




Finite Element Study on the Influence of Structural Parameters on the Ballistic Performance of 3D Networked Fabrics

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Abstract

Networked fabrics are a type of three-dimensional multilayer fabrics having predetermined interconnections between layers by combining yarns from two adjacent sublayers into one. This paper reports the research on the influence of structural parameters on the ballistic performance of networked fabrics using finite element analysis in parallel with experiment. The widths of separate and combined sections are found to affect the energy absorption (EA) of regular networked fabrics against high-velocity impact. Separate sections of networked fabrics generally outperform combined sections. The optimal width of the separate section is around 9.5 cm for both dense and loose networked fabrics when impacted at the separate section. The optimal width of combined section decreases from 2.38 cm to 1.15 cm with the decrease of weave density in this area. For the studied structural parameters, highest EAs of dense and loose networked fabrics are around 13.3% and 17.1% higher than those of their counterpart layouts of dense and loose plain-woven fabrics, respectively. These findings suggest networked fabrics could be engineered to improve the ballistic performance of flexible fabrics.

Keywords Finite element modelling · 3D networked fabric · Ballistic impact

1 Introduction

Fabrics made with high-performance materials such as para-aramid and UHMWPE are widely used for soft body armours. During the past decades, a lot of experiments and theoretical work have been conducted to understand the impact behaviour of soft body armours, which were reviewed in [1–3]. Flexible armour undergoes minimal transverse deformation and spreads

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impact energy over an area to provide protection. When a projectile impacts into a protective fabric, the kinetic energy of the projectile is converted and dissipated as kinetic energy of the fabric, strain energy of the yarns, and energy consumed due to frictional sliding. The ballistic performance of a fabric assembly depends on its ability to absorb and convert energy through impact interaction and to dissipate energy quickly to a large area to avoid early local failure. This ability is affected by the energy dissipation performance of the fibres, fabric weave construction, number of fabric layers and boundary condition, and by the characteristics of the friction, projectile shape and trajectory.

Plain and basket woven fabrics are most widely used structures for ballistic protection because their high intersection ratios are recognised advantageous to transfer impact energy to the adjacent yarns [4]. Narrow fabrics with selvedge could have improved ballistic performance over full-width fabrics in the same structure [5] but have the disadvantage of yarn discontinuity in off-set ballistic panel [6]. Sun et al. [7] reported that gripping and/or jointing making wide fabrics simulate the effects of fabric selvedges as those in narrow fabrics can overcome this disadvantage while keeping the effects of narrow-fabric-with-selvedge. Their experimental work showed leno structure and networked structure have higher specific energy absorption than plain-woven fabrics. Networked fabrics are also known as cellular (or honey-comb) fabrics, patented by Takenaka and Sato [8] in 1991, but used in their flattened state.

Networked fabrics are a subset of 3D multilayer textiles where adjacent fabric layers are connected and kept separate in a predefined pattern, instead of dense connection. The combining methods include 2D weaving with a doubled warp density, stitching of two layers, and 3D orthogonal weaving [9, 10]. Apart from the stitching methods, the widths of separate and combined sections and the number of sublayers are several important structural parameters of networked fabrics. In a case of combining the 2 layers into a single joint layer, the cover factor of fabric in the joint section would be high [11]. When 2D weaving method is used, the doubled warp density makes the combined section, which has increased tightness, perform similarly to the selvedge in leno structure. The separate sections then are similar to narrow fabrics but the combining yarns are in continuity throughout the whole fabric. Combining yarns could also switch sublayers they initially belonged to resulting in the warp yarn interchange networked fabrics. Multilayer networked fabrics could also reduce the effort of layering up and stitching in soft body armour construction. Networked fabrics could also be used as reinforcements of composites to provide improved delamination resistance due to the interconnections between sublayers.

This paper reports the influences of structural pattern, the widths of separate and combined sections, on the energy absorption ability of 2-sublayer networked fabrics utilising finite element (FE) method. The structure of this paper is as follows. The specifications of the FE model are detailed first. This includes the fabric architecture, material properties of the yarn, and the formulation of the ballistic impact at flexible fabrics. Obtained results are presented and discussed in the following section. The final section gives the main conclusions drawn from this work.

2 Experiment

Ballistic tests give empirical data of the energy absorption ability of different areas of the networked fabric. The energy absorption data are used to validate the FE model and serve as a baseline for further parametric study.

