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Computational determination of in-plane shear mechanical behaviour of textile composite reinforcements

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Abstract

The knowledge of the mechanical behaviour of woven fabrics is necessary in many applications in particular for the simulation of textile composite forming. This mechanical behaviour is very specific due to the possible motions between the fibres and the yarns. In this paper, the in-plane shear behaviour is analysed from virtual tests on the Representative Unit Cell. The in-plane shear strains can be very large (up to 50°) in case of draping on a double curved surface. These virtual tests avoid performing tricky experimental tests. The presented 3D finite element analyses involve two main specific aspects. Firstly the boundary conditions have to render the periodicity at large deformations and, in some cases, the evolution of contacts between neighbouring yarns during the motion. Secondly the yarn that is made of thousand of fibres is modelled as a continuous medium but its constitutive law has to take its fibrous nature into account. For that reason a rate constitutive equation using a specific objective stress rate is used. It is based on the rotation of the fibre. The analysis is performed for two unit cells. Both results are in good agreement with the experiments, but the use of one of the cells turns out to be much easier.

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1. Introduction

Textile reinforcements are used in composite materials, in particular in case of double curvature geometries requiring large shear strains in the plane of the reinforcement. Simulation codes of the draping of dry textile reinforcements (i.e. before resin injection) are necessary at the stage of design of composite structures to determine the feasibility of a forming and to know the directions of fibres in the final composite part. A lot of work has been done to improve these kinds of codes. A first type of method has been developed from the fishnet algorithm [1–3]. These methods are purely geometric and assume the yarns to be non-stretch and free to rotate. The advantage is the simplicity and efficiency of these methods. However they do not take into account the mechanical properties of the textile reinforcement and the static boundary conditions, particularly the loads on the tools like the blank holders. Finite element methods do take into account the mechanical behaviour of the textile reinforcement and the loads on the boundaries during forming [4–11]. They constitute the main alternative to the geometric methods. The use of these methods requires knowledge of the mechanical behaviour of the dry reinforcement during the draping process. During forming, the deformations of the reinforcement are complex. Textile performs undergo biaxial tensile deformation, in-plane shear deformation, transverse compaction and out-of-plane bending deformation. If all these deformations can be significant, the in-plane shear strains can be very large in comparison with others. They allow the forming on a double curved shape. Tensile strains remain

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small (less than 1% for a carbon fabric) whereas the shear angle can reach 50°. Many studies have been conducted about the shear mechanical behaviour of composite textiles [12–27]. A large part of these studies deals with experimental work mainly based on two tests: the picture frame and the bias test. Though they are frequently carried out, these tests are tricky. A comparison of the results obtained by several different laboratories on the same textile reinforcement showed important differences [23]. Moreover it may be interesting to know the mechanical behaviour of a fabric before manufacturing. The present study introduces a 3D finite element analysis of a woven unit cell aiming at determining the in-plane shear behaviour of a woven reinforcement. This analysis is not a standard one, it has several delicate aspects. The first one concerns the mechanical behaviour of the yarns made of several thousands (or several tens of thousands) of fibres. It is not conceivable (at least currently) to model each fibre, therefore the yarn will be modelled as a continuous material, the mechanical behaviour at finite strains of which has to give an account of the fibrous nature of the yarns. Especially it must strictly follow the direction of the fibres. For this purpose, a hypoelastic law is used. It uses on an objective derivative that is based on the fibre rotation. The second difficulty relates to inter-yarn contacts and periodic boundary conditions. When the shear angle reaches large values, lateral contacts between yarns lead to a so-called shear locking. Contacts are very complex and the shear rigidity of the reinforcement is a consequence of lateral compression of the yarns. When performing a simulation on a single unit cell, boundary conditions have to treat this issue of contact with neighbouring yarns (which are not part of the model). Even though FE analyses of a woven unit cell have already been introduced [18,22,28], they do not address, in our opinion, the previous two aspects.

If the first objective of the numerical analysis of the unit cell in in-plane shear is the determination of the shear behaviour, another interest is to provide local mesoscopic (cell-scale) results such as crushing and section changes which are very difficult to obtain from experiments. Furthermore, the presented mesoscopic analysis can be used to determine the permeability of the deformed reinforcement by computing the Stokes flow in the deformed fabric [29]. This permeability is very different from those of the undeformed fabric.

2. Experimental study

Two principal devices are used: the hinged framework or "picture frame" and the tensile test at 45° or "bias test". The picture frame test will be briefly presented and used in this work to give a reference shear curve to the computational analyses.

A tensile force is applied across diagonally opposite corners of the picture frame device (Fig. 1). The initially square picture frame moves into a rhomboid. Consequently the specimen within the picture frame is subjected to a pure shear strain field [13,14,19,22,23,25]. The total load on the tensile machine F_c characterizes the shear response but it depends on the picture frame side length L_{frame} and on the fabric specimen side length L_{fab} and is not suitable for comparison of different experiments or different methods. In this work, the measured torque T applied by warp yarns on weft yarns for an initially 1×1 fabric square is given as a result of the test. This torque (per unit surface) is related to F_c, for a shear angle γ by

$$T = \frac{F_c L_{frame}}{L_{fab}^2} \frac{\cos\gamma}{\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \quad (1)$$

The tested plain weave (Table 1) is shown in Fig. 2. It has been experimentally studied in [30,31]. This glass plain weave is balanced, i.e. the warp and weft yarns have close

Table 1
Balanced glass plain weave dimensions

Weaving	Plain weave
Yarn width (mm)	Warp: 3.2 Weft: 3.1
Densities (Yarn/mm)	Warp: 0.251 Weft: 0.248
Crimp (%)	Warp: 0.5 Weft: 0.54
Surface weight (g/m^2)	600

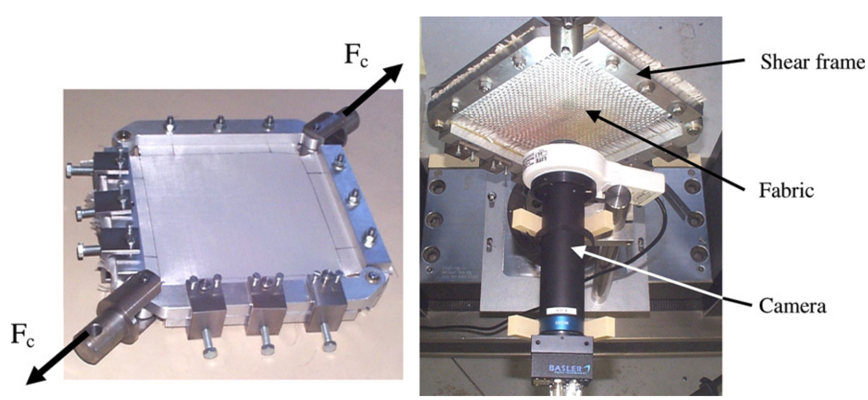

Fig. 1. Picture frame and optical strain measurement.