5.1. Characterization with AP 7.62mm ammunition (880 m/s)

Table 1: *Ballistic results using AP 7.62mm bullet on hybrid ceramic and textile composite structure*

Sample		Weft density (PE interlock)	Weight of sample	Area density of the backing (textile composite)	Area density of the sample	Estimated area density (full ceramic on strike face)	Thickness	Velocity	Energy	Perforation
Units		picks/cm	Kg	kg/m²	kg/m²	kg/m²	mm	m/s	J	Yes/No
Reference	1-1	87,56	1,379	10,816	31,27	40,16	22,50	882,3	3892	No
	1-2	87,56	1,379	10,816	31,27	40,16	22,50	845	3570	No
	1-3	87,56	1,379	10,816	31,27	40,16	22,50	861,8	3713	Yes
	2	75,34	1,344	10,483	30,65	40,00	21,50	874,8	3826	No
	3	75,94	1,391	11,165	32,32	41,23	22,00	874,9	3827	No

The area density of the final target is closed to 11 kg/m² so we keep the same weight by using UD sheet as the reference target of the patent (29). The impacted ceramic is totally destroyed but ceramics around remain glued on the target (Figure 7). The total deformation of the backing after impact keeps the same depth than for the previous test (about 20mm) but the width is more important (about 55 to 75 mm). It means that the whole structure is more involved during the impact which lead to more energy absorption. UD sheets allow a better propagation along the fibres direction and warp interlock fabrics limit the delamination (Figure 8).

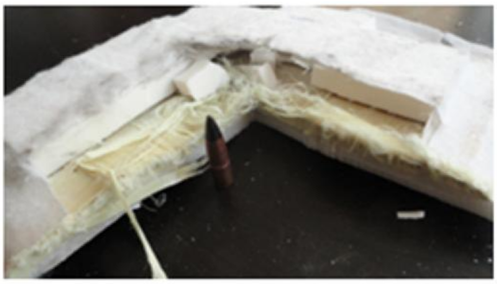

Figure 7: *Cohesion of non impacted and remaining glued ceramic tiles on the final target*

Figure 8: *Front impact hole of the target after a single shot*

Only the first UD sheets have been destroyed by the impact. A small square located on the middle of the target can be observed where the UD sheets are destroyed (Figure 9Error! Reference source not found.).

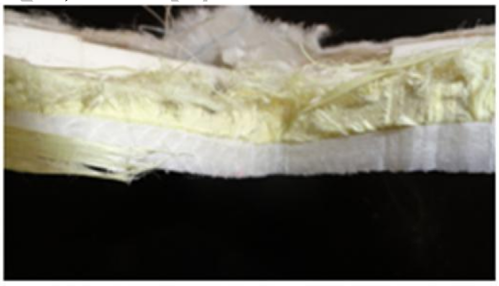

Figure 9: *Transverse view of the top destroyed UD sheets*

To prove the multi hit performance of the new textile hybrid solution, two additional shots have been performed on the same target (Figure 10) with a respective distance equivalent to a ceramic tile size. The second shot was stopped but not the third even if fragments from the core were close to the sample. Moreover, the target was really small (20 x 20cm) and the side effect may cause the penetration for the third shot. The sample was a bit delaminated after the second shot which was close from the first one. Finally, the fibres used to stop the second and the third shot were the same (they have been shot on the same line). We can assume that, with a bigger sample and different positions of shots on the target, the sample would defeat all the shots.