2.1 The Fabric

A 2-sublayer regular networked fabric, NFL2s51c27P, is woven in-house with a Northrop Shuttle loom with mechanical Dobby to perform energy absorption test for model validation. Here, s51 stands for 51 wefts in the separate section and c27 for the combined section. Using weft number in the naming is only for simplicity. Both sections have been designed as balanced plain-woven structure. The weave density is 16 threads/cm. For the double-layer separate section, each layer has a thread density of 8 /cm in warp and weft directions. These lead to a width of 6.375 cm of separate section, which is close to 6 cm that was found to be the optimal band width for the jointing narrow fabrics [7].

Figure 1 shows the woven 2-sublayer regular networked fabrics NFL2s51c27P. Weave density is measured by counting threads in certain fabric length then averaging it. The warp and weft densities are both 8.00 threads/cm in separate section respectively. Warp density is doubled in the combined section. Weft density of combined section is lower than the designed value although the gears controlling pick density are set such that the thread density is 15.9 picks/cm according to the loom specification. This is because that weft density higher than 13.0 makes the fabric too tight to weave and causes weft yarn broken during weaving. The measurements have avoided the areas that have transitional changing of weave density. Based on this measured fabric density, the width of combined section is 2.08 cm. It is kept narrow because the work of Yang [12] showed that the specific energy absorption of fabrics decreased upon fabric density increasing from 8.3 to 12.6 /cm. On the other hand, the combined section is wide enough for testing its ballistic performance when projectile lands directly at this area although studies on striking on this area are not included in this paper.

2.2 Energy Absorption Test

The fabric is cut into pieces prepared for shooting testing with planned striking locations as separate section, combined section and the joint between these sections. Photonic detectors are used to detect velocities of the projectile before (v_i) and after (v_r) the impact. Energy absorption (EA) can then be calculated as the kinetic energy loss of the projectile,

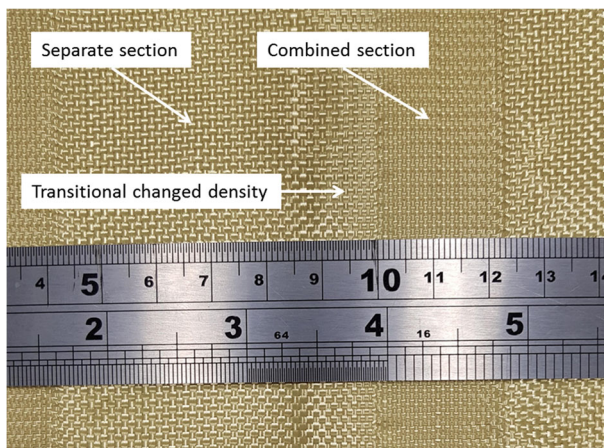


Fig. 1 Photo of networked fabric NFL2s51c27P

$$\Delta E = \frac{1}{2} m (v_i^2 - v_r^2)$$

where m is the mass of the projectile. The EAs are shown in Table 1.

3 Finite Element Model

This section provides a detailed description of the FE analyses used to study the strain wave propagation and effect of in-layer structural parameters on energy absorption ability of networked fabrics against ballistic impact. The FE simulations were performed with the commercial FE analysis code ABAQUS.

3.1 Material Model of Yarns

In this paper, meso-scale FE model is used in order to reflect the architecture of networked fabrics. This means the warp and weft yarns are modelled explicitly assuming they are continuum entities and the cross-section is defined as lenticular [13], i.e. the shape formed by a pair of symmetric arcs. In yarn-level, FE modelling, the fibre-scale effects are not explicitly considered. The cross-sectional areas of the yarns are assumed same for simplicity although yarns in the structures with different fabric densities normally have different packing tightness and different thickness. The area is 0.0795 mm² and the density of the yarn is 1.170 g/cm³ for the 93 tex Twaron[®] yarn based on a fibre volume fraction of 81.26%.

Fibres and voids among them within the yarn are homogenised as a single material, which is considered to be orthotropic linear-elastic material up to the point of failure. Yarns usually consist of hundreds even thousands of fibres. Within untwisted yarn, the fibres are close to parallel align along the fibre-length direction. This direction is associated with the highest level of stiffness of high-performance yarns such as those made with Twaron[®] and Dyneema[®]. Previous research [14–17] has shown that the orthotropic elastic continuum can model the yarn behaviour if the transverse and shear moduli are set to around one-hundredth of the longitudinal modulus. For Twaron[®] 2040 fibre based 93 tex yarn, the longitudinal tensile modulus is set to 72 GPa [18]. The transverse and shear moduli are set to 0.7 GPa for the flatter yarns or yarn segments in separate sections where the yarn thickness is 0.10672 mm. For yarns or yarn segments in combined sections, this value is slightly reduced to 0.555 GPa to account for a larger transverse deformation allowance to failure because the yarns have larger thickness (0.2024 mm) in these areas. Poisson's ratios are chosen to be 0.2 for transverse direction and 0.45 for longitudinal direction.

