EFFECT OF TEXTILE ARCHITECTURE ON ENERGY ABSORPTION OF WOVEN FABRICS SUBJECT TO BALLISTIC IMPACT

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1 Introduction
Fabrics made from high-performance fibres such as Kevlar® and Dyneema® possess high flexibility, high strength-to-weight ratio, and outstanding energy absorption capacity for offering protection against ballistic impact. Among the various mechanisms influencing the impact resistance of textiles, textile architecture has been identified as one of the major factors capable of significantly influencing the mechanical performance and energy absorption of woven fabrics. This study aims at investigating the effect of textile architectures towards fabric ballistic resistance through computational modeling in meso-scale. Material models of aramid yarns (Kevlar® 29) were constructed using mechanical properties obtained through experiments. Fabric models of four different woven structures: Plain, Satin, Twill, and Basket were then created using LSDYNA package. Simulation results focusing on impact energy absorption and failure mechanism were then analyzed, in order to provide detail comparison in impact resistance between the four woven textiles.

2 Background

2.1 Influence of Textile Architecture
Experimental studies on fabric with different textile architectures have revealed significant variance in their mechanical properties, including permeability, tension wave speed [1], tensile and tear strength [2-5], and impact energy absorption[6]. Identifying the influencing factors however was known to be difficult due to the complex interaction between yarns, in which multiple factors were often studied in the coupled manner and cannot be isolated. This is particularly true in the case of textile ballistic impact, where most structural responses can only be measured in post-test stage. While results from recent work demonstrated considerable difference in reduction of projectile residual speed from different woven architectures [6], little work has been presented on analyzing the individual causing factors and their influencing mechanisms[7].

2.2 Meso-scale textile modeling
Meso-scale textile modeling considers the yarn-level millimeter-length scale of the fabric by modeling the interlacing of individual yarns [8]. This allows the model to capture the detail mechanism in the yarn-yarn interaction such as contact friction and breakage, which enables the model to provide in-depth simulation in the evolution of fabric damage and energy transfer during ballistic impact.

In the ballistic impact case, research efforts in modeling woven fabrics have suggested three main energy absorbing channels: kinetic energy, strain energy and friction energy [7, 9, 10], with the friction energy component being more dominant during low speed impact. There is however very limited research in modeling and analysis of other woven fabric types. Comparison between energy absorption capacity and mechanical properties of different woven fabrics, damage mechanisms, and influencing factors remains an area yet to be explored.
3 Experimental Studies

Ballistic impact experiments were carried out using a Gas-Gun assembly with 0.5 caliber gun barrel (Fig. 1). Samples of single layer, 163gsm aerial mass, 880 dtex Kevlar® 29 plain woven fabric were trimmed to size 250mm by 350mm (Fig. 2a), and tightly clamped between two steel frames using eight M8 bolts (Fig. 2b). Fully covered 0.33 caliber bullets weighted 7.5g were used as projectile for the test (Fig. 2c). Custom made sabots were also used to support the bullets in the barrel. They were made of 3D printed ABS plastic and designed to separate from the projectile prior to impact.

The pressure in the gas chamber was calibrated between 0.17–0.22MPa for the bullet to acquire the impact speed ranging between 83~105 m/s. Projectile initial velocity was recorded using a laser guided gate positioned immediately after the gun barrel, the residual velocity was captured by analyzing the bullet image captured using the high speed camera as shown in Fig. 1. Both the laser channel and the camera were initiated using a trigger switch connected to the oscilloscope.

All four plain woven fabric samples were penetrated by the projectile at the center, with failure patterns showing agreement with the literature studies [3]. Test results listed in Table 1 reveals the captured initial and residual velocity related in close correlation. Relative difference between 12~20% was also observed when comparing ∆V with the velocity difference, which also increases with the initial velocity. The results suggested an increase in fabric energy absorption capacity with greater bullet impact speed.

