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Modelling of Textile Structure for Advanced Applications

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Abstract. In general, textiles are perceived as soft materials and structures and textile fibres can be organised into fabrics of different complexities to form new materials and structures. Textiles are widely used in many applications, ranging from clothing to advanced technical applications such as textile composites for the aerospace and other industries. Accurate understanding the relationships between the construction and technical behaviour of textiles is the key in engineering textile materials for the intended applications. This keynote paper introduces the modelling techniques for different textile materials and structures and reports on the latest progress in modelling textiles for ballistic protection. In this area of work, it is shown that the modelling results agreed with the experimental work well and modelling tool can be used to guide the ballistic materials effectively.

Keywords: textiles; structures; behaviour; modelling; ballistic protection

1. Introduction

Textiles refer to fibres and fibre assemblies that are principally used as raw materials for different types of products. Under this definition, textiles will include fibres, yarns, and fabrics. For garments, beddings, curtains, floor coverings, as well as technical end-use (such as a type of textile composites), textile fabrics are the raw materials, providing not only the appearance, texture and decorative features but also the various properties that make the textile suitable for the intended applications. Textiles are a popular type of materials that has been widely used domestically and industrially [1].

However, textiles as a type of materials is special when compared to materials such as metal. Textiles are far from homogenous and isotropic because they are assemblies of fibres. In addition, fibres are made of wide range of different chemical compositions, and when different fibres are used for making textiles, the physical and chemical properties can vastly different. Because of all these special features, modelling of textile structures and behaviour has always been an attention focus.

The textile hierarchy ranges from fibre as the basic element. Fibres are the construction units of yarns and some non-woven fabrics. Then yarns are used as components for making fabrics based on the weaving knitting and braiding technologies. It is essential to understand the fibre behaviour which is largely determined by the chemical structure of the polymer and physical configuration of the molecular chain. Based on the fibres, it could be claimed that the behaviour of a textile assembly is a function of the property of the building block and the way how these building block are constructed in the assembly. Following this logic, the behaviour of yarn depends on the fibre property and the yarn construction and the fabric behaviour is determined by the composing yarn property and construction of the fabric. A Fabric contains tremendous amount of fibres of the same or different types, and there are endless ways that a fibre is configured individually or collectively in a fabric. Phenomena such as these make the modelling of textiles very challenging.

2. Weave modelling

Woven fabrics are produced by interlacing two systems of yarns perpendicular to each other; the one in the length direction of the fabric is the warp and the one that goes in the width direction of the fabric is the weft. There are many different ways of interlacing the warp and weft yarns into a fabric, and a particular plan for constructing a fabric is know as a weave. Weaves can be classified into four different categories, which are elementary weaves, derivative weaves, combined weaves, and complex weaves. In addition to these,

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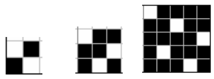
woven fabrics can be made to have a considerable thickness from multiple sets of yarns in each of the two directions, and these are sometimes termed as 3D woven fabrics.

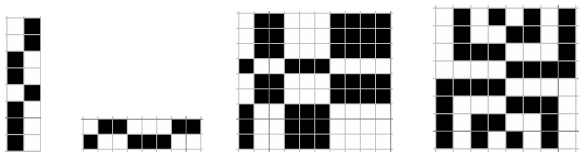
The elementary weaves are defined as those having two floats in the weave repeat and with one the float length being 1. It typically includes the plain weave, simple twill weaves, and satin/sateen weaves [2]. The weave diagrams of some of these weaves are illustrated in Figure 1. The elementary weaves can be manipulated to derive new weaves.



(a) (b) (c)

Figure 1 Elementary weaves (a) the plain weave (b) 2/1 twill (c) 5-end satin

The derivative weaves are created from the three types of elementary weaves. From the plain weave, two methods can be applied to create new weaves. The plain weave can be extended in warp, weft or both directions in order to derive new weaves. Extending the plain weave in the warp direction will result in warp rib weaves, and extending in the weft direction leads to weft rib weaves. When the plain weave is extended in both directions, hopsack weaves will be created. Figures 2(a), (b) and (c) show a warp rib, a weft rib and a hopsack weave respectively. A plain derivative can also be created following the plain weave logic, where the derivative weave will have 4 quarters with the adjacent ones having opposite images, leading to a basket weave. This is illustrated in Figure 2(d).

