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Shear behaviour of architectural fabrics subjected to biaxial tensile loads

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ABSTRACT

Broad assumptions are made in the testing and simulation of architectural fabrics used for tensile fabric structures. In particular, fabric shear behaviour is poorly understood and is not routinely determined. Tensile structures are continuously subject to a combination of biaxial tensile stress and shear stress, yet there is no accepted method for accurately determining shear behaviour in a tensioned fabric. A novel picture frame shear test design and associated test protocol is described here that aims to provide a practicable solution for the accurate determination of the in-situ shear stiffness of architectural fabrics. Results of shear tests on fabrics subjected to increasing levels of biaxial prestress are presented and the implications for analysis are discussed.

1. Introduction

1.1. Tensile fabric structures

Twenty years ago it was common practice to neglect the influence of shear in architectural fabrics when analysing tensile fabric structures [1]. Shear behaviour remains absent from some analysis methodologies used by industry [2]. Where shear stiffness is considered, the available guidance advises rule-of-thumb estimates [3] despite it being known that shear stiffness can impact significantly on the analysis results [3,4].

Tensile fabric structures have been used in state-of-the-art buildings (Fig. 1) for over forty years [5], including airports, sports stadia, shopping centres and large enclosed public spaces. All imposed loads are resisted by in-plane tensile and shear stresses by virtue of the structure's anticlastic (doubly curved) surface shape, applied pretension and large deflection behaviour [6].

Understanding and quantifying shear behaviour of architectural fabrics is important to designers, as large shear deformations are inherent in tensile fabric structures, both during installation and under imposed loading. As pretension is applied during installation, flat panels of fabric must undergo shear deformation to achieve the required smoothly curved anticlastic form. Shearing of the fabric will also occur due to large deflections in response to wind pressure and snow load. Furthermore, it is asserted that woven materials have a limiting shear deformation after which wrinkling will occur [7]. Wrinkling is unacceptable, both aesthetically if it occurs during installation, and as a potential cause of failure if it occurs under imposed loading. Despite this, neither the shear deformations that occur in membrane structures, nor the values of limiting shear angle for particular fabrics, have been quantified.

Accurate determination of shear stiffness will allow for the improved prediction of deflection and formability of tensile fabric structures as well as avoidance of wrinkling. Therefore, safer and more efficient structural solutions will be possible and designers will be able to explore more innovative architectural forms.

1.2. Architectural fabrics

Architectural fabrics are composite materials that generally comprise a base cloth of plain woven yarns encased in a polymeric coating. Coatings protect the base cloth from damage, provide stability to the weave pattern and make the fabrics impermeable to water. Predominant material combinations are polyvinylchloride (PVC) coated polyester yarns and polytetrafluoroethylene (PTFE) or silicone coated glass-fibre yarns. The combination of two different materials and the woven yarn structure of the base cloths results in complex in-plane tensile and shear behaviour. Crimp interchange (the interaction between the woven yarns) results in non-linear biaxial stress–strain behaviour that is both hysteretic and anisotropic [8]. Elastic moduli, Poisson's ratios and shear stiffness are not constrained by the same relationships as for homogeneous, isotropic materials and elastic constants are arguably inappropriate for describing the complex mechanical behaviour of coated woven fabrics [9]. The mechanical properties of architectural fabrics are not proportional to their thickness, and it is

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