The failure of yarn in different load conditions is modelled with maximum stress criterion [19] given the fact that the yarns are bundles of loose individual fibres. Maximum stress in longitudinal direction is 3.08 GPa, which is equivalent to a maximum strain of around 0.043

Table 1 Energy absorption data of NFL2s51c27P against ballistic impact

Impact locations	Energy absorption (J)	Number of shots	Standard deviation
Separate section	15.51	10	1.54
Combined section	9.34	5	0.79
Joint	9.93	5	0.96

[18]. Maximum stresses for transverse and shear failure are set to the same as 0.86 GPa by reverse reasoning according to energy loss shooting tests against plain-woven fabrics. After the onset of failure, the stiffness of the material is gradually reduced under an exponential rule and the elements experiencing extreme deformation are eroded from the model to avoid convergence problem.

The model has been validated by matching the energy absorptions of 1-, 2- and 4-layer assemblies of plain-woven fabric with a thread density of 7.8/cm recorded in the energy absorption shooting tests presented in Wang's work [20]. It is verified to be suitable for networked fabrics since the predicted energy absorptions of striking at different locations of NFL2s51c27P agree to the experimental results.

3.2 Configuration of the Model

In the FE analyses, a right-end cylinder projectile transversely strikes onto the centre of the fabrics. An initial velocity of 475 m/s is prescribed for the projectile. This velocity is around the average striking velocity in the experiments.

Figure 2 illustrates the model of NFL2s51c27P against ballistic impact in different views. The dimension of the fabrics is 200 mm × 200 mm, which is comparable to the size of the fixture holding the fabric assemblies during shooting experiment. Fabrics are perfectly fixed at four edges. The warp yarns are along the axis x and the weft yarns are along the axis y . The projectile lands at the centre of a separate section. Projectile flying direction is normal to the x – y plane (the fabric plane). The frictional coefficient of yarn-yarn and yarn-projectile is chosen to be 0.2 based on the study of Zeng et al. [21] and Chu [18] for general contact to model the interactions among them.

The projectile is a 1.018 g right-end cylinder steel fragment-simulating projectile (FSP). The diameter and length of this FSP are both 5.56 mm. Since steel has significantly higher stiffness (210 GPa) than Twaron[®] yarn (72 GPa) does and the FSP shows no visible deformation during shooting tests, the projectile is modelled as rigid body in ABAQUS. All parts are modelled with 3D solid element C3D8R (first-order eight-node solid-brick elements with reduced integration) and/or C3D6 (six-node). Note should be taken that the C3D6 elements at the edge of the yarns imported from TexGen are treated as C3D6R in ABAQUS/Explicit. Other FE controlling techniques, such as hourglass control, distortion control and solver accuracy, are kept at their default settings.

The computational cost of the model is reasonable. The adopted mesh scheme for the yarns is 8 elements in cross-section and 7 to 12 elements along the fibre direction in one crimp wavelength. This rough mesh is chosen to balance the accuracy of geometric modelling and computational cost [22]. Simulations are run on the Computational Shared Facility of the University of Manchester. A single model uses 8 CPU cores and 128 GiB memories, taking around 20 to 30 h when the time of impact process is set to 35 μ s for the dense (8 threads/cm in separate sublayer) networked fabric models.

3.3 Fabric Specifications

The FE analyses are targeted on the effects of structural parameters, i.e. different widths of the separate and combined sections as shown in Fig. 1, of the 2-sublayer regular networked fabrics.

