3D WARP INTERLOCK FABRIC STRUCTURE AS A NEW MATERIAL FOR WOMEN BALLISTIC PROTECTIVE VEST DESIGN

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ABSTRACT

Designing of women ballistic vest following their unique morphology for better ballistic protection and comfort are very imperative. For such purpose, accommodating the women bust shape without dart stitch using good "drapable" and ballistic material such as 3D warp interlock fabrics based on moulding principles has been proposed by different researchers. This paper presents the ballistic performances capabilities of 3D warp interlock fabrics made of high performance aramid fibres according to NIJ Level - III. The result revealed that the 3D warp interlocks fabric is the promising material to be applied in women ballistic protection vest not only its moulding capability but also its ballistic performance.

Key Words: Women ballistic vest, 3D warp interlock fabric, High performance fibres, Ballistic performances

1. INTRODUCTION

Body armour is one of the piece of equipment used by different customers including many military and law enforcement agency personnels which helps to protect themselves from various critical and fatal injuries [1]. Such demands of the body armour and the advancements of high-speed projectiles makes the researchers and stakeholders for progressive improvement of the ballistic protection system using various new and proper materials and designing techniques [2]. Moreover, the designed body armour should possess both good ballistic performance toward projectile penetration and reasonably light in weight, flexible, and comfortable [3]. The ballistic impact is a very complex mechanical process when a low-mass high-velocity impact by a projectile propelled by a source onto a target which mainly effects near the location of impact. For the last many decades, various materials of ordinary and innovative material such as from felt to metal, high performance fabrics to composite and ceramics, and further bioinspired materials were applied [4]. While developing soft body armour, apart from vest design technique, its ballistic performance and comfort depend on the material characteristics including fibre types [5], yarn properties [6], material areal density [7], target plies numbers [8], target ply sequence [9] and textile construction, such as woven/nonwoven and 2D/3D fabrics [10].

Women personnels of law enforcement police and the military services were used male-based pieces of body armour systems for the last many decades [11]. However, fitting women with such body armour exposed them disproportionate protective and functional sacrifices. Due to their unique curvilinear body shape, manufacturing of women soft body armour needs special attention both in designing and material selection. The designing technique and the material used should properly accommodate the curvilinear shape of the body including the bust for better fitness, comfort and ballistic performance. To achieve such targets, the moulding designing techniques are the best techniques to develop the female soft body armour with the required domed shape without applying any kind of cutting and stitching to improve both comfort and ballistic protections [12][13][14]. However, in order to achieve such techniques, applying proper materials with better mouldability is imperative. 3D warp interlock fabric structures becomes popular and widely used in many technical applications including ballistic applications due to their excellent moulding capability. Moreover, researches made on angle-interlock fabrics show better ballistic performance with good mouldability and lightweight as compared to its counterpart 2D structures [15].

This research paper presents the ballistic performances of 3D warp interlock fabric for the developments of seamless women ballistic vests.

2. MATERIALS AND METHODS

2.1 Material

3D warp interlock fabrics made with the high performance yarns (Twaron®) is manufactured as orthogonal layer to layer (O-L) architecture in the automatic dobby loom. The fabrics were cut with 50 x 50 cm^2 dimensions using a specialized electronic aramid fabric cutting machine due to its high thickness and prevent the fabric from crumple. Details of the produced fabrics parameters are given in ***Table** 1*.

Table 1. *Material parameters for the selected woven p-aramid fabric constructions.*

Material parameters	**3D fabrics**	
Construction type	Warp interlock orthogonal layer-to-layer	
Fibre materials	P-aramid (Twaron)	
Linear density,	930 dTex	
Areal density	1000 g/m^2/panels	
Number of layers	5	
Yarn density	Warp	52.5 yarns/ panels (8.75 yarns/layer)
	Weft	52.5 yarns/ panels (8.75 yarns/layer)
Material thickness	1.55 mm/panels (0.258 mm/ layer)	

2.2 Sample preparations and testing conditions

2.2.1 Sample preparations

Two target panels were developed using each thirty and forty layers of 3D warp interlock fabrics layers. The different layers in the final panel target were firmly attached together with tapes at the edge in order to avoid not only fibre unravelling but also prevent the fabric layers from slipping off within their layer positions. Later before ballistic test, the panels were also moulded at the two defined points to resemble the frontal contour of the women body. The bust-shaped punch and an adapted forming bench were applied to mould the panels at the desired shapes. The panels were clamped using narrow fabrics with self-gripping ribbon at the four sides of the test frame with uniform clamping pressure to avoid the inconsistent results while impact. **Figure1** shows the panel sample preparation and target positions for the ballistic test.

