BALLISTIC PERFORMANCE OF KEVLAR FABRIC PANELS CONTAINING SHEAR THICKENING FLUID

J. Park[1], B. Yoon[2], J. Paik[2], T. Kang[1]*
[1] NCL, MSE, SNU, Seoul, ROK, [2] ADD, Daejeon, ROK
* Corresponding author (taekang@snu.ac.kr)

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1 General Introduction

Currently used body armors, particularly those for military use, are considered too heavy, limiting the agility and mobility of the wearer and eventually leading to increased casualties. Therefore, the demand for substantial improvement in the performance-to-weight ratio of body armor as well as the performance-to-thickness ratio is very high.
In this study we investigated the ballistic performance of Kevlar fabrics impregnated with shear thickening fluid (STF) against 9mm bullet at 436 m/s as well as the effect of laminating sequence in hybrid panels. Analysis with the method of accumulating successive line segments was also given to present the energy dissipation route of each panel during the impact.

2 Experiments

2.1 Materials

The STF used in this study was composed of 68wt% silica particles (45nm) and 32wt% polyethylene glycol (MW200) medium.
The fabric used was a plain woven Kevlar KM-2 600 denier 1027 style (28 yarns/inch for warp and weft) with an areal density of 149 g/m^2 in dried state.

2.2 Preparation of ballistic panels

The STF was impregnated onto the fabric with the add-on of 20%owf (on the weight of fabric).
Three types of panels were prepared; an all neat 32 ply panel (N), and two 29 ply hybrid panels of 15 ply STF impregnated Kevlar and 14 ply neat Kevlar, where the neat plies were placed in the front of the panel (N/S) or the back of the panel (S/N). All three types of the panels were either cross-diagonally stitched or unstitched.

2.3 Ballistic impact test

A 9mm bullet (FMJ RN, 8.0g) described in NIJ Standard 0101.04 was used as the impactor and the target measured velocity for back face signature (BFS) measurement was around 436m/s (NIJ threat level III-A).

3 Results and Discussions

3.1 Effect of laminating sequence on the ballistic pperformances of STF/Kevlar

The test results of 6 different types of panels having the same areal density of 4.768 Kg/m^2 are given in table 1. The results of a one-way analysis of variance of the data are shown in table 2. The experimental results are also shown in figures 1~3.

3.2 Analysis of the experimental results

The impregnation of STF onto the Kevlar fabric resulted in the increase of yarn pull-out force and the decrease in total strain to failure (figures 4~5).
From the single yarn pullout data, we obtained frictional force acting on each crossover of a single yarn in a fabric, which is the ratio of the maximum pullout force to the number of crossover. The stress distribution by the frictional force was determined by the method shown in fig.6.
The stress distribution will affect the total elongation of a single yarn in the fabrics of neat and STF impregnated. And the total elongation of a single yarn in a fabric can be calculated as follows (eqn 1).

$$\sum \Delta l_i = \sum \frac{F_i \cdot l_i}{E} = \frac{l_i}{E} \cdot \sum F_i \qquad (1)$$

Fig.7 shows the relative amount of increase in the apparent modulus of a single yarn within a fabric by STF impregnation with the increase of gauge length.

For the calculation of tensile dissipation of a multi-layered fabric panel, the method of accumulating successive line segments was devised in this study. Chocron *et al.* [2] has experimentally shown that the approximate time of initiation of elongation at early time of impact is almost at a regular interval. For simplicity of the calculation, the complex variable of time in kinematics was eliminated, and instead, tension-displacement of facing yarns in each layer was directly used. The coupling of elongational states of facing yarns in each layer will be different among the panels with different laminating sequence as shown in fig.8, where the yarns in STF treated layers have a higher tensile modulus.