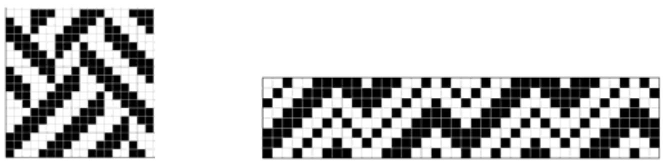


(a) (b) (c) (d)

Figure 2 Plain derivative weaves (a) a warp rib (b) a weft rib (c) a hopsack and (d) a basket weave

Twill weaves are featured by the twill lines in either Z or S direction. Therefore, ways for changing the twill line thickness and direction play important role in creating twill derivative weaves. When the mirroring technique is applied, twill lines will be made to change their directions while keeping the continuity. This technique is used to create waved weaves and diamond weaves. Figure 1.14 shows a horizontal waved weave, a vertical waved weave, and a diamond weave derived from the $\frac{3\ 1}{2\ 2}$ S twill. When changing twill line direction and breaking the continuity, i.e., by applying the inverse mirroring technique, herringbone weaves and diaper weaves can be achieved. Figure 1.15 displays a horizontal herringbone weave, a vertical herringbone weave, and a diaper weave based on again the $\frac{3\ 1}{2\ 2}$ S twill.

More fanciful twill derivatives can also be created using different rules. Figure 3 demonstrates two other types of twill derivative weaves, an entwined weave and a saw tooth weave.

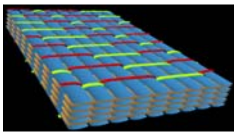


(a) (b)

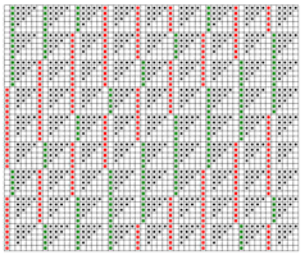
Figure 3 Twill derivatives achieved using other principles (a) an entwined weave and (b) saw tooth weave

The traditional weaving technology is also capable of weave fabrics with thickness, or 3D fabrics. 3D fabrics can be made as broad solid panels (3D solid), with porous cross-sections (3D hollow), or 3D shapes. 3D solid woven fabrics can be manufactured based different principles such the multilayer, orthogonal and angle interlock. Figure 1.17 shows the 3D model as well as the weave for an orthogonal woven fabric with 4 layers of warp yarn.

Modelling the structure of the woven fabrics is regarded as an important step towards the computerised generation of weaves. Chen and his colleagues started the structural modelling of woven fabrics by defining weaves into regular and irregular. A regular weave is one whose float arrangement and the step number do not change in a repeat of the weave. All other weaves are defined as irregular weaves. Many commonly used weaves are regular them selves or further developed from regular weaves. Whilst each type of the irregular weave would need a distinct mathematical model to describe its construction, all regular weaves will need same mathematical model for it construction.



(a)



(b)

Figure 4 The (a) model and (b) weave for an orthogonal woven fabric with 4 warp layers

A model describing the regular weave construction was reported by Chen *et al* [2], which yields the 2D binary weave matrix, W, upon the specification of the float arrangement, F_i, and the step number, S. Suppose that $w_{x,y}$ is the element of this matrix at co-ordinate (x, y), where $1 \le x \le R_e$ and $1 \le y \le R_p$ with R_e and R_p being the warp and weft repeat respectively, then the first column of the weave matrix can be generated using the following equation:

$$W_{1,y} = \begin{cases} 1 & \text{if } i \text{ is an odd integer} \\ 0 & \text{if } i \text{ is an even integer} \end{cases} \tag{1}$$

where $y = \left(\sum_{j=1}^{i} F_j - F_i + 1 \right) \text{to} \sum_{j=1}^{i} F_j$; and $1 \le i \le N_f$. N_f is the number of floats in the float arrangement. Then, the rest of the matrix will be assigned values as follows:

$$W_{x,z} = W_{1,y} \tag{2}$$

where $z = \begin{cases} y + [S \times (x-1)] + R_p & \text{if } \{y + [S \times (x-1)]\} < 1; \\ y + [S \times (x-1)] & \text{if } 1 \le \{y + [S \times (x-1)]\} \le R_p; \\ y + [S \times (x-1)] - R_p & \text{if } \{y + [S \times (x-1)]\} > R_p; \end{cases}$ $\quad 2 \le x \le R_e$; and $1 \le y \le R_p$.