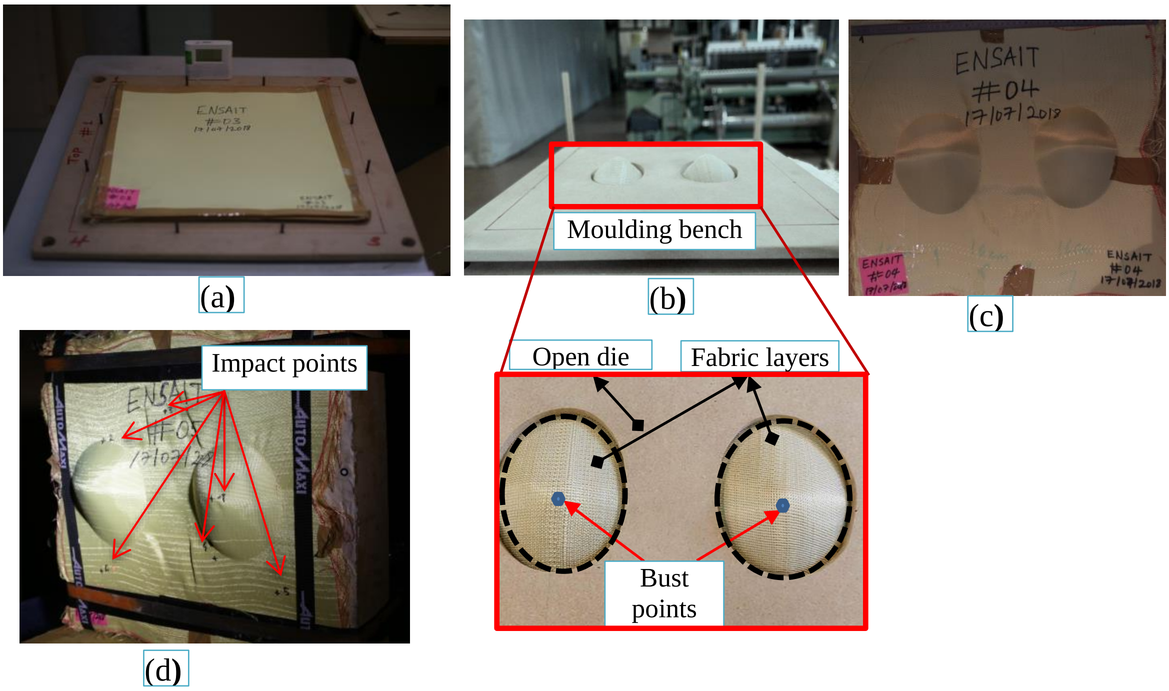

Figure 1. Ballistic impact panel preparations (a) Different layers of panels (b) The newly adapted moulding apparatus and moulding of the different layers panel to mimic the women front body contour (c) Final moulded target panels and (d) Prepared target for ballistic test.

2.2.2 Ballistic testing conditions

The ballistic tests were carried out according to the NIJ 0101.06 level – IIIA standard [17]. The test used a Delcour N°2 with blocked 280 long tube Gun barrel with 9 X 19 mm calibre. The Full Metal Jacket Nose (FMJ RN) bullet with 8 g of was used. Both Radar Doppler and chronograph were installed at a distance of 9 and 5 m from the target respectively. This would help to measure the exit and impact velocity of the projectile before the impact. Each panel were shot with 6 bullets at different moulded (d) and non-moulded (f) target positions. Normally the target was positioned at a distance of 10 metres from the gun barrel. **Figure 2** shows the schematic diagram of the ballistic tests which were conducted at the Centre de Recherche et D'Expertise De La Logistique (CREL) of France.