Following is the calculation result of the possible maximum tensile dissipation of each panel with the assumptions: 125 mm gauge length, 10% increase in tensile modulus by STF, 0.15 mm compressed thickness (one layer), 1.6 % warp and 1.3 % weft crimp ratio, 3.8 % strain to failure, and 160 N/yarn breaking strength. If we show it just as in fig.8, the N-panel that consists of 32 layers of neat fabric can be represented with 32 dotted lines for the warp and 32 for the weft with slightly different starting positions due to the difference in crimp ratio, where each line segment denotes initial 10 yarns (*i.e.* 10 yarns/9 mm). Each dotted line will have a maximum y-value of 3200 N (*i.e.* 10 yarns x 160 N/yarn x 2, fig.9), and a maximum displacement of 4.75 mm (*i.e.* 125 mm x 0.038). The S/N- and N/S-panels that consist of 29 layers can be represented with 15 solid lines for the warp, 15 solid lines for the weft, 14 dotted lines for the warp and 14 dotted lines for the weft yarns, where the solid lines have a steeper slope than dotted lines and reverse position in each panel. The increase in apparent modulus of a single yarn by STF treatment (solid line) will lead to a maximum displacement 10% lower than the above value. If the bullet hits the center of each yarn, the tension of both side of the yarn will work as shown in fig.9. At an increased tension value at which the bullet begins to expand, the number of facing yarns will increase with the bullet expansion. The tension-pressure relationship shown in fig.9 was used to simulate the bullet expansion, where the conical angle was assumed to be constantly 65 ^{o}. The yield stress of compression of the bullet was determined to be 0.36 GPa, which well matched the experimentally measured value of bullet expansion.

Fig.10 shows the tension-displacement curve of each panel. Down-arrow in the figure indicates the boundary between the perforated (failed) layers and layers that survived in each panel, which were obtained from the experimental results. Each local peak in a curve indicates the failure of all facing warp or weft yarns in a single layer. An earlier onset of bullet expansion and that of perforation of frontal layers were observed with the S/N-panel compared to the others, while the N/S-panel showed a larger tension value at its maximum than the others.

The total energy dissipation at their ballistic limit, which is equal to the impact energy (*IE*), includes the kinetic dissipation (E_K), which is the energy transferred to the backing clay, as well as the tensile dissipation (E_T). We have found that the trauma depth of 32 and 44 mm correspond to E_K of 50 and 90 J, respectively. Fig.11 shows the possible maximum tensile dissipation-displacement curve of each panel, which is the integrated area of each curve in fig.10. In the figure, the energy dissipation through E_K, $E_{T, L}$, and $E_{T, R}$ routes by each panel was marked with arrows, and the right end of each curve is not the real tensile dissipation (E_T), but just a fit to the tensile dissipation ($E_{T, max}$) of each panel at their ballistic limit.

The best result was obtained from the N/S-panel, which is attributed to right combination of neat and STF treated layers. At a certain point of early time of impact, the ‘high-elongation/ high-tension’ of facing yarns within neat frontal layers coupled efficiently with the ‘low-elongation/high-tension’ of facing yarns within STF impregnated rear layers, and this resulted in a better ballistic protection.

This way of analysis can be partly supported by the fact that unidirectional (UD) fabrics are generally more effective in expanding of a frangible bullet than woven fabrics. The ratio of areal density to thickness is related to how much closely fibers or yarns are packed together. The theoretical packing density of yarns in a UD fabric is over 75 vol% (tetragonal packing), while that in a woven fabric is merely less than 55 vol%. So a UD fabric will have a smaller interval between adjacent line segments if shown in fig.8, which will bring about a similar result to our experiment. And an additional work with UD/woven hybrid panels against a .44Magnum SJHP resulted in a similar result in terms of laminating sequence.

4 Conclusions

The impregnation of STF to the fabric increases the frictional force of a single yarn in the fabric and this increases the apparent modulus of the yarn compared to that of a single yarn in the neat fabric. The laminating sequence was found to be important to improve the ballistic performance of hybrid panels containing STF, which affected not only the BFS value but also the perforation ratio (or ballistic limit) and bullet expansion. The increase in ballistic performance of the N/S-panel than the other panels was assumed to be due to the higher synchronization of elongation of facing yarns in frontal layers and those in following rear layers during the impact, and this was supported by the method of accumulating successive line segments.