Chen and colleagues also worked on weaves for other 2D fabrics and 3D fabrics [3] [4].

3. Geometrical modelling of woven fabrics

The performance of a textile fabric is basically a function of the property of the constituent fibres/yarns, and the geometrical construction of the fibres/yarns in the fabrics. Study on the geometry of fabrics has been continuing for almost a century. Geometrical models of fabrics have led to the estimation of some structural and physical properties of the fabrics, such as the areal mass and the porosity, and the results from the modelling have been used as guidance to fabric manufacture in giving the maximum areal density of the fabrics. Geometrical modelling of textile assemblies becomes more important nowadays as the geometrical models are, arguably, the most reliable solution in providing geometrical information of the textile assemblies for finite element (FE) analysis for performance simulation.

Peirce's work in 1937 [5] is regarded as the beginning of modelling woven fabric geometries. Under certain assumptions including circular yarn cross-section, complete flexibility of yarns, incompressible yarns and arc-line-arc yarn path, he derived the following equations describing the geometry of the plain woven fabrics. The cross-section of the plain woven fabric based on Peirce's assumption is shown in Figure 5.

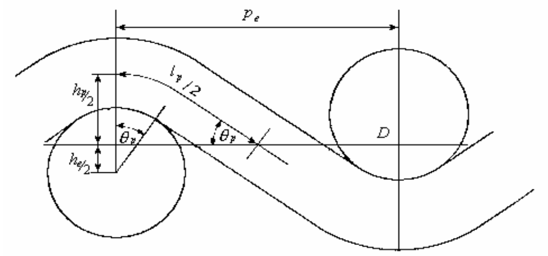


Figure 5 Peirce's model for the plain woven fabric

$$D = d_e + d_p \quad (3) \qquad h_e + h_p = D \quad (4)$$

$$c_e = \frac{l_e}{p_p} - 1 \quad (5) \qquad c_p = \frac{l_p}{p_e} - 1 \quad (6)$$

$$p_p = (l_e - D\theta_e)\cos\theta_e + D\sin\theta_e \quad (7) \qquad p_e = (l_p - D\theta_p)\cos\theta_p + D\sin\theta_p \quad (8)$$

$$h_e = (l_e - D\theta_e)\sin\theta_e + D(1-\cos\theta_e) \quad (9)$$

$$h_p = (l_p - D\theta_p)\sin\theta_p + D(1-\cos\theta_p) \quad (10)$$

where

h_e, h_p - the modular heights of the warp and weft yarns normal to the neutral plane of the fabric

c_e, c_p - the crimps of the warp and weft yarns

D -the sum of the diameters of the warp and weft yarns

d_e, d_p - the diameters of the warp and weft yarns

p_e, p_p - the thread spacing between adjacent warp and weft yarns

l_e, l_p - the modular lengths of the warp and weft yarns in one repeat

θ_e, θ_p - the weaving angles of warp and weft yarns

Subscripts 'e' and 'p' in the variables above refers to warp (ends) and weft (picks) respectively.

There are thirteen variables in these eight equations. Therefore, with five variables known, such as the two spacings (p_e, p_p), the two yarn diameters (d_e, d_p) and one crimp (either c_e or c_p), these simultaneous equations can be solved. Ai [6] presented an algorithm to calculate the geometry assuming that five variables, p_e, p_p, d_e, d_p and one of c_e and c_p are specified. If p_e, p_p, d_e, d_p and c_e are known, the other fabric parameters can be worked out.

The yarn cross-section in a real fabric is hardly circular because of the pressure between the war and weft yarns during the weaving process. Peirce himself proposed an alternative model for the plain woven fabric assuming the yarn cross-section to be elliptical. It proved to be mathematically too complicated to describe the relationship among the structural parameters. Peirce model of plain woven fabrics was extended by others notably Kemp [7] who assumed the yarn cross-section is racetrack shaped and Shanahan and Hearle [8] who proposed a lenticular yarn-cross section. These extended models kept all assumptions Peirce used except for the yarn cross-section, and are regarded as Peirce derivative models.

4. FE modelling of woven structures

Based on the achievements made in weave modelling and fabric geometric modelling, solid models for different types of woven fabrics are created using the algorithm. For example, a programme called *UniverWeave* was developed to create woven fabric geometrical models efficiently. The defined geometry can be picked up by major FE software packages to carry out FE simulations for material and component analysis.

