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# A continuum mechanics analysis of shear characterisation methods

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ABSTRACT

The shear response of fabrics and fabric reinforced materials is primarily characterised by means of Picture Frame and Bias Extension experiments. Normalisation methods have been proposed earlier to enable comparison between different measurement results. Here, a continuum mechanics based analysis is presented for biaxial fabric materials without intra-ply slip, subject to constraints of fibre inextensibility. The fibre stresses are separated from the constitutively determined extra stresses, leading to a scalar equivalent stress resultant which makes the analysis of these tests more transparent. The equations are elaborated for both shear characterisation experiments and a direct measurement evaluation is proposed, without the need for iterative parameter identification methods.

## 1. Introduction

Composite forming simulations can be used for successful part design and process optimisation, provided the relevant deformation mechanisms are included in the simulations appropriately and the materials are properly characterised, such that the simulations make use of the right material property data. Forming composite laminates usually involves significant bending and inplane shear, in particular for fabric reinforcements. In light of this, shear behaviour of fabrics and fabric reinforced polymers has received considerable attention in the last decades. 2D woven fabrics are amongst the most used and researched fabrics in this respect, with the often cited Esaform benchmark as a prime example [1]. The two tests evaluated in this benchmark, Picture Frame (PF) and Bias Extension (BE), are the primary experiments currently used for shear characterisation of fabric materials, with BE appearing to be the most preferred option. Both methods have their advantages but also their limitations, in terms of control of the experimental boundary conditions (in particular the occurrence of undesirable fibre stresses for PF) and in terms of homogeneity of the deformation field (BE specimens have zones of different shear deformation). Ideally, both tests would provide comparable basic material property data, independent of specimen dimensions. This has proven difficult to be achieved in general. The preferential approach in BE testing nowadays is to determine the external power from the applied force and clamp displacement rate and to iteratively determine the stress power contributions of the different regions in the specimen to this total power.

Continuum models have proven their use in defining invaluable concepts such as equivalent stresses, strains and strain rates, and related material constants such as yield stress, shear and elongational viscosities, which are commonly applied in material characterisation and selection. Such concepts are not in use for fabric reinforced plastics, which is remarkable when realising that these materials ideally have only a single inplane deformation degree of freedom, related to the relative angle between the two fibre directions (as long as bending and intraply slip are absent). However, the measured stress power versus deformation or deformation rate data cannot be translated simply and uniquely to a total stress as a function of deformation or deformation rate. The total stresses can be considered to be simply the sum of fibre stresses and structural/material related stresses, where the fibre stresses do not contribute to the stress power when there is no fibre extension. Nevertheless, they are expected to affect the resistance to shear deformation, probably in some nonlinear manner. However, the level of fibre stresses is unclear from the currently used evaluations of test results.

As it is not obvious what part of the actual stresses is carried by the fibres during testing, also the test results cannot easily be reduced to the constitutively determined material/structural related shear stress terms or a related material constant such as a modulus or a viscosity. Moreover, various authors [2–4] have been unsuccessful in attempting to get to a transparent unified interpretation of both tests and to prove the assumption that both tests measure essentially the same phenomenon of trellis shear with only a single inplane deformation degree of freedom under plane stress conditions. Launay et al. [5] achieve better agreement between the shear forces for PF and BE testing if the fibre tension in the picture frame is kept zero during the test. It is suggested that the fibre tension is negligible during BE testing as the yarn ends are free at the edge, which seems strange when considering that the

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longitudinal force in the specimen can only be transferred by the fibres. Hivet and Duong [4] conclude that 'the bias extension and picture frame tests do not exactly impose the same loading on the sample, and therefore, the results obtained cannot be identical.' On the other hand Harrison [6] shows good predictive capabilities of a comprehensive method (including bending and torsion measurements) applying the normalisation method as summarised above.

In order to derive an analysis of the shear test results which is free from these spurious terms, this paper presents the continuum theory to separate the fibre stresses from the constitutively determined extra stresses, leading to a scalar equivalent stress resultant (different from the equivalent stress in [2]) in which these fibre stresses are excluded. It will be shown that this equivalent extra stress resultant fully captures the constitutively determined stress state as it governs all extra stress resultant components. This reduces the characterisation efforts to determining the relation between this equivalent stress resultant and the relevant state variables, such as shear deformation, deformation rate and fibre tension. The theory applies for arbitrary material behaviour, whether or not path or rate dependent. Depending on the observed material response, this can lead to viscosities or moduli, which may depend on state variables such as fibre tension, temperature and pressure.

The theory is applied for PF and BE experiments, leading to simple expressions to derive the relevant fibre and equivalent stress resultants from the local deformation and the applied load. By this means, the results of both tests can be compared and observed differences can be related directly to differences in the underlying state variables, e.g. due to the boundary conditions imposed.

## 2. Previous work

The mechanical behaviour of fabric materials has been subject of many scientific publications in the past century. Various reviews are available in the open literature on this subject area. Hu [7] presented a broad overview on characterisation and modelling techniques for the structural mechanics of fabric materials. Bassett et al. [8] reviewed the development of inplane fabric testing, whereas Boisse et al. [9] reviewed the issues encountered in bias extension testing and modelling, such as fibre bending and intraply slip. A limited subset of the earlier publications on the mechanical behaviour of fabric materials will be addressed briefly in the current context.

