Energy absorption among layers in the multiply system under ballistic impact

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Abstract. In this study, the energy absorption of each layer in the multiply system has been investigated experimentally and numerically to improve the theoretical understanding for the armour panel engineering. To achieve accurate results and to improve the calculation efficiency in FE simulation of multiply systems, different mesh sizes were used for the primary and the secondary yarns. The FE results were validated by the ballistic experimental results. The FE simulation results indicated that the energy absorption of each layer is not uniform, but increased from front to back layer. The energy absorption of front layers was constrained with more layers added in a panel, which is due to the high stress concentration and the constrained transverse deformation in front layers. Such energy absorption distribution in the multiply system suggested it is possible to obtain improvement of the ballistic performance by optimizing the construction of the armour panel.

Keywords: Soft body armour, energy absorption distributions, FE simulation

1. Introduction

Most of the soft armour panels are constructed from multiple layers (20-50 layers) of woven fabrics. However, combining uniform layers into a panel cannot be an efficient construction for an armour panel. To improve the performance of the soft body armour, optimizing the construction of the armour panel will be an efficient way.

The multiply system has been investigated for many years. Some studies have demonstrated that the ballistic resistance characteristics of each layer are not the same because of their different positions in the panel. Zohdi [1] analysed the energy absorbed per sheet is not uniform in a ballistic panel, and the energy absorption is controlled by the deformation modes, dictating the amount of kinetic energy and elastic strain energy absorbed by the sheet. Prosser [6] experimental discussed the ballistic behaviour of nylon cloth system impacted by the fragment-simulating projectile (FSP). He founded the work of penetration per interior layer is essentially constant, which were different from the strike layer and back layer. Cunniff [3] indicated the material near the strike face had little effect on the performance and failed before significant strain energy is absorbed. Joo and Kang [4] numerically analysed the energy absorption is the lowest for the first layer and increased along subsequent layers because the deformation of first layers is much smaller than back layers. Three-dimensional continuum finite element models have been employed in many previous studies to understand the nature of the response of the panel upon ballistic impact. But for the multiply system above one layer, the FE model at the yarn level was found to be computationally very expensive and became unstable with the number of layers increasing leading to the number of elements exceed a certain value. [5] The findings from all these investigations indicate that optimizing the panel construction of the soft body armour would be a feasible measure to improve the ballistic performance of the armour panel.

This paper reports on the investigation on the energy absorption capacity of each layer in the multiply system at the perforation case. The ballistic performance of different panels was evaluated by the ballistic test. To take insight into different ballistic characteristics of each layer, the energy absorption distribution in the multiply systems was analysed by FE simulation.

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2. Experiment

2.1 Experiment materials

In this study, Twaron woven plain fabric was used for the ballistic test and numerical simulation. The yarn count is 93tex and the weave densities are 8.3 ends/cm in the warp and weft direction. The multiply fabric panel is layered up by a certain number of fabric layers.

2.2. Ballistic test and results

The ballistic test was conducted at the ballistic laboratory of the University of Manchester. The fabric panels were impacted by cylindrical steel projectiles at an average velocity of 483 m/s and were clamped in a square steel frame (240×240 mm) with a circle in the middle (150 mm in diameter). The projectile was of 5.5 mm in diameter and height, and its weight 1.004 (+0.008) g in mass, which was located in plastic sabots. The energy absorption (EA) can be calculated from the impact velocity and residual velocity. To remove the areal density effect, the specific energy absorption (SEA) of armour panels was used to reflect the energy absorption capacity of different samples. The sample specifications and ballistic test results are listed in Table 1.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Number of layers</th>
<th>Thickness (mm)</th>
<th>Areal density (g/m²)</th>
<th>Energy absorption (J)</th>
<th>STD</th>
<th>SEA of panel (J.cm²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8F</td>
<td>1</td>
<td>0.20</td>
<td>155.35</td>
<td>6.07</td>
<td>0.87</td>
<td>390.79</td>
</tr>
<tr>
<td>8F₂</td>
<td>2</td>
<td>0.40</td>
<td>310.70</td>
<td>12.15</td>
<td>0.93</td>
<td>423.20</td>
</tr>
<tr>
<td>8F₃</td>
<td>3</td>
<td>0.60</td>
<td>466.05</td>
<td>18.43</td>
<td>1.46</td>
<td>395.49</td>
</tr>
<tr>
<td>8F₆</td>
<td>6</td>
<td>1.20</td>
<td>932.10</td>
<td>35.69</td>
<td>2.98</td>
<td>382.94</td>
</tr>
<tr>
<td>8F₉</td>
<td>9</td>
<td>1.80</td>
<td>1398.15</td>
<td>40.48</td>
<td>6.51</td>
<td>289.53</td>
</tr>
</tbody>
</table>