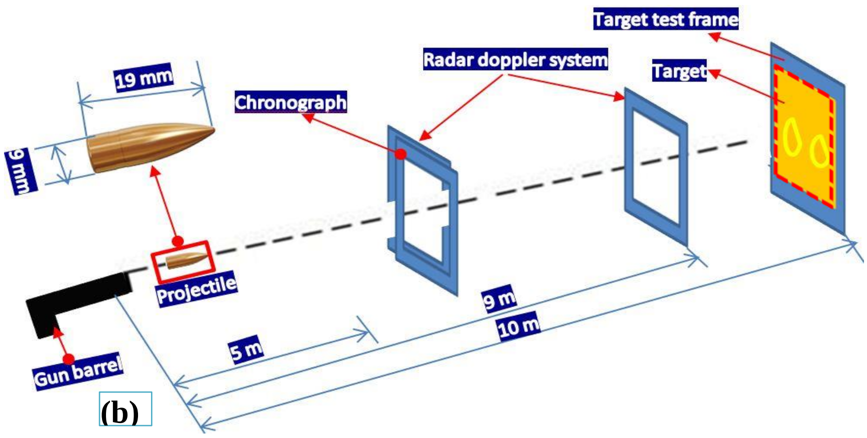

Figure 2. The schematic diagrams of the ballistic testing apparatus

After the ballistic test, the blunt trauma formed at the backing material was measured using handy scanning device for better and precise result in a short time. The scanned geometry then transferred to the 3D design concept software to compute the different volumes of blunt trauma

The measured value later helps to determine the amount of energy absorbed by the different panels and transmitted to the backing materials.

3. RESULTS AND DISCUSSION

Based on the computed trauma geometry, the energy absorbed by the panels and the different number of layers arrested the projectile at different shooing points will be discussed.

3.1 Energy absorption capability of 3D warp interlock fabrics

While ballistic impact, the 3D warp interlock fabric panels will undergo to different deformation to resist the propagating energy exerted by the projectiles. Moreover, different impact energy was generated at different target points of panels made with 3D warp interlock fabrics. The different absorbed and transmitted energy and their percentages (%) of different shoot points of panels made with 40 layers of 3D warp interlock fabric are illustrated in **Figure. 3 (a) and (b)** Based on the result, the total impact energy exerted and energy absorbed by the panels at target point T1 (d), T2 (d), T3 (f), T4 (d), T5 (f) and T6 (f) were found 639.88, 656.78, 627.16, 669.53, 679.12 and 662.43 J respectively. It is not possible solely to compare the energy absorption capabilities of each target using numerical energy (Joule) values. For better understanding, computing percentages of energy absorption for each point will give a better the insight for comparisons. Based on this, the percentages of energy absorption of T 1(d), T2 (d), T3 (f), T4 (d), T5 (f) and T6 (f) were recorded as 94.98%, 97.74%, 97.89%, 97.51%, 99.54% and 98.69% respectively. This clearly indicated that energy percentage values will give a better room for comparisons of different target points within the same target than specific energy values (J).