4.1. FE modelling of filtration through fabrics

Since the geometry and porosity of the fabric filter is determined by the weave pattern and the various parameters of yarns constituting the fabric [9], it is important to optimise its structure to achieve the most efficient filtration. The past and current practice is to rely on the practical skill and experience of the fabric designers and empirical trials. Readily available computational power provides an opportunity to develop computer-aided design (CAD) procedures. CAD software would enable predictions of filter performance to be made, leading to improved filters and reduced cost of trials. In the first stages of developing CAD programs, it is necessary to produce good models of fabric structure and then predict the flow through the fabrics.

Among the numerous outputs from the analysis, the fluid pressure, fluid velocity and shear stress on the fabric are used as the performance indices [10]. Fluid pressure is read on the front face and the back face of the filter fabric. Fluid velocity is taken on the planes that are one mesh size away before and after the filter fabric and on the fabric centre (middle) plane. The shear stress, on the other hand, is measured at the front side and inner-side of the yarns constituting the fabric. The fluid velocity and pressure through the chamber are also simulated, which give an overall effect of the fabric filter on the fluid flow. Figure 6 shows the positions where the data were extracted in relation with the fabric and to the direction of the flow.

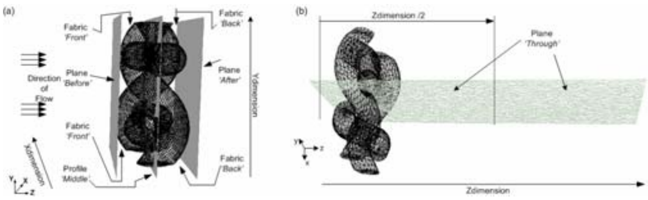


Figure 6 Fabric in relation to planes *before*, *middle*, *after*, and *through*

In each analysis, 3 different fabric models (all plain) are used. Every fabric model is specified using warp yarn linear density (t_1), weft yarn linear density (t_2), warp density (d_1), weft density (d_2), warp crimp (c_1), cross-sectional shape of the yarns and the Width to Height Ratio (WHR) of the yarn cross-section. Warp crimp is then a dependent parameter. The inlet pressure for all cases is 3 bars and the operating pressure 1 bar. Density and viscosity of the fluid were assumed to be constant, corresponding to the isothermal approach. Liquid-water was used as the Newtonian fluid (with density of 998.2 kg/m^3 and viscosity at 10^{-3} kg/m.s). As an example, when the cross-section of the yarns in the filter fabrics are taking circular, racetrack and lenticular shapes, Figure 7 summarises the effect of yarn cross-sectional shape on fluid pressure on the front and back surfaces.

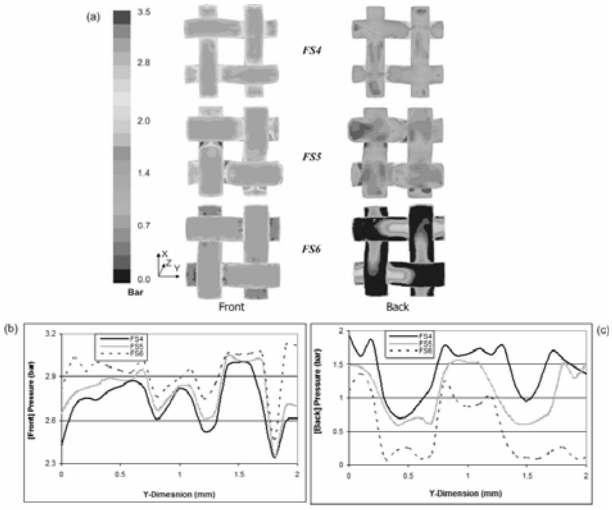


Figure 7 Effects of varying yarn cross-sectional shape on fluid pressure

In this experiment three rather ideal yarn cross-sectional shapes namely circular (FS4), racetrack (FS5) and lenticular (FS6) shapes are investigated. From circular to racetrack to lenticular, the yarn width increases as its height decreases. Figure 7 illustrates influence of variation of the yarn cross-sectional shape on fluid pressure exerted to the *front* and *back* surfaces of the fabric. By changing yarn cross-sectional shapes from circular to racetrack to lenticular, the fluid pressure is increased on the front face of the fabric due to higher flow resistance and drops dramatically at the back face.