3. FE simulation

3.1 Material properties

Twaron woven fabric panels under impact were modelled at yarn level using ABAQUS/Explicit. The yarn in the fabric was modelled to be 3D solid continuum material. Each individual yarn was assumed to be isotropic material with the yield stress is 3.6 GPa and the fracture strain is 4.0%. The Young’s Modulus is 90 GPa. The projectile was defined as rigid body with the Young’s Modulus of 206.8 GPa. [6]

3.2 Geometrical modelling

The FE model of the single layer woven fabric was modelled at a quarter-symmetry with the size of 75×75 mm and the thickness of 0.2 mm. Each yarn in the fabric was meshed using the 8-node solid brick element. The yarn cross-section was meshed using 10 elements and yarn wavelength using 12 elements shown in Figure 1 (a).

![Fig. 1: Two mesh sizes](image)

(a) High mesh density; (b) Hybrid mesh density

To save the computational expense, the elements of the multiply system have to be cut down. In this study, the hybrid mesh densities are adopted in the model. For the primary yarns, the high mesh density was adopted as that of the single layer fabric shown in Figure 1 (b). For the secondary yarns, the elements in the cross-section reduced to 4 elements and the yarn path has 2 elements. For a single layer fabric, the FE model with hybrid mesh size only have 77,368 elements, which reduced 83%
compared with the FE model with the high mesh density. The multiply systems with the number of layers of 2, 3, 6, 9 were modelled by coping the single layer fabric with the hybrid mesh size. The computer running time is around 1-8 hours depending on the number of fabric layers.

3.3 Validation of the FE model

The FE model was validated according to the integral performance obtained from the ballistic test. The energy absorption of the FE model is close to the ballistic test result shown in Figure 2. The less energy absorption of the FE model is analyzed due to ignore of the friction between filaments and the yarn slipping from the clamps.

![EA of the single layer fabric](image1)

![EA of FE models with different mesh](image2)

To verify the mesh density effect on the performance of the single layer fabric, two FE models with uniform mesh and with the hybrid mesh were compared. The energy absorption of the FE model with the hybrid mesh doesn’t show much difference, which only a little difference of 0.19J has shown in Fig.3. This indicated such hybrid mesh density didn’t have too much negative effect on the energy absorption of the fabric, which can be used to develop the FE model of the multiply systems.

4. Results and discussions

4.1 The ballistic performance of armour panels

In the ballistic tests, the energy absorption capacity of the multiply system decreased with the number of layers increasing shown in Fig.4, which was analysed as the system effect by some researchers. [3] Such results indicated the energy absorption capacity of some fabric layers in a panel decreased with more additional layers added.

![The SEA in the multiply system](image3)

![EA of each layer in a Twaron woven panel](image4)

![EA of the first layer in Twaron panels](image5)

![Stress distribution of the ply-1 of 8F1 and 8F3](image6)
According to numerical results, in the multiply system, the energy absorption of each layer is not the uniform value, which increased with the position from front to back in a panel. Fig 5 showed the energy absorption of each layer in 6-layer panel before each layer perforated. In addition, with more layers added in the multiply system, the energy absorption of front layers become less and less, which can be indicated from the first front layer in different multiply systems with 2-, 3-, 6- and 9-layer shown in Fig 6. But the energy absorption reduction of front layers seemed to have a limit minimum value when additional layers increasing to a certain number.

With the number of layers increasing in the multiply system, the transverse deformation of front layers was constrained. Compared with 2-layer panel, the transverse deformation of first two layers in 6-layer panels was rather small shown in Fig 8. According to the stress distribution in the multiply system, there was high stress concentration on the first layer in a local area around the edge of the projectile shown in Fig 7, which leading to the first layer failed quickly and absorbed less energy. With the position back in a panel, the stress can be dissipated in larger area. More materials can produce transverse deformation and be involved into the energy absorption. As a result, the energy absorption of each layer increased from front to back in a panel.

5. Conclusions

In the multiply system, the energy absorption of each layer is not uniform, which increased from the front layer to the back layer. The energy absorption of front layers was constrained with more additional layers added due to the high stress concentration and the constrained transverse deformation. Such energy absorption distribution in the multiply system suggested it is possible to achieve the improvement of the ballistic performance by combining different components in optimum positions in an armour panel.

6. Reference