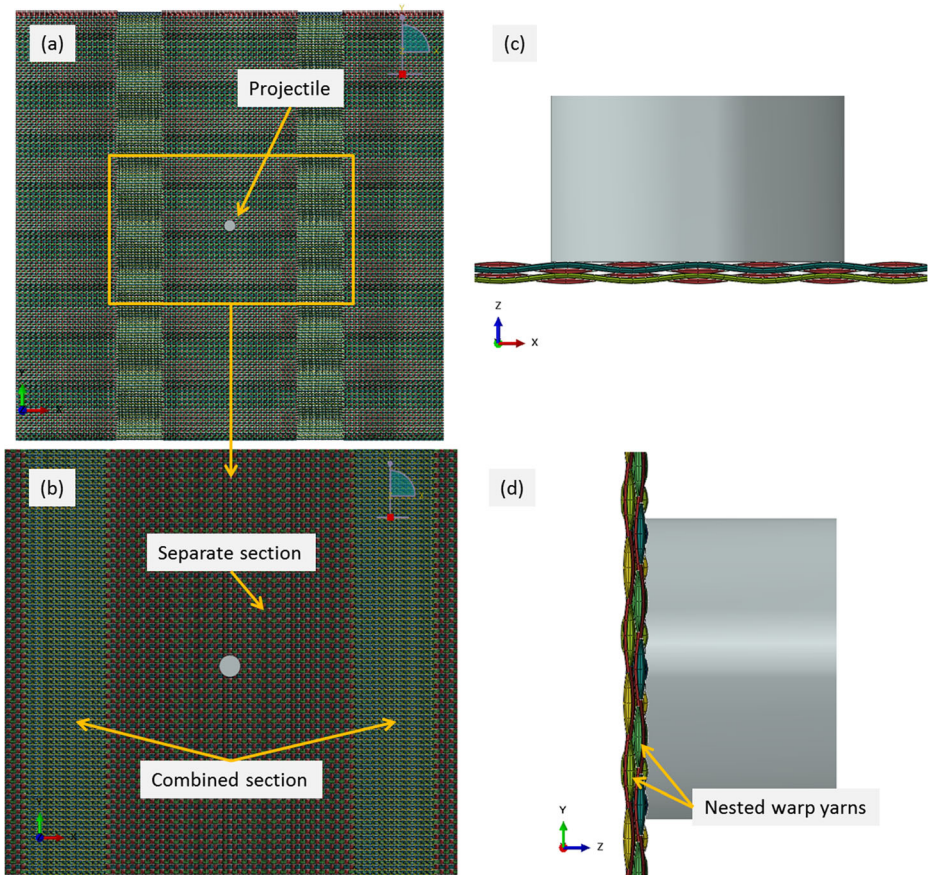


Fig. 2 Different views of the FE model for NFL2s51c27P: **a** the whole model, **b** zoom-in of the central part, **c** side-view toward z-x plane and **d** side-view toward y-z plane

Two types of networked fabrics are modelled, which are dense networked fabrics (DNF) and loose networked fabrics (LNF) classified based on the fabric density of their separate sections. Weave densities of the DNFs are the same as those of the manufactured fabric described in previous section. As for the LNFs, weave density of the separate sections is 4 threads/cm for warp and weft yarns and the number is doubled for the combined sections. Therefore, the combined section of the LNFs has the same structure, which has a balanced 8 threads/cm fabric count, as a single sublayer in the separate section of DNF. To be noted, the cross-section of yarns or yarn segments in the separate sections of LNF is assumed the same as that in the combined section because the yarns are already much flattened at a weave density of 8 /cm.

The widths of the separate and combined sections of networked fabrics are chosen in reasonable ranges to investigate the influences. Pick numbers in both sections are used to indicate different networked fabric models. As shown in Table 2, only those cells filled with width values in centimetres are selected so that the widths of separate sections are in a range around the optimal width (6 cm) for gripping fabrics [7]. Width increment is around 1.5 cm for separate section and halved for combined section. Odd numbers are chosen so that the networked fabrics have minimal repeat lengths for each pair of parameters [23]. The width

of the separate section does not range too high considering the characteristics of local response of fabrics during high-velocity impact [24, 25].

The FE simulations of two-layer layouts of the dense plain-woven fabric, which has weave density of 8 threads/cm, are used as baselines to reveal the characteristics of the responses of networked fabrics under ballistic impact. FE simulations give an EA of 15.71 J for non-nested specimen (PWNN) and an EA of 15.26 J for bias-nested specimen (PWBN) for this plain-woven fabric. “Bias-nested” means the fabrics are nested only on warp yarns as shown in Fig. 3. Nesting of yarns in the model significantly affects the energy absorption in case of low fabric density. As for LNF, FE simulations show an EA of 12.89 J for PWBN and 9.88 J for PWNN. The PWBN models show significant higher EA than PWNN in case of LNF while they are close in case of DNF.

4 Results and Discussion

4.1 Energy Absorptions of Different Areas of Networked Fabrics

Networked fabrics show different energy absorption when being impacted at different areas because of their different structures. For the studied DNF and LNF, the EA when impacted at separate sections is superior to those being hit at combined sections and the joint area.