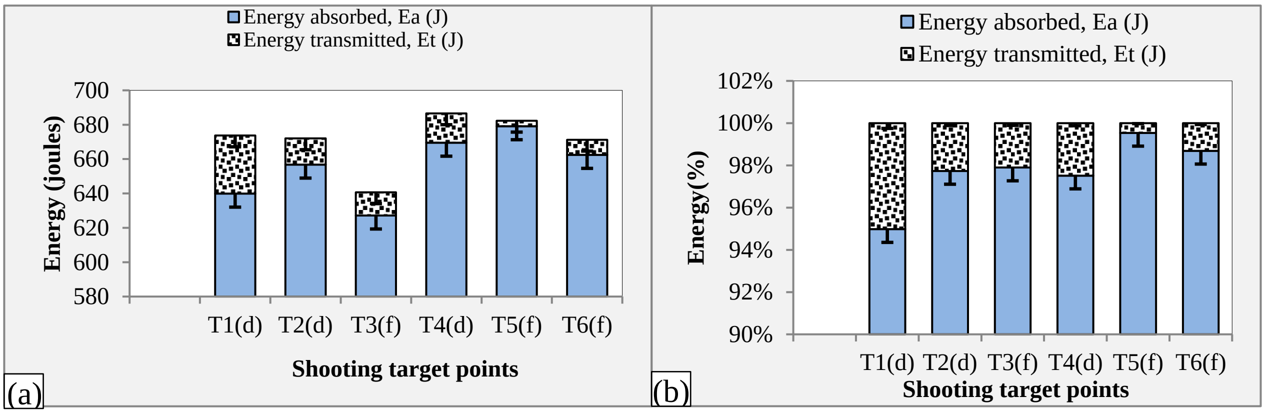

Figure 3 Ballistic results of 40 layers of 3D warp interlock fabric at different shooting areas (moulded (d) and non-moulded (f) area) (a) Values of absorbed and transmitted energy in Joules and (b) Percentages (%) of absorbed and transmitted energy.

Similarly, the energy absorbed and percentage (%) values of panels made with 30 layers of 3D warp interlock fabric at different moulded (d) and non-moulded (f) points were shown in **Fig.4 (a) and (b)**. In this panel target, since the energy absorbed by the panel was calculated only when the panel is not penetrated, except for T1 (d), all target points were unable to resist the ballistic impact from penetration and not considered for further analysis. The energy transmitted percentage in T1 (d) for panels made with 30 and 40 layers of 3D warp interlock fabrics were recorded as 93.28% and 94.98%. The number of layers involved in the panels made with 3D warp interlock fabrics were affected and contributed for energy absorption capacities. Moreover, the panel target point conditions (moulded and non-moulded) were also more or less affected by the energy absorbing capabilities of 3D warp interlock fabrics panels. However, only limited outcomes on the energy absorption and transmitted values were observed in the moulded target points of the panel made with 3D warp fabric layers. This indicates that shots on moulded (d) and non-moulded (f) target areas of 3D warp interlock fabrics show nearly similar energy absorbed percentages. This is due to the fact that a 3D warp interlock fabric shows good mouldability without affecting the mechanical performances of the final products.

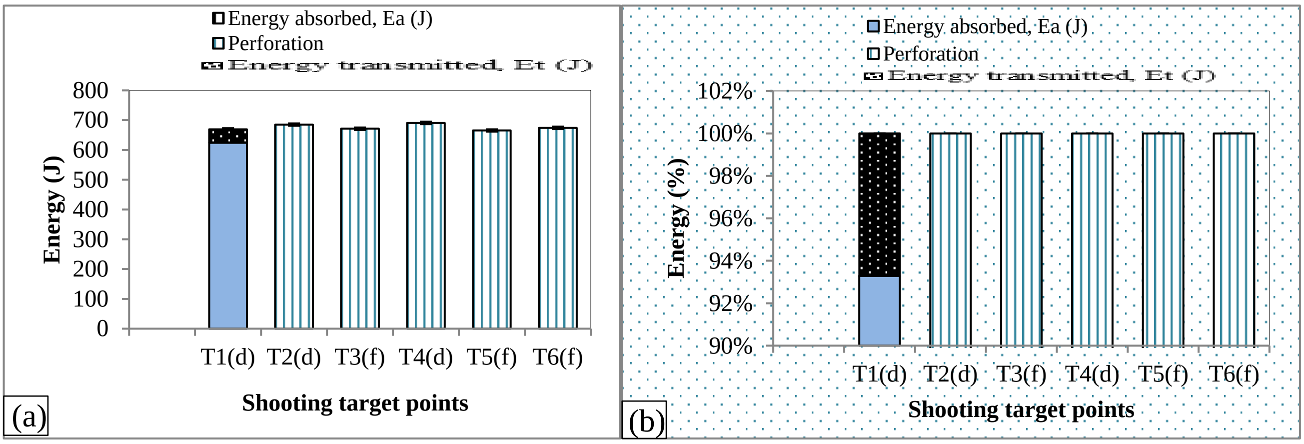

Figure 4 Ballistic results of 30 layers of 3D warp interlock fabric at different shooting areas (moulded (d) and non-moulded (f) area) (a) Values of absorbed and transmitted energy in Joules and (b) Percentages (%) of absorbed and transmitted energy.