Acknowledgements

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[2] Sidney Chocron, Charles E. Anderson Jr., K. Ranjan Samant, Eleonora Figueroa, Arthur E. Nicholls, James D. Walker, "*Measurement of strain in fabrics under ballistic impact using embedded nichrome wires, part II: Results and analysis*" International Journal of Impact Engineering, 37, pp 69–81, 2010.

Figures;

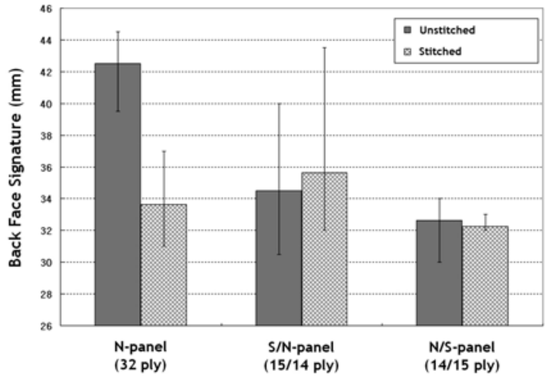

Fig.1. Effect of laminating sequence on the backface deformation.

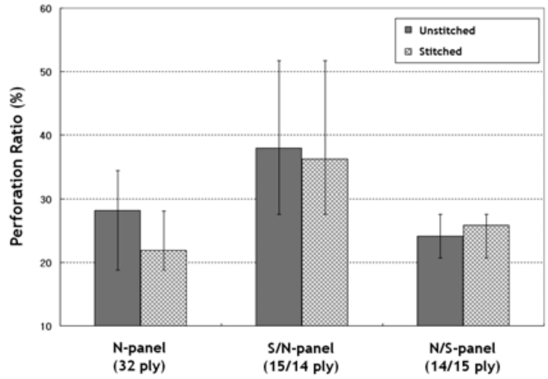

Fig.2. Effect of laminating sequence on the perforation ratio.

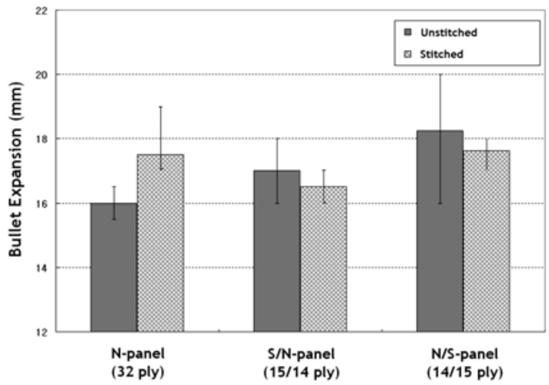

Fig.3. Effect of laminating sequence on the expansion of a 9mm FMJ RN bullet.

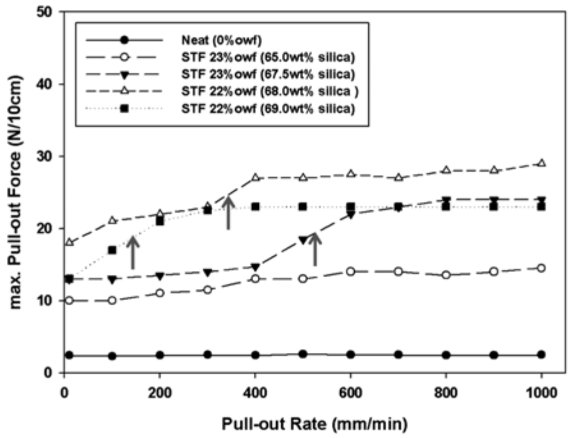

Fig.4. Effects of particle content in STF and pullout rate on maximum pullout force of a single yarn with the gauge length of 100 mm.