Figure 4 gives the comparison of energy absorptions of networked fabric NFL2s51c27P between experimental results and FE predictions. FE simulations report EAs of 15.11 J and 9.19 J for impacts on separate and combined sections respectively, agreeing well with the experimental results. Predicted EA, when impacted at joint, is 11.05 J, which is 11.3% higher than experimental result. This, however, is not recognised as a stopper of this FE modelling being applicable because of uncertainties caused by following situations. Firstly, the real fabric has transitional changed pick density on the separate section side to the joint while the modelled networked fabric has no such issue. The higher density of the transitional area, compared to that in separate section, could lead to an inferior ballistic performance of the fabric. The work of Yang [12] showed that the specific energy absorption of fabrics decreased upon weave density increasing from 8.3 to 12.6 ends/cm. Secondly, the joint is too small for perfect striking in experiment but the striking location in FE modelling is ideal. Last, the dual-material model cannot ideally represent the cross-section-changing segment of the yarn. In this dense networked fabric, the inferior performance of combined section might root in the fact of high weave density in this area because it leads a much stiff fabric that is prone to shear failure and the yarns are prone to be degraded by the weaving process [7, 11, 12].

Experiment and FE modelling show that the combined section and joint area are weak points between adjacent separate sections for both DNFs and LNFs as shown in Fig. 5. This indicates

Table 2 Selected widths of separate and combined sections for DNFs and LNFs

DNF	Number of picks	15	27	39	51	63	75	87	99
	Width of separate section (cm)	1.88	3.38	4.88	6.38	7.88	9.38	10.88	12.38
	Width of combined section (cm)	1.15	2.08	3.00	3.92	4.85	5.77	6.69	–
LNF	Number of picks	7	13	19	25	31	37	43	49
	Width of separate section (cm)	1.75	3.25	4.75	6.25	7.75	9.25	10.75	12.25
	Width of combined section (cm)	0.88	1.63	2.38	3.13	3.88	4.63	5.38	–

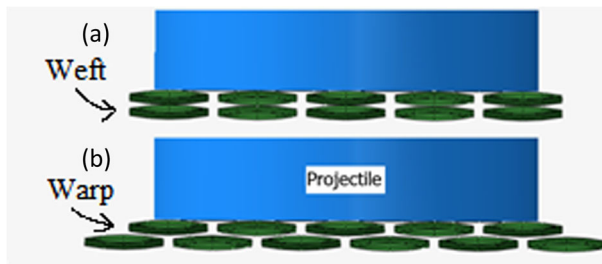


Fig. 3 Relative position between projectile and (a) weft yarns without nesting and (b) bias-nested warp yarns

that the separate section should dominate in such structure and the presence of combined section should be minimised. The following analysis, therefore, focuses on the effect of widths of separate and combined sections on the ballistic performance of the separate areas.

4.2 Influence of Widths of Separate Sections on EA

Networked fabrics are modelled with the two sublayers in separate section being bias-nested for the convenience of arranging the combining yarns. The bias-nested feature is by no means the realistic situation in networked fabrics because of the flexible characteristic of dry yarns in such materials. This is also true for layup of plain-woven fabrics. However, FE simulation shows that non-nested and bias-nested structures demonstrate different energy absorption when normally impacted by high-velocity projectile. In order to focus on the effects of networked structure, the following analyses use bias-nested layup of plain-woven fabrics as a reference.

As shown in Fig. 6, energy dissipation performance of networked fabrics is influenced by their widths of separate sections. However, the influence is not always positive and the EAs fluctuate around the EA of their counterpart PWBN fabrics. For DNFs, their energy absorptions are equivalent to or higher than that of the counterpart bias-nested layup of two layers plain-woven fabric in the given range of section width. For LNFs, the EAs are mostly lower than that of their counterpart PWBN fabric. Both DNFs and LNFs have an optimal separate

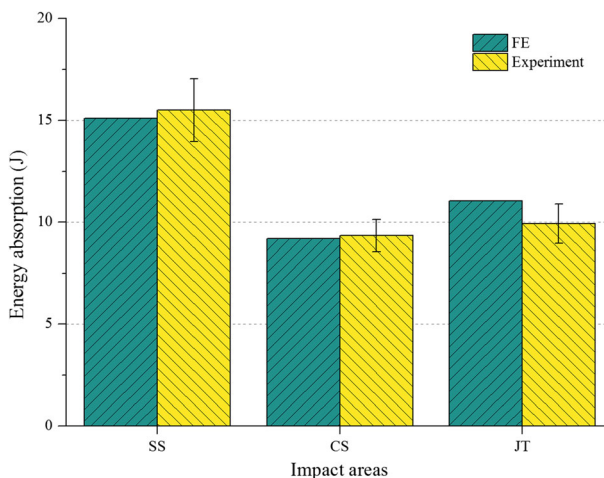


Fig. 4 Comparison of energy absorptions between experiment results and numerical predictions for NFL2s51c27P for projectile landing locations: SS – separate section; CS – combined section; JT - joint