Table 1. Kevlar® 29 ballistic test results

<table>
<thead>
<tr>
<th></th>
<th>V_initial (m/s)</th>
<th>V_residual (m/s)</th>
<th>∆V (m/s)</th>
<th>R_diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test_1</td>
<td>83.5</td>
<td>73.2</td>
<td>10.3</td>
<td>12.3%</td>
</tr>
<tr>
<td>Test_2</td>
<td>90.0</td>
<td>80.5</td>
<td>9.5</td>
<td>10.6%</td>
</tr>
<tr>
<td>Test_3</td>
<td>99.2</td>
<td>81.3</td>
<td>17.9</td>
<td>18.0%</td>
</tr>
<tr>
<td>Test_4</td>
<td>105.3</td>
<td>84.8</td>
<td>20.5</td>
<td>19.5%</td>
</tr>
</tbody>
</table>

4 Numerical Modeling of Fabrics

4.1 Meso-Scale Model

A meso-scale fabric model comprises of warp and weft yarns were modeled using the geometry obtained from micro-scan. A transversely isotropic elastic section was applied to the associate block elements. As tensile tests of both Kevlar® yarns and fibres suggested non-strain rate sensitive, and strong linearity for its modulus, an elastic orthotropic
material model MAT221 in LSDYNA was hence applied using the test data obtained.

4.2 Modeling Individual Yarn

Geometry and mechanical properties of Kevlar® 29 yarns obtained from physical tests has suggested an elliptical cross section having a width of 1.095mm, thickness of 0.13mm, and spacing of 0.219mm in between yarns. These properties were applied along with density of 1230 kg/m³ and a failure strain of 3.5%. Referencing the model by Rao et al [11] in simulating yarns as bundles of individual fibres, poisson’s ratios were set to zero, while transverse and shear moduli was approximated by assigning the longitudinal tensile moduli $E_{11}$ (79.8Gpa) to two and three orders smaller respectively.

Validation of individual yarn model was carried out using the approach suggest by Duan et al. [12], where the velocity of two mechanical wave generated during impact of yarns: longitudinal, and transverse, can be obtained analytically and compared with numerical and experimental results. The longitudinal wave speed $c$ is given by:

$$c = \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} (1)

The tensile strain $\varepsilon$ travels behind the longitudinal wave front can be obtained by using Eq (2), which is determined by the yarn tensile modulus $E$, density $\rho$, and impact velocity $v$.

$$2\varepsilon \sqrt{\varepsilon(1+\varepsilon)} \cdot \varepsilon^2 = \frac{\rho v^2}{E}$$  \hspace{1cm} (2)

By computing the tensile strain using an iterative solver, the transverse wave speed $u$ can eventually be obtained using Eq (3).

$$u = c \sqrt{\frac{\varepsilon}{1+\varepsilon}}$$  \hspace{1cm} (3)

Attempts in determining the $c$ of Kevlar® 29 yarns was carried out using a Dynamic Modulus Tester by CSIRO material and science division. The obtained data can also be used to calculate the associate $u$ using Eq (3). Validation of LSDYNA model using $c$ and $u$ from experiment and analytical method was then performed as shown in Table 2.

<table>
<thead>
<tr>
<th>Yarn</th>
<th>Analytical</th>
<th>Test</th>
<th>LSDYNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal ($c$)</td>
<td>8054</td>
<td>8179</td>
<td>8778</td>
</tr>
<tr>
<td>Transverse ($u$)</td>
<td>1013</td>
<td>1029</td>
<td>1457</td>
</tr>
</tbody>
</table>

The simulated result of $c$ was over-predicted by approximately 7%, which has shown agreement with both analytical and tests data. The data thus provided a reasonably good prediction in the propagation of mechanical waves and tensile strain from the constructed meso-scale model.

4.3 Modeling Woven Fabric

The model of a plain woven fabric was then been built as shown in Fig. 3. The single layer fabric model is 0.3 mm in thickness, 120mm by 120mm in size with 100 yarns in both warp and weft directions, and fixed at all four boundary edges in all DOF. The projectile model with dimension identical to the bullet used in experiments was positioned in the centre of the fabric, with the frontal surface 3mm apart from of the closest yarn. An initial velocity of 90m/s was assigned for the bullet to travel towards the fabric in normal direction. Friction coefficient of 0.23 and 0.19 were assigned for static and dynamic contacts between the yarns, while a coefficient of 0.18 was assigned for bullet-yarn contact as suggested in the literature [11].