3.2 Ballistic projectile arresting layers in the panel

In general, during ballistic impacts, complete penetration, partial penetration or no penetration of panels may happen depending on the various external and internal parameters including material properties, target conditions and projectile parameters. Complete penetrations might occur when the impact energy get either higher or same (ballistic limit) values with the material energy absorbing capability. Unlike complete perforation, investigating and identifying the number of layers which is required to capture the projectile during partial penetrations is very important for further improvements of armour panel design. **Figure 5** shows the number of penetrated layers of different 3D warp interlock panels with respect to target shoot points. In general, the number of layers arresting the projectile at the different target points was found significantly scattered at a wider range for panels made with different layers. Moreover, the 30 layers panels of 3D warp interlock fabrics, except shoot targets region one, the complete penetration (p) were recorded for all shoot target regions.

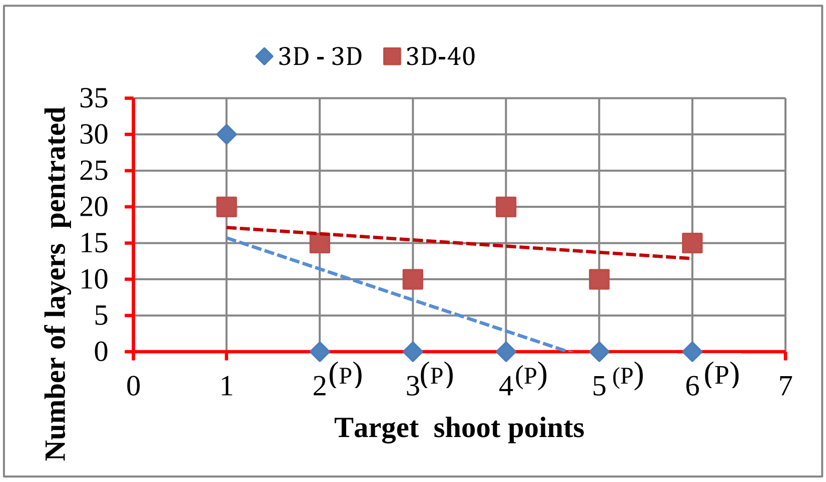

Figure 5. The number of layers penetrated at different target shoots points for 3D warp interlock fabric panels with different number of layers (P represented as fully Penetrated shoot target)

On the other hand, for the 40 layers of 3D warp interlock aramid fabrics, the ability to capture the bullet was at the minimum layer of ten layers and the maximum layer of 25 layers. Moreover, the number of penetrated layers was significantly affected by the target shoot points. Target shoot points on the moulded area need more number of layers to capture the projectile as compared to the shoots at the non-moulded. This is due to the fact that, even though less panel's surface damage occurs due to its good moulding ability, however, its less recovery ability will also reduce the areal density and increased the tension and straightening of the yarn. As discussed earlier those phenomenon during moulding process may affect both the mechanical and ballistic performances of the materials.

4. CONCLUSION

Two different ballistic panels made of 3D warp interlock p-aramid fabrics (Twaron) were moulded to resemble the frontal female body shape and tested against ballistic impact according to NIJ-Level IIIA. The amount of absorbed energy by the panels was computed based on the measured trauma volumes. Based on the result, the ballistic protection capabilities of 3D warp interlock fabric show significant both impact resistance and number of layers arresting the projectile while using higher number of layers. Moreover, the energy absorption capabilities of the panel at the non-moulded target area was also revealed not much significant than the moulded target areas. This is due to the fact that 3D warp interlock fabric shows better shaping ability according to the female contour while designing the body armour without affecting the mechanical and ballistic performances of the panel.

5. ACKNOWLEDGEMENTS

Authors would like to thank all the members of the ballistic facility test ("Centre de Recherche et d'Expertise de la Logistique" (CREL)) based in France. This work has been done as part of Erasmus Mundus Joint Doctorate Programme SMDTex-sustainable Management and Design for Textile project, which is financially supported by the European Erasmus Mundus Program

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