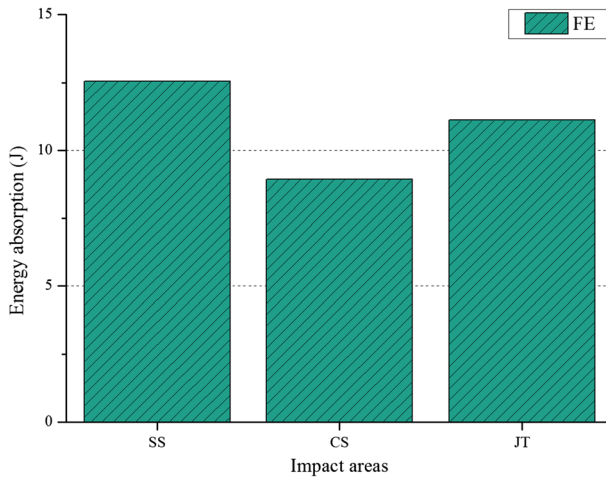


Fig. 5 Energy absorptions of NFL2s25c13P impacted on different locations: SS – separate section; CS – combined section; JT - joint

section width in the range of 8 cm to 10 cm. The EA of DNF is about 13.3% higher than that of the PWBN (17.29 J to 15.26 J), and LNF 17.1% (15.09 J to 12.89 J) when widths of separate sections are 9.38 cm and 9.25 cm respectively.

The curves of energy changes as functions of time for the DNF models are shown in Fig. 7, in which (a), (b) and (c) show changes of KE, SE and FD over time and (d) illustrates the maximum values of these energy forms during the changing. Kinetic energy shares the largest portion in case of DNF against ballistic impact, as can be seen from Fig. 7(d), followed by strain energy. Although kinetic energy transfer from projectile to fabric contributes the most (around 50%) to the total energy absorptions, KE and SE have the same fluctuation trend among models. The fluctuation range is around 1.5 J (around 10% of EA of the PWBN). Energy dissipated by frictional effects does not fluctuate too much between different DNF models as shown in Fig. 7(c) and (d). Variances of all the three forms of energy dissipated, which are the results of subtracting the maximum KE, SE and FD of PWBN model from those

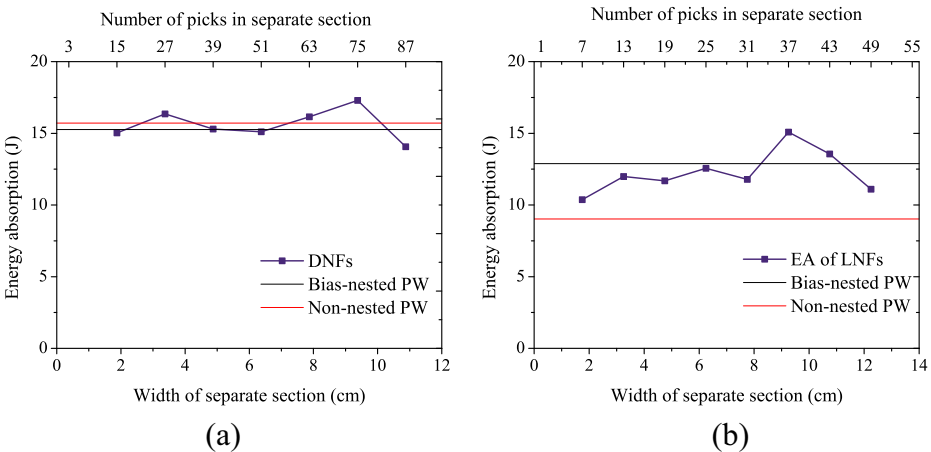


Fig. 6 Energy absorption as function of widths of separate section for dense networked fabrics (a) and loose networked fabrics (b)

of DNF models, show that all FD values in DNF models are smaller than that in PWBN model as shown in Fig. 8. To be noted, these maximum values are extracted at a per energy form and per model basis. These features indicate that different networked structures affect the efficiency of transferring KE from projectile to yarns, the degree of deformation of yarns in the fabrics and the relative movements between yarns.