Fig. 3. Plain woven fabric a) full impact model, b) top, c) isometric, d) projectile, e) side view
In order to simulate the breakage of yarns, element erosion criteria of 3.5% in maximum strain was applied in the orientation of the yarn principle axis. Amount of total absorbed energy can thus be obtained by deducting the residual velocity of the penetrated projectile with its initial velocity.

To study the influence of woven structure and variance in their associate energy absorption mechanism, three additional models with different woven architecture but similar areal volume: twill, 2-by-2 basket, and 3-harness satin was also constructed using identical yarn geometry, material properties, contact settings and boundary conditions as shown in Fig. 4.

![Fig. 4. Geometry of four different weaves. plain(a), basket(b), satin(c), twill(d).](image)

5 Results and Discussion

5.1 Model Validation

Model validation of was first carried out for the plain woven fabric model. Evolution history of projectile velocity shown in Fig. 5 indicated a simulated residual velocity of 85.1 m/s. By comparing with Test_2 data listed in Table 1, a relative difference of less than 5.6% in residual velocity was observed. The simulated result has thus shown good agreement with the experimental outcome. The model also presented similarities in the shape of yarn fractures and damage patterns. As shown in Fig. 6a and 6b, the model has successfully simulated the “diamond shape” deformation in the out-of-plane direction of the fabrics, which appears immediately before the penetration of the projectile. Fracture damage of yarns at the location of impact also shown similar failure pattern in yarn deformation and location of breakage, as shown in Fig. 6c and 6d.

![Fig. 5. Evolution history of projectile velocity](image)

![Fig. 6. Comparison in fabric damage progression (a,b), failure modes (c,d)](image)
**5.2 Energy Absorption of Plain Woven Fabric**

Evolution history of the plain weave model in Fig. 7 shows a steep raise in energy absorption from the moment of impact at 0.010s, this was caused by the initial movement and elongation of the fabric yarns. As the bullet begins to puncture through due to the fracture of yarns at 0.015s, energy absorption rate was immediately eased. The gradient of the curve was then gradually relieved as the bullet passes through the fractured hole, and eventually left the fabric at 0.280s.

Fig. 7 also revealed three main contributing channels of fabric energy absorption from the impacting projectile: 1) yarn kinetic energy $KE$, 2) yarn internal energy $IE$, and 3) friction energy $FE$. Impact energy transfers through $KE$ leads to the acceleration and movement of fabric yarns, while energy absorbs through $IE$ results in the deformation and elongation of yarns. $FE$ on the other hand absorbs the impact energy through friction contact between yarn-yarn and yarn-projectile during impact. The sum of these three channels contributes to the majority of energy loss of the penetrating projectile, while other minor mechanisms such as yarn fracture energy and vibration counts for the remaining amount.

The evolution history of fabric energy absorption also suggested the dominance of $KE$ and $IE$ during the early stage of impact. Evolution of von-mises strain and stress shown in Fig. 8 and Fig. 9 presents strain and stress concentration area exists around the impact location during the initial impact stage, where both large deformation and acceleration were experienced by the yarns. As the concentrated strain pattern continues to propagate outwards, this high-strain region begins to expand, and eventually break up upon bullet penetration at 0.095s, which transformed into four wave-fronts travelling towards the four corners of the fabric. The reduction of strain distribution from a large concentrated pattern to four relatively smaller wave fronts causes the $IE$ to drop with a considerable amount. $KE$ also cease to increase immediately after bullet penetration, the movement of the yarns however remains due to the velocity caused by the impact. Separation of $IE$ and $KE$ can thus be seen at the location indicated by the red arrow in Fig. 7.