Early work in this field, related to the development of Zeppelin airships, dates back to 1912, later translated to English [10]. In the field of apparel fabrics, efforts were made to translate subjective expert's feel or 'handle' of textile materials to objective physical tests of which the results were subsequently elaborated to physical properties such as the flexural rigidity [11]. Some years later, Peirce presented the basis for mesomechanical analyses of plain weave structures [12]. In 1961, Kilby [13] noted that also the shear resistance affected 'fabric hand' which required to be further examined. An instrument inducing uniform shear, e.g. as introduced by Mörner and Eeg-Olofsson [14] could be used for this purpose, but also extension testing in the bias directions as described by Weissenberg [15] (presenting one of the earliest images of BE experiments) or in other directions different from the fibre direction [16]. The latter references already apply the concept of trellis deformation, adopting the deformations of 'two sets of parallel rigid rods, mutually pinpointed where they cross, and capable of extending and contracting in certain directions without a change in the length or the form of the rods'. Note that this is different to simple shear, where the normal strains remain zero during shearing.

Spivak and Treloar [2] compared the responses for trellis shear testing and bias extension. An equivalent shear strain and shear stress were introduced, where the latter includes possible fibre tension. This increasingly affects the results for bias extension with increasing shear, at least partially causing discrepancy between the equivalent stresses for both experiments at equal equivalent strains. The authors therefore preferred 'simple' shear experimentation (imposing trellis shear) and suggested energy loss as a better way to compare the two type of fabric shear experiments. Skelton [17] further analysed the origin of fabric shear stiffness in terms of friction between the yarns. The fabrics' maximum shear angle was found to be related to the fabric tightness. Skelton further noted that fabrics have no relevant out-of-plane dimension and hence advised against the use of thickness to define stresses, preferring the use of mesomechanical analyses considering the crossover points in particular.

Again in order to precisely define subjective 'handling' or 'feeling' of materials, Kawabata [18] presented a series of mechanical tests enabling objective measurements, which do need to be interpreted by 'the man who well knows about the mechanical properties relating with its end use'. The resulting Kawabata Evaluation System for Fabrics (KES-F) quickly became the standardised fabric characterisation system [7], containing a variety of fabric tests to be carried out. An analysis of the forces encountered during KES-F shear testing, relating the torque around the intersection points to the overall shear force, was presented in [19]. An international interlaboratory trial comparing the outcomes of KES-F measurements [20] from 1988 showed poor reproducibility between the labs.

Research on characterisation for composites forming purposes started around the same time. Early work on the rheology of fabric reinforced plastics concerned continuum modelling of viscous, viscoelastic and (elasto-) plastic materials, by Rogers [21], McGuinness and Ó Brádaigh [22] for both modelling and experimental characterisation, and a generic continuum theory for fabric-reinforced fluids by Spencer [23]. Later, especially mesomechanical approaches as introduced earlier [17,19] were elaborated in detail by e.g. Hivet et al. [4,24] to obtain a better understanding of the deformation behaviour of fabric materials, describing the fabric structure and studying the structural deformations during forming operations. The global loads on the material are expressed in terms of the loads and torques acting on the crossover points of the yarns, which can be elaborated to covariant and contravariant stress components in the two fibre directions. As can be expected, the fabric geometry with often non-orthogonal fibre orientations leads to fairly lengthy mathematical expressions. Lomov et al. [25] evaluated the deformations during PF testing on the mesoscale by means of optical strain field measurements, and concluded that fibre tension dominates the fabric's shear resistance. The spatial variation of shear deformation was found to be limited for these tests. In order to provide good control of the shear deformations in BE specimens, deformations in theoretically undeformable regions can be prevented by locally bonding aluminium foil to the fabric [6].

From the perspective of a macroscopic power balance, Harrison et al. [26,27] presented a normalisation method for PF and uni-axial BE experiments, applied for thermoplastic and thermoset matrix composites. A similar approach was used by Peng et al. [28] for dry fabrics, and taken further by Cao et al. [1] in the earlier cited international shear characterisation benchmark exercise. These approaches use the measured force – displacement data to determine a relation between the stress power and the shear angle, assuming the shear behaviour is rate independent. According to the theory, there are two different regions with different non-zero (unknown) stress powers and (known) different shear rates. A single solution can be found for the stress power versus the shear angle by means of an iterative procedure [3,4,29,30], employing a constitutive equation for the shear stress as a function of the shear angle. Alternatively, specimens of different sizes can be used to achieve a similar result [31]. This stress power can be translated to an equivalent shear force per unit length, which is being related to the force imposed in the longitudinal direction of the BE specimen [27]. In this approach it is assumed that fibre tension does not contribute to the deformation energy as a consequence of the inextensibility constraint.

Here, an attempt is made to clarify the magnitude and the role of the fibre stresses in shear characterisation experiments. The material will be described as a homogeneous continuum on the macroscopic scale,