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Experimental and numerical study of plain-woven aramid fabric

E.A. Flores-Johnson[1,a], J.G. Carrillo[2,b] , R.A. Gamboa[2,c] and L. Shen[1,d]

[1]School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia

[2]Centro de Investigación Científica de Yucatán, A.C., Unidad de Materiales, C. 43, No. 130, Chuburná de Hidalgo., C.P. 97200 Mérida, México

[a]emmanuel.flores-johnson@sydney.edu.au, [b]jgcb@cicy.mx,

[c]ragcicy@cicy.mx, [d]luming.shen@sydney.edu.au

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Abstract. In this paper, the tensile properties of plain-woven aramid fabric style 724 (Kevlar® 129 fibre, 1000 denier, 24×24 yarns per inch) and the tensile properties of individual aramid yarn extracted from the fabric are presented. It was found that this fabric is balanced with less than 5% difference in strength between the warp and weft directions. The mechanical properties of the individual yarns were found to be lower than those reported for Kevlar® 129 fibre, which is explained by the fact that the yarns were damaged during the extraction process or weaving process.

A 3D finite-element model of the tensile testing of plain-woven fabric was built at the mesoscale in Abaqus/Explicit by modelling individual crimped yarns and taking into account friction. Material properties and yarn geometry for the model were obtained from experimental observations. An orthotropic elastic model with failure criterion based on the yield stress was used. Numerical results were analysed and compared with experimental results. It was found that the numerical model can reproduce the physical experimental observations, the yield strength and the failure strain.

Introduction

High performance polymer fabrics are extensively used for protection against impact because of their excellent mechanical properties and energy-absorption ability [1]. For example, aramid fibre (aromatic polyamide), has remarkable properties such as lightness, flexibility and high Young's modulus making it an attractive option to manufacture modern protective shields. Aramid fibre with the commercial name Kevlar® is very well-known [2]. Woven fabrics made with this fibre have high strength, high modulus and good tenacity, which make them ideal for ballistic protection.

It has been shown that ballistic impact energy absorption in woven fabrics is rather a complex event and treating fabric layers as a continuum material in numerical modelling may lead to inaccurate results unless a robust constitutive formulation or an optimisation algorithm is implemented [3]. There is experimental evidence that friction largely influences the impact energy absorption of high-strength fabrics at different levels [4], i.e., fibre-fibre, yarn-yarn, layer-layer and projectile-fabric interactions. An experimental and numerical investigation by Rao et al. [5] showed that fabric and projectile geometry, material properties, boundary conditions and friction are coupled and all of them should be taken into account when determining the ballistic resistance of fabrics [5].

It has been shown that modelling fabric behaviour at the mesoscale offers a practical approach to capture impact behaviour of fabric and fabric composites [5,6,7]. While the complex behaviour of a fabric may be difficult to capture with a single material model, the behaviour of single yarn can be captured using an elastic constitutive model with a failure criterion.

In this work, the tensile testing of plain-woven aramid fabric style 724 (Kevlar® 129 fibre, 1000 denier, 24×24 yarns per inch) and the tensile testing of individual yarns extracted from the fabric are presented and discussed. A 3D finite-element model of the tensile testing of the plain-woven fabric was built at the mesoscale in Abaqus/Explicit [8] by modelling individual crimped yarns and taking into account friction. Numerical and experimental results are compared and discussed.

Experimental

Materials and mechanical testing. Plain-woven aramid fabric style 724 (Kevlar® 129 fibre, 1000 denier, 24×24 yarns per inch) supplied by Carolina Protect® [9] was used in this investigation. The tensile mechanical properties of individual Kevlar® 129 yarns extracted from the fabric were measured in accordance to ASTM D 7269. The test was performed in a universal testing machine with a crosshead displacement rate of 250 mm/min.

Tensile testing of the woven fabric was performed in accordance to ASTM D 5035 using the ravel strip method, which requires 20 yarns in the direction of the tensile testing and a total specimen length of 150 mm (Fig. 1a). Tests were performed in a universal testing machine with a crosshead displacement rate of 300 mm/min using the built in-house grips shown in Fig. 1a.