![Graph showing energy absorption](image)

**Fig. 7.** The simulated evolution of total energy absorption and contributed channels during fabric ballistic impact.

![Images of strain distribution](image)

**Fig. 8.** Simulated evolution of fabric Von-Mises strain during ballistic impact.
A significant increase in $FE$ was also observed immediately after penetration began at 0.015s. As the textile architecture was damaged, the sudden increase in relative movement between the yarns caused large amount of frictional contacts in the textile architecture, $FE$ then increases gradually and surpasses $IE$ at 0.15s, and $KE$ at 0.20s, until the complete penetration of the bullet. $FE$ was thus the dominating mechanism in the later stage of the impact. Overall, the plain woven fabric has suggested the three energy absorption channel $IE$, $KE$ and $FE$ each accommodates approximately 27%, 27% and 38% of the total energy absorption respectively.

5.3 Comparison of Various Woven Structures

The four curves presented in Fig. 10 showing projectile velocity evolution of different woven structures suggested similar impact progressions and characteristics for all models. The velocity of the projectile in all fabric models experienced a steep decline upon impacting the fabrics. Plain woven structure enabled the yarns to dislocate and formed around the projectile until penetration begins at 0.115s, as oppose to around 0.100s for the remaining three woven structures. Residual velocity of projectiles in the plain weave model was thus stabilized at a lower velocity 85 m/s, while the other three models possess the residual velocity in the range of 86.3–86.0 m/s.

Energy progression of all four woven structures presented in Fig. 11 also indicated similar behaviours over the three man energy absorbing mechanisms among the four models considered. A simple comparison of the four results presented in Fig. 11 reveals that:

(a) Plain weave structure absorbs 20%, 19.5%, and 16.5% more energy when comparing to satin, twill and basket weave.
(b) The evolution of $KE$ and $IE$ appears similar in all four models, where the two absorbing mechanisms initially increased and later separated after penetration of projectiles as observed in the plain weave model. $KE$-$IE$ dominance at the early stages was thus true for all woven structures considered.
(c) The absorption mechanism of $FE$ has shown greater contribution comparing to $KE$ and $IE$ in the case of plain and twill weave, while the three mechanisms appear equivalent in the satin and basket weave cases.
Fig. 11. Energy absorption channels of fabrics

Fig. 12a. Evolution of fabric kinetic energy

Fig. 12b. Evolution of fabric internal energy

Fig. 12c. Evolution of fabric friction energy
As shown in Fig. 12, greater energy absorption capacity from the plain weave structure can be observed in all KE, IE and FE mechanisms when comparing between the four different woven structures. Greater energy absorption capacity of the plain woven fabric is thus promoted by the superiority in all its major energy absorption mechanisms. Evolution of both KE and IE has shown little difference in magnitude and trend between the case of twill, satin, and basket weave. In the case of FE, superiority in energy absorption shown by the plain weave case also demonstrated greater energy absorption capacity from the plain weave structure can be observed in all KE, IE and FE mechanisms when comparing between the four different woven structures. Greater energy absorption capacity of the plain woven fabric is thus promoted by the superiority in all its major energy absorption mechanisms. Evolution of both KE and IE has shown little difference in magnitude and trend between the case of twill, satin, and basket weave. In the case of FE, superiority in energy absorption shown by the plain weave case also demonstrated a slight delay in the time of projectile penetration, follow by twill, basket, and satin weave case.

6 Concluding Remarks

Based on the discussed experiment results and the validated models, several conclusions and summary remarks can be drawn as listed below:

1. A meso-scale modeling approach has been utilized to construct a series of FE models simulating the ballistic impact of woven fabrics with various structures.
2. Ballistic experiments of plain woven Kevlar® 29 fabrics have been conducted to verify the simulation results from the constructed model.
3. The verified meso-scale model has provided important information in the evolution and significance of internal energy, kinetic energy, and friction energy on the total energy absorption mechanism of woven fabrics.
4. By obtaining the modeling results of four different woven textile architectures, detail comparison between the progression of KE, IE, and FE has been studied for gaining a better understanding of their energy absorption mechanisms.

Meso-scale modeling of textile structure remains at the pre-mature stage where several areas are yet to be explored. This preliminary investigation provided an encouraging insight into the variance of textile performance with different woven structures, which may aid further studies in identifying the influencing parameters for the enhancement and optimization of fabric ballistic protection performance.

7 References