4.2. FE modelling of ballistic impact through fabrics

FE modelling of ballistic impact on fabrics is another field that is much needed in order to understand the strain/stress distribution in each of the fabric layers and among all fabrics layers. Results from such work provide guiding information for body armour engineering. Modelling of ballistic fabrics is carried out on two levels, one a single layer of fabric, another layered panels of fabrics.

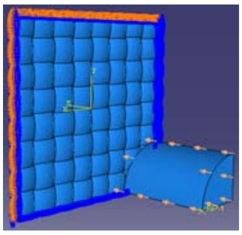


Figure 8 The geometrical model and constraints

Figure 8 is the geometric model of the fabric and the impacting projectile. A quarter of the fabric and that of the projectile is considered because of symmetry, the fabric involved 8 warp and 8 weft yarns constructed in the plain weave. This is a square fabric with the same value of warp and weft densities (7.6 threads/cm). The material type is Kevlar whose specific density is 1.55 g/cm^3. The following describes the boundary conditions For the projectile, the translational freedom along X and Y axes and the rotational freedom along Z axis are constrained and set to zero, i. e., $v_x=v_y=0$. For the fabric, the translational freedom perpendicular to the symmetrical plane and the rotational freedom in the symmetrical plane are constrained and set to zero, i.e., $U_x=UR_y=UR_z=0$ and $U_y=UR_x=UR_z=0$. The circumference of the quarter of the target fabric is fixed, i.e. $U_x=U_y=U_z=UR_x=UR_y=UR_z=0$.

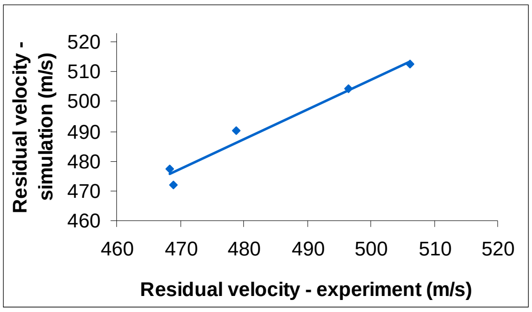


Figure 9 Agreement between the model and experiment

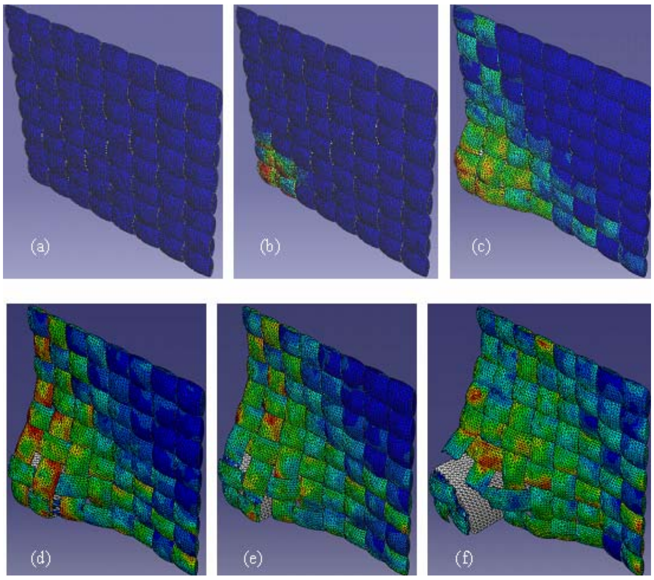


Figure 10 Stress distribution on an impacted fabric at (a) t=0 μs (b) t=0.75 μs (c) t=1.37 μs (d) t=5.25 μs (e) t=6.0 μs and (f) t=8.12 μs

Figure 9 shows that the modelled exit velocities agree well with the measured exit velocities, with the correlation coefficient being 0.9939. With the models validated by the experimental data, a series of FE simulation was carried out. Figure 10 reveals the ballistic impact process, with the projectile impact velocity v0=494.217m/s.

It is clear in Figure 10 that the distribution of stress caused by the ballistic impact on the fabric is mainly along the warp and weft yarns in the fabric before the projectile penetrates the fabric. This implies that the currently used plain woven fabric may not be the most efficient construction for ballistic applications, because such constructed fabric is unable to mobilise more areas of fabric to absorb the impact energy. To improve the fabrics ability to absorb impact energy, fabrics with better yarn gripping have been designed and manufactured. The test results confirmed the superiority of such fabrics.