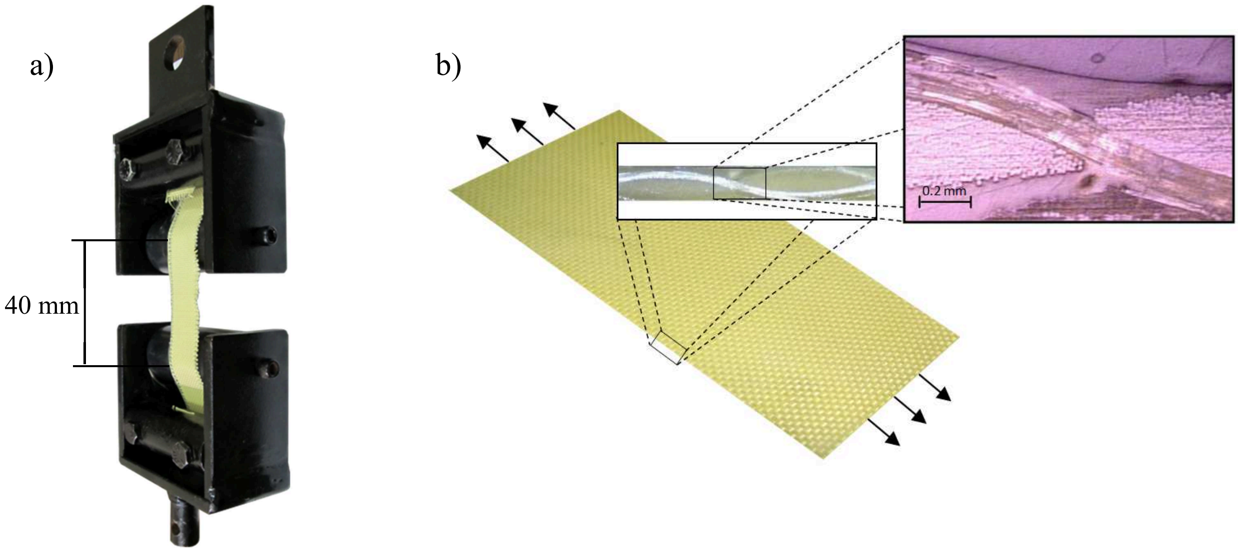

Fig. 1 a) Tensile testing of plain-woven fabric, b) plain-woven aramid fabric style 724.

Results

Tensile testing of individual yarns. A total of 6 yarns with a length of 500 mm were tested. A transversal area of 0.077 mm^2, calculated from the fibre density and yarn denier [10], was used to calculate stresses. Figure 2a shows the stress-strain curves obtained from the tests. The tensile mechanical properties obtained from Fig. 2a are shown in Table 1. It can be observed in Fig. 2a that the failure strength of the yarns is lower than that reported for Kevlar® 129 fibre (3.4 GPa) [10]. This is explained by the fact that, although the yarns were extracted from the fabric with care, some of the fibres may have been damaged during the extraction process [10,11] or before the extraction, i.e., during the weaving process [12].

Tensile testing of fabric. Six specimens were tested in each fabric direction, i.e., warp and weft. A transversal area of 1.54 mm^2, corresponding to the transversal area of 20 individual yarns, was used to calculate stresses. Figure 2b shows the stress-strain curves in the weft direction. The measured strengths are shown in Table 1. It can be seen that the strength in the weft direction is slightly higher than that in the warp direction, which can be attributed to a greater damage caused on warp yarns during the weaving process [10]; however, the difference is less than 5% and the fabric can be considered to be balanced. The elastic modulus of the fabric is considerably lower than the elastic modulus of individual yarn (Table 1). This difference may be attributed to the decrimping of yarns in the fabric during the tensile test [13].