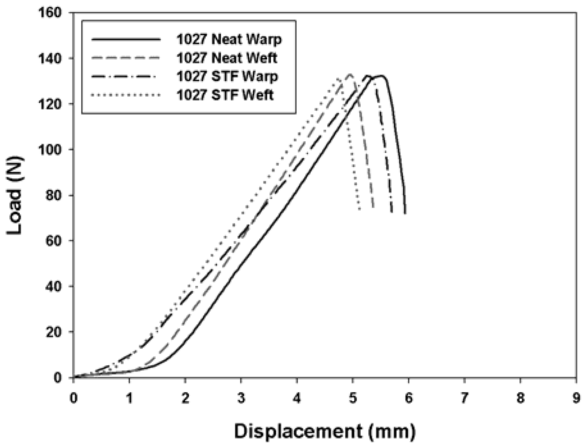

Fig.5. Load-elongation curve of a warp and a weft yarns within a neat and a STF impregnated fabrics. (gauge length 100 mm, primary load 0.75 N, cross-head speed 1000 mm/min)

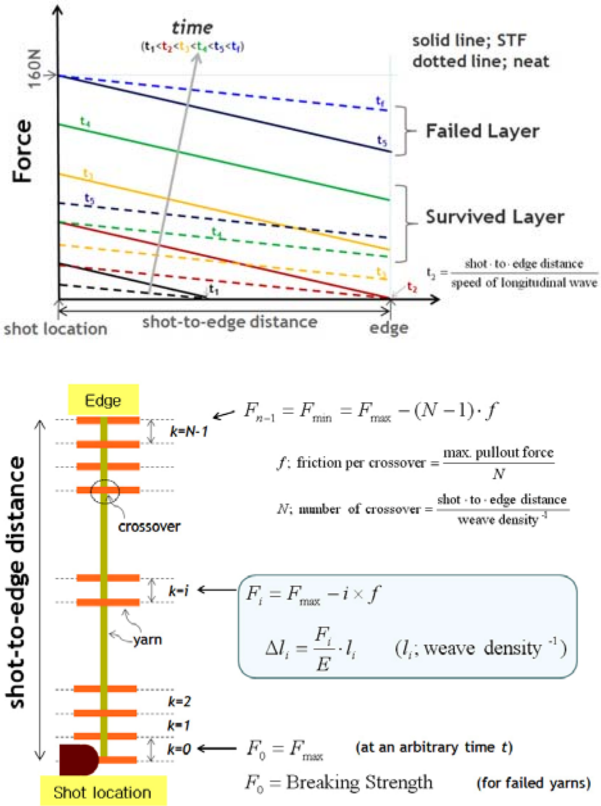

Fig.6. The stress distribution of a single facing yarn; the change of stress distribution with time (top) and the stress distribution along the yarn direction (bottom).

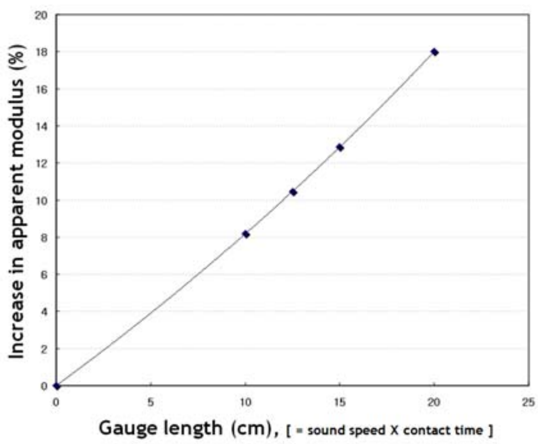

Fig.7. The relative amount of increase in the apparent modulus of a single yarn within a fabric by STF treatment.