Structure of LNFs also has influences on their energy absorption abilities but in different forms. In LNFs, as shown in Fig. 9a, the contribution of strain energy is generally larger than kinetic energy dissipation, which is contrary to the situation in DNFs. This is because there are less primary yarns under the direct impact of the projectile for LNFs due to their lower weave density. The low weave density also causes a low contribution of frictional effects in energy absorption because fewer primary yarns are pulled directly. By comparing the maximum KE, SE and FD of LNFs to those of their counterpart PWBN model as shown in Fig. 9b, it is obvious that SE shows the most divergence. It also shows that all three energy dissipation forms are lower than those of the counterpart PWBN.

4.3 Influence of Widths of Combined Sections on EA

Figure 10 illustrates the variances of energy absorptions of DNFs and LNFs with the changes of their combined section widths when they are impacted at the centre of separate section. EAs of

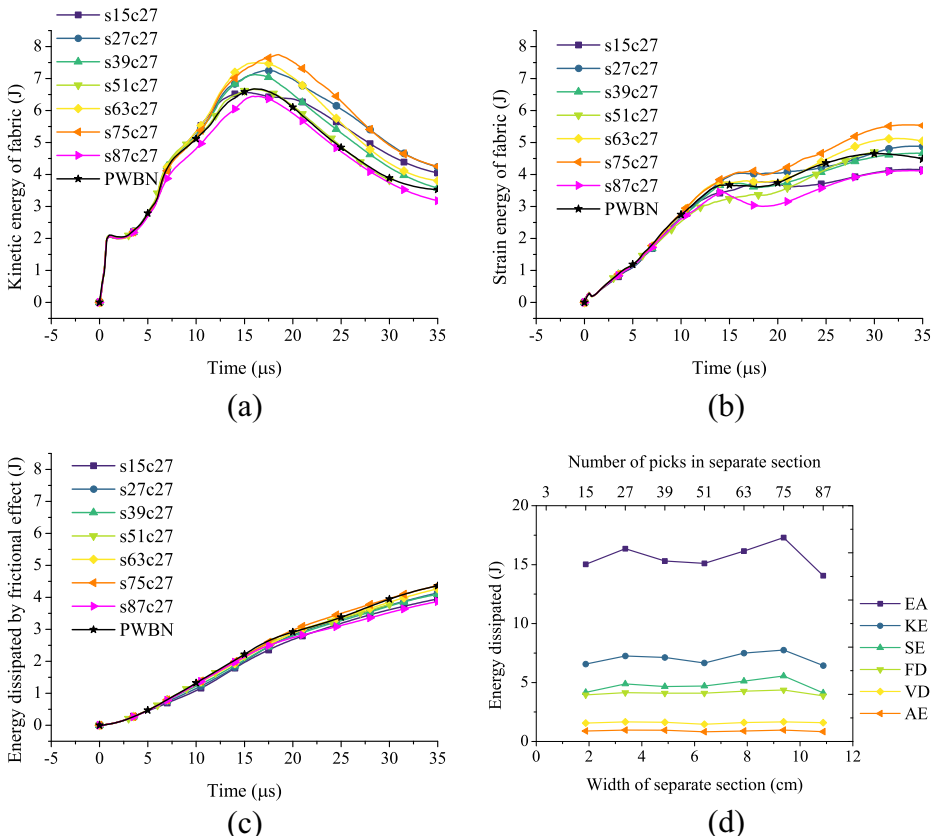


Fig. 7 Energy absorptions of DNFs: (a) KE, (b) SE, (c) FD and (d) maximum values in different energy forms

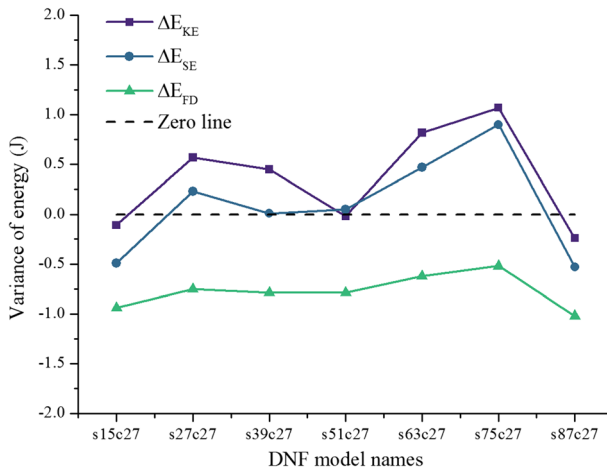


Fig. 8 Variance of KE, SE and FD of DNF models to the counterpart PWBN

both DNFs and LNFs decrease significantly, around 13.4 and 14.2% lower than those of their PWBN counterparts when the width of combined section is larger than 3 cm. The optimal widths of combined section are around 1.15 cm and 2.38 cm for DNFs and LNFs. This indicates that the optimal width of combined section is smaller when the weave density is higher.