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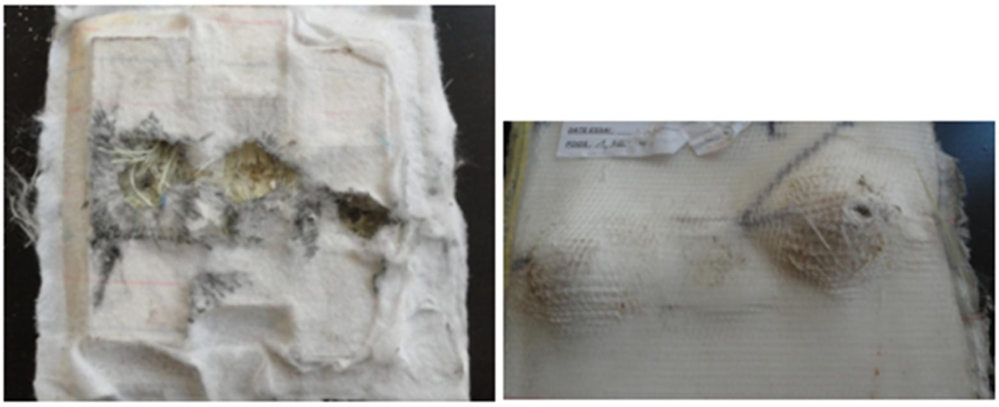

Figure 10: *(left) Front view of the impacted textile composite solution without the ceramic tiles (right) Back view of the deformed warp interlock fabricsafter multi-impact shots*

5.2. Characterization with AP 12.7mm ammunition (615 m/s)

Table 2: *Ballistic results using AP 12.7mm bullet on hybrid ceramic and textile composite structure*

Sample		**Weft density (PE interlock)**	**Weight**	**Area density of the backing**	**Area density of the sample**	**Estimated area density (full ceramic on strike face)**	**Thickness**	**Velocity**	**Energy**	**Perforation**
Units		yarn/cm	Kg	**kg/m²**	kg/m²	kg/m²	mm	m/s	**J**	**Yes/No**
Reference	4	77,14	1,365	**10,185**	30,09	38,72	21,50	612,40	**8063**	**Yes**
	5	73,64	1,321	**10,220**	29,67	39,29	21,00	612,20	**8058**	**Yes**
	6	73,64	1,350	**10,861**	31,66	41,21	21,00	625,50	**8412**	**Yes**

None of the target has defeated this AP 12.7 mm threat. The impact energy was such high that all ceramic has been projected from the sample to the ground. Ceramics doesn't enough destroy the jacket and the core of the AP ammunition. After impact inspection of the backing solutions (Figure 11) it can be observed that the bullet still remains intact and leads to the delamination of the two textile composite solutions respectively the UD sheets (yellow layers) and the warp interlock fabrics (white layers). The resulted impact hole was not large enough to spread the energy over the whole structure.

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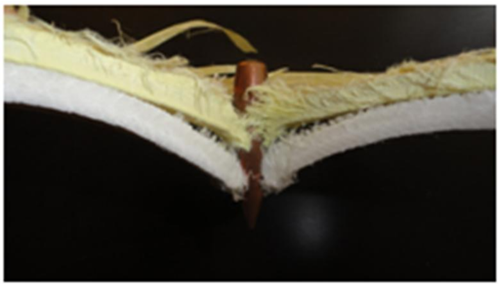

***Figure 11:** 1Transverse view of the delaminated textile composite solutions impacted with 12.7mm AP ammunition*

6. Conclusion

Considering the ballistic tests performed with an initial velocity of 615m/s of AP 12.7mm ammunition, the new proposed hybrid textile composite solutions seems to not resist to these impacts. Ceramic tiles are not suited to be enough resistant to lead to the destruction of the jacket ammunition and the AP core. Then the new hybrid textile composite solution is not stressed with the expected functions as shearing, delamination and deformation during the impact mechanism. In future work, this threat may be defeat by using other ceramic tiles.

Considering the ballistic tests performed with an initial velocity of 880m/s of AP7.62mm ammunition, the new proposed hybrid textile composite solutionsappears to be resistant against this threat and a bit lighter compared to the patented existing solutions. The anti-ballistic performance and lightweight may be increased by using UD made in high resistant polyethylene yarns.

This encouraging trend needs further ballistic tests to prove an accurate and safe resistance of the new textile composite structure. Future works needs to be push on the hybridization of textile composite solutions to exploit the advantages from both structures.

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