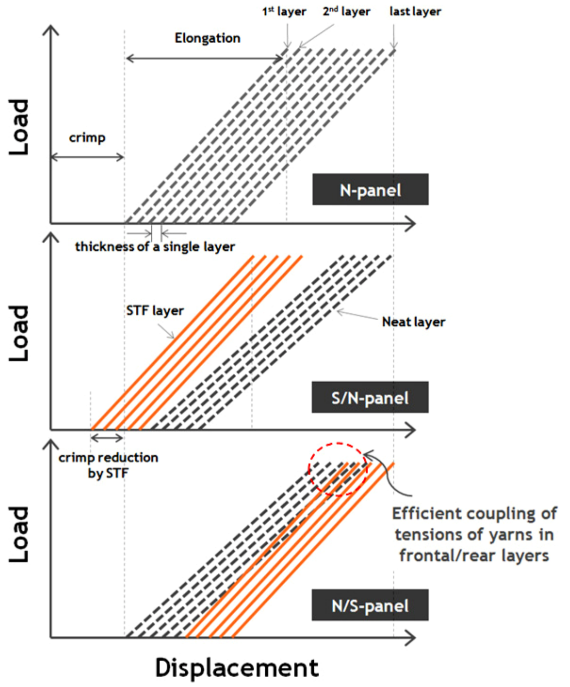

Fig.8. Schematic drawing of the elongation of multi-layered N-panel, S/N-panel and N/S-panel.

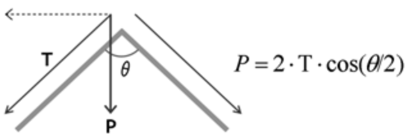

Fig.9. Relationship between the tension and the pressure acting on a bullet.

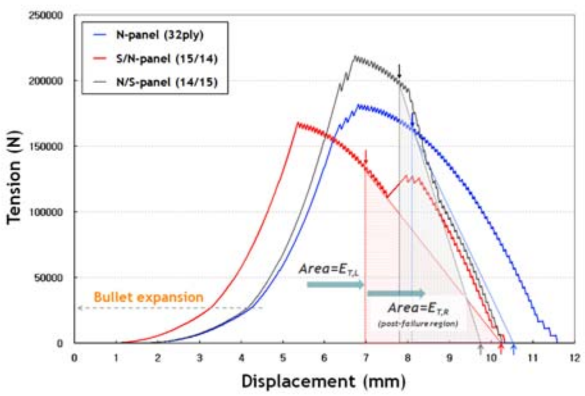

Fig.10. A presumed tension-displacement curve of sum of all facing yarns in each panel including the effect of bullet expansion.

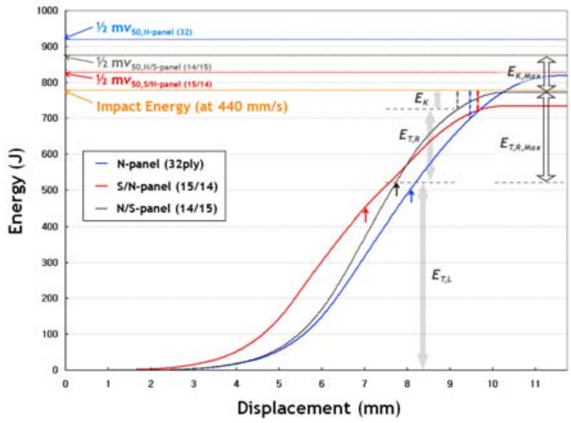

Fig.11. A presumed energy dissipation curve of each panel used in the ballistic experiment.

Tables;

Table 1. Effect of laminating sequence

Panel	BFS[a]	PR[b]	BE[c]
N	42.5	28.2	16.0
N_{3s}*	33.6	21.9	17.5
S/N	34.5	37.9	17.0
S/N_{3s}*	35.6	36.2	16.5
N/S	32.6	24.1	18.3
N/S_{2s}*	32.3	25.9	17.6

BFS[a]; back face signature (mm)
PR[b]; perforation ratio (%), perforated plies per total laminated plies
BE[c]; bullet expansion (mm), forward diameter of expanded bullet after the impact
3s*, 2s*; cross-diagonally stitched with 3 inch and 2 inch interval

Table 2. One way analysis of variance of the data of unstitched panels in Table 1

	BFS	PR	BE
p-value	0.001851	0.061205	0.055183