The breakdown by energy forms of EA for DNFs and LNFs with various combined section widths shows similar weigh of different energy dissipation forms as those features appear in changes to separate section width. The FD is barely affected by the width change. KE and SE vary in the same pattern when the width of combined section changes.

5 Conclusions

Based on energy absorption shooting tests and the FE analyses on the influences of structural parameters on the energy absorption ability of 2-sublayer networked fabrics against high-velocity impact, the following conclusions can be drawn:

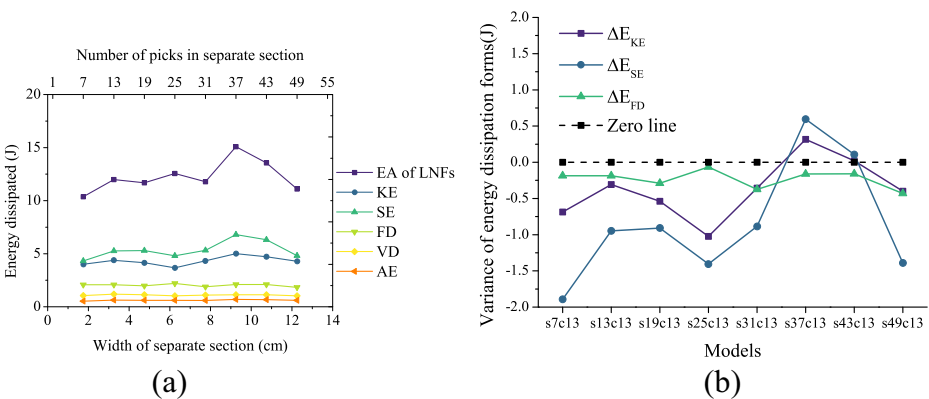


Fig. 9 Breakdown of energy dissipation forms in LNFs (a) and changes of maximum values of KE, SE and FD to PWBN (b)

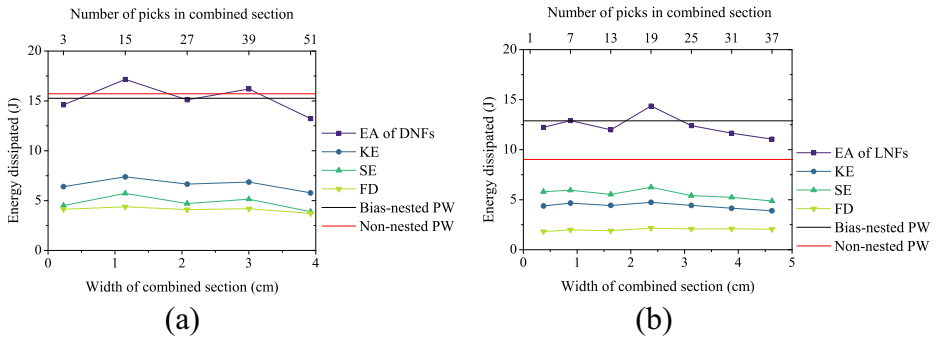


Fig. 10 Energy absorption as function of widths of combined section for dense networked fabrics (a) and loose networked fabrics (b) with maximum values of KE, SE and FD

1. Networked fabrics show higher EA when impacted at the separate section than at the combined section. When fabrics are dense, the combined section shows inferior ballistic performance than layout of plain-woven fabrics with the same areal density. Loose networked fabric, on the other hand, will not weaken the ballistic performance of combined section.
2. Ballistic performance of networked fabrics is affected by their structural parameters, i.e. the width of separate and combined sections. For both dense and loose networked fabrics, the optimal width of separate section is around 9 to 10 cm. The optimal combined section width (1.15 cm) of dense networked fabrics is lower than that (2.38 cm) of loose networked fabrics.
3. The structure has different influences on different energy dissipation forms. Energy dissipated by frictional effects is less affected than kinetic energy and strain energy are.

Networked structure could enhance the ballistic performance of fabric assemblies with same weave density when the density is low (e.g. 4 threads/cm). Such low-density plain-woven fabrics are deemed to be not suitable for ballistic protection because projectile could wedge through them easily. Further investigation could be put into the role of the nesting effect in layout and the interchange of combining yarns between sublayers over regular networked fabrics. Furthermore, networked fabrics with multiple sublayers (larger than 2) are also interesting because they have further constraints on the configuration between more layers.

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