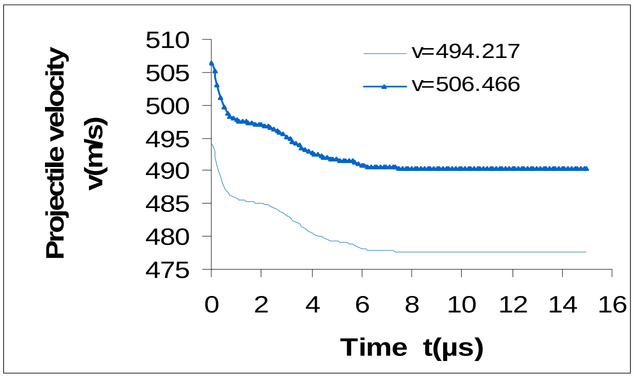


Figure 11 Modelled project velocity change due to impact

The models also give information that enhances understanding on of the impact process. Figure 11 shows the change of the projectile velocity due to the impact on the fabric. The curves for both cases demonstrate similar trend. The curves indicate that the initial impact causes a sharp reduction of projectile velocity before the fibres start to break at about 1 μs into the impact. Projectile going through the fabric further reduces its velocity. The penetration of the projectile for both cases seems to have taken place at around 8 μs.

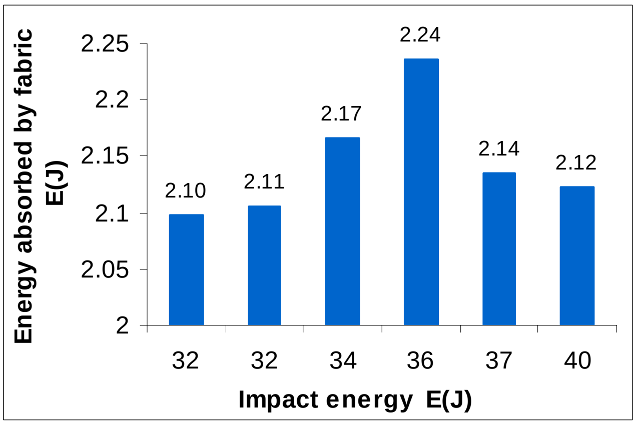
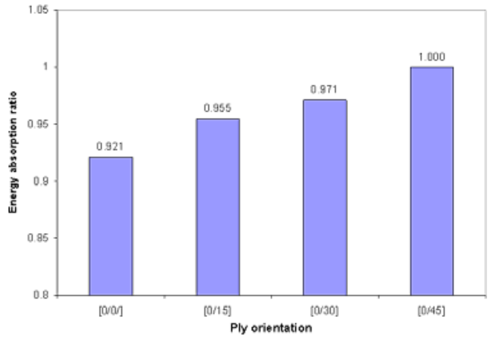


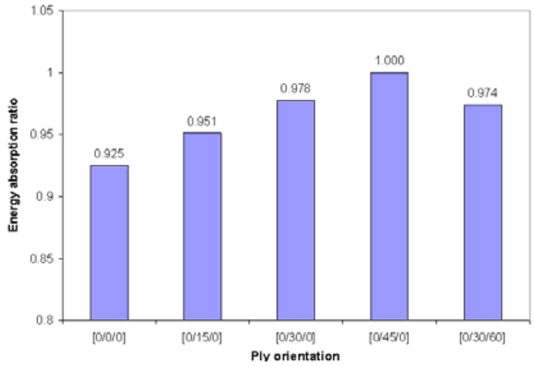
Figure 12 Energy absorption vs. impact energy

Figure 12 reveals that for a given assembly of ballistic fabrics there exists an impact energy that relates to the maximum energy absorption of the assembly of the fabrics. The impact energy is only a quarter of the energy applied to the fabric assembly due to the geometrical symmetry of the projectile. Under this circumstance, the fabric assembly absorb most of the energy at 36 J. This provides support to the use of V50 in ballistic test.