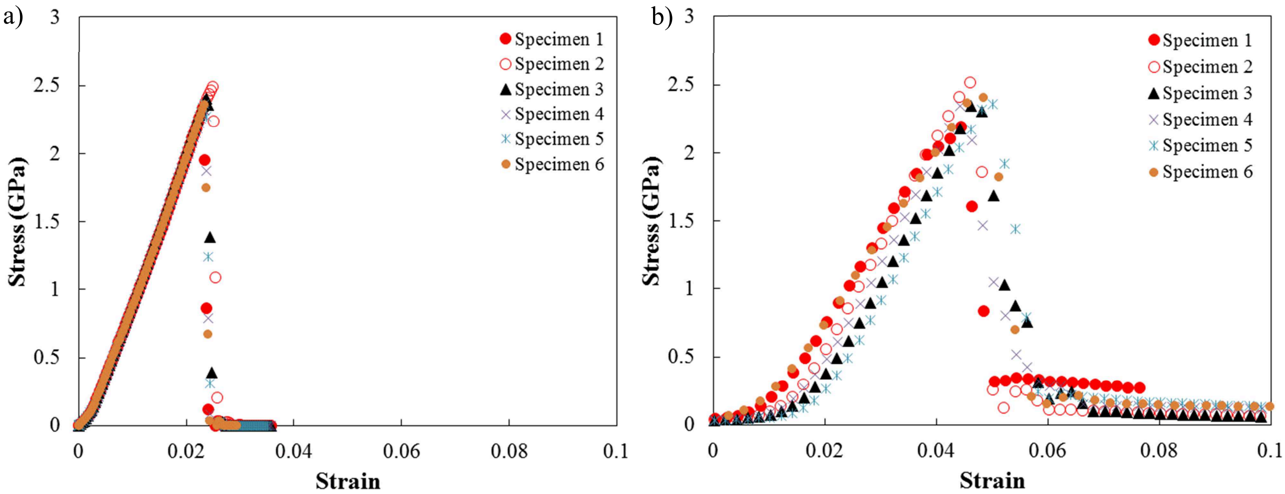

Fig. 2 Typical stress-strain curves of a) individual yarns and b) plain-woven fabric (weft direction).

Table 1 Measured material properties of aramid yarns and aramid woven fabric.

Material properties	Yarn	Fabric
Density ρ, A	1440 (kg/m^3) [9]	0.21 (kg/m^2) [9]
Young's modulus E_{11} (GPa)	108.56±1.25	64.79±2.79 (weft), 63.12±2.67 (warp)
Tensile strength t_n (GPa)	2.38±0.05	2.35±0.07 (weft), 2.26±0.02 (warp)
Failure strain	0.024±0.05	0.047±0.47 (weft), 0.044±0.27 (warp)
E_{22}, E_{33}, G_{12}, G_{13}, G_{23} (GPa)	3.5	-
v_{12}, v_{13}, v_{23}	0	-

Numerical simulations

Finite-element model. The tensile testing of the plain-woven fabric described in the experimental section was simulated using a 3D finite-element model built in Abaqus/Explicit (Fig. 3). The 1-layer fabric dimension was 21 × 40 mm^2. Individual yarns were modelled discretely (Fig. 3) and considered as a continuum allowing friction between yarns at crossovers [4]. Six and ten elements were used to mesh the yarn cross-section and a full-wave length yarn crimp, respectively. The average element size in the thickest part of the yarn was 0.12 × 0.16 × 0.2 mm^3 giving a total of 45828 reduced-integration linear hexahedral elements (C3D8R). Friction between yarns was taken into account by using the penalty contact algorithm available in Abaqus/Explicit and defining a constant coefficient of friction μ [8].

An orthotropic elastic material model was used to describe the behaviour of the yarns. The material properties are shown in Table 1. Small values of shear moduli, Poisson's ratios and transverse elastic moduli were used [4] (Table 1). Material orientation was defined with E_{11} along the fibre direction using a local coordinate system. When the longitudinal elastic modulus is much larger than shear and transverse moduli, the tensile stress in the fibre direction is close to the maximum principal stress [14]. This approximation allows using the equivalent stress to failure as the failure criterion, which is defined as the yield stress in Table 1. When the equivalent stress exceeds the yield stress at a strain of approximately 0.024, the material fails and the corresponding element is deleted from the mesh.

Numerical results. Figure 4 shows a comparison of the stress-strain curves between experimental and numerical results. It can be seen that the predicted behaviour is very close to the experiment. The initial part of the predicted curve is somehow different from the empirical data. This difference may be attributed to dynamic effects since the numerical test was performed at 0.1 s^{-1}. Dynamic effects may be reduced via viscous damping; however, since the model is intended to be used for ballistic impact behaviour in future work and both aramid fabric and yarn have shown to be strain-rate independent below 0.1 s^{-1} [15], this option will not be used in this work. Figure 4 also shows that the coefficient of friction does not have a significant effect on the numerical results for the fabric tensile test at this particular strain rate. Figure 5 shows a comparison of the deformed fabric after failure between experiment and simulation and good agreement is observed.

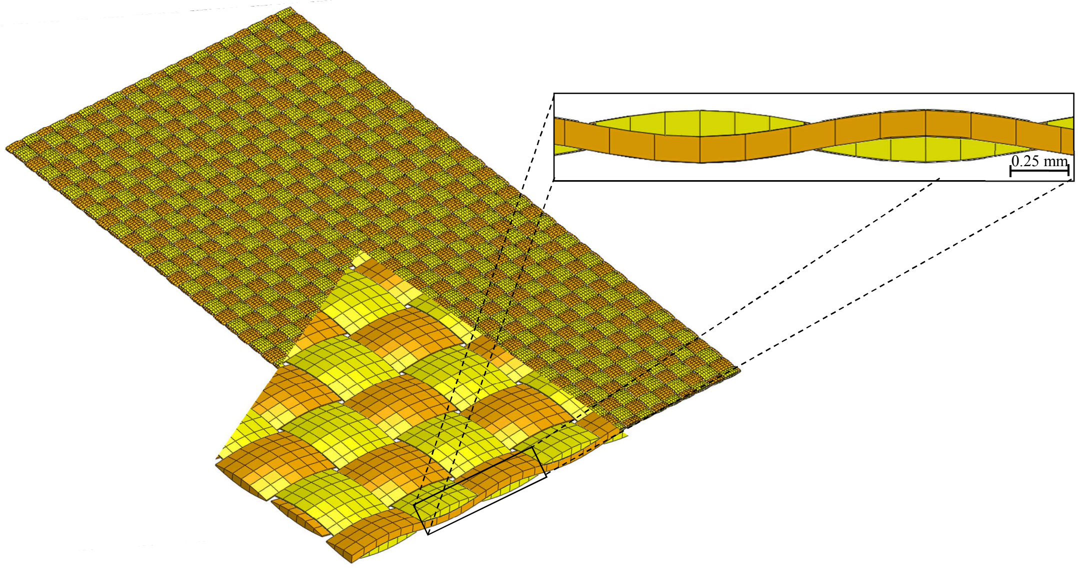

Fig. 3 Finite-element 3D mesh for the plain-woven fabric.

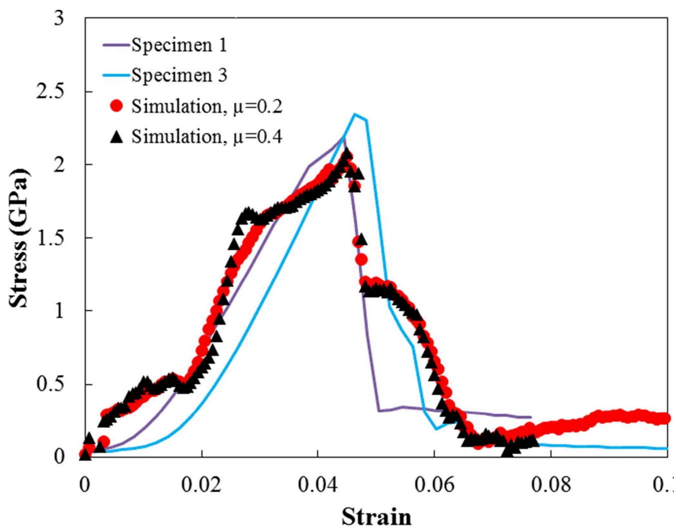

Fig. 4 Comparison between experimental and numerical results for two different friction coefficients.

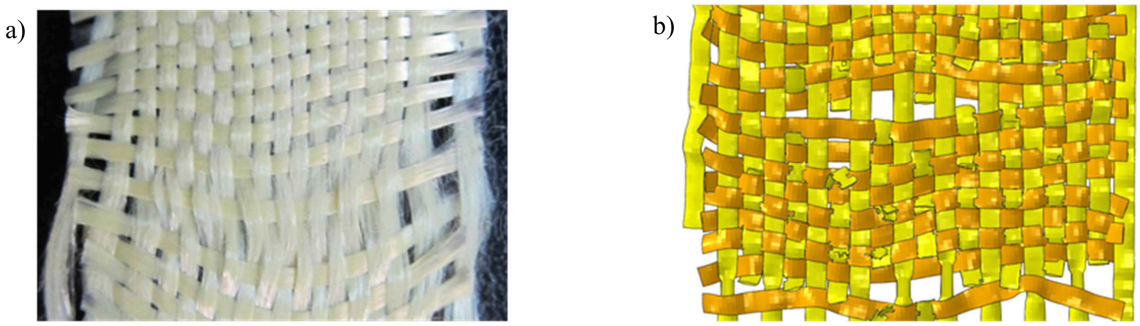

Fig. 5 Deformed fabric after failure in a) experiment, and b) simulation.

Summary

The tensile properties of plain-woven aramid fabric style 724 and individual yarns extracted from the fabric were studied. It was found that this particular fabric is balanced with a difference in yield strength of less than 5% in the weft and warp directions.

Geometry and mechanical properties obtained in the experiments were used to build a 3D finite-element model at the mesoscale including individual crimped yarns and the effect of friction. It was found that the numerical model can reproduce the physical experimental observations, the yield strength and the failure strain obtained in quasi-static tests. However, further numerical work needs to be done to validate the numerical model for use in ballistic impact of plain-woven fabric.

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