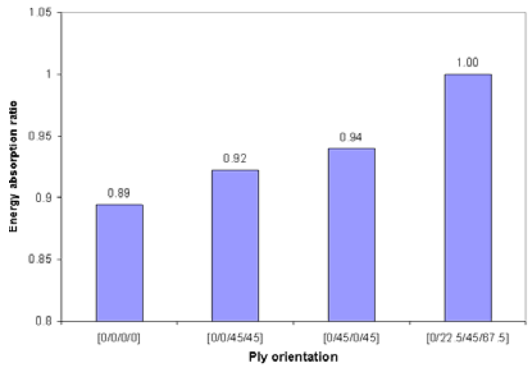
The results from simulating single layer fabrics are valuable information for fabric design so that the fabric is more absorbent to impact energy. It is also important to consider how the fabric is used in the fabric assembly. Obviously, different fabrics/materials can be used at different position in the assembly because the impact action and reaction are different at different layer. Even if the same fabric is used, the fabric orientation in the assembly will also matter as fabric orientation has a direct influence on the strain/stress distribution. Figure 13 (a), (b) and (c) shows that fabric layers with different orientation angle leads to better impact energy absorption.



(a) A 2-layer assembly

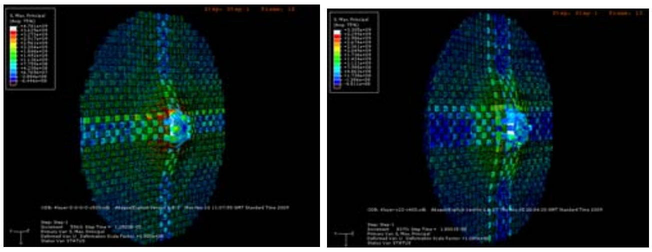


(b) A 3-layer assembly



(c) A 3-layer assembly

Figure 13 Effect of fabric orientation on energy absorption



(a) Aligned 4-layer (b) Angled 4-layer

Figure 14 Stress distribution of the 4-layer fabric assembly

From Figure 13 demonstrates that up to 4 layers of fabrics, a more evenly aligned fabric assembly absorbs the most of impact energy, and the aligned fabric assemblies are related to the least energy absorption. Experimental results show the same trend.

5. Conclusions

As an important field for modelling and simulation, this paper explained the technique developed by the author for woven textiles. The weave modelling is a mathematical description where the weave is parameterised. This technique has been adopted in CAD software for weave design. Geometrical modelling is explained by adopting Peirce model. This work enables fabric models to be created and exported for property analysis using the FE packages. Two examples were used to demonstrate the application of the geometrical models. Through the filtration modelling, information was created giving the relationship between the fabric geometry and the fluid behaviour passing through the fabrics. The second example is on the performance of ballistic fabrics. The modelling lead to understanding what happens when a high velocity rigid projectile impacts on a soft woven fabric. It also demonstrated that fabric assemblies with evenly angled orientation absorb more impact energy than the aligned fabric assembly.

6. Acknowledgement

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7. References

[1] X. Chen (Ed.). *Modeliing and predicting textile behaviour.* Oxford: Woodhead publishing Ltd, 2009.

[2] X. Chen, R.T. Knox, D.F. McKenna, R.R. Mather. Automatic generation of weaves for the CAM of 2D and 3D woven textile structures. *J. Text. Inst.*. 1996, **87**(Part 1, No. 2): 356.

[3] X. Chen, P. Potiyaraj. CAD/CAM of the orthogonal and angle-interlock woven structures for industrial applications. *Text. Res. J.* 1999, **69**(9): 648.

[4] X. Chen, H. Wang. Modelling and computer aided design of 3D hollow woven fabrics. *J Text Inst.* 2006, **97**(1): 79.

[5] F.T. Peirce. The Ggeometry of cloth structure. *J. Text. Inst.* 1937, **28**: T45

[6] X. Ai. *Geometrical modelling of woven and knitted fabrics for technical applications.* MPhil Thesis, UMIST, 2003.

[7] A. Kemp. An extension of Peirce cloth geometry to the treatment of noncircular threads. *J. Text. Inst.* 1958, **49**: T44.

[8] W.J. Shanahan, J.W.S. Hearle. An energy method for calculations in fabric mechanics, part II: examples of application of the method to woven fabrics. *J. Text. Inst.* 1978, **69**(4): 92.

[9] S. Backer. The Relationship Between the Structural Geometry of Textile and Its Physical Properties, I: Literature review. *Text. Res. J.* 1948, **18**: 650-658.

[10] M. A. Nazarboland, X. Chen, J. W. S. Hearle, R. Lydon, and M. Moss. Modelling and simulation of filtration through woven media. *International Journal of Clothing Science and Technology.* 2008, **20**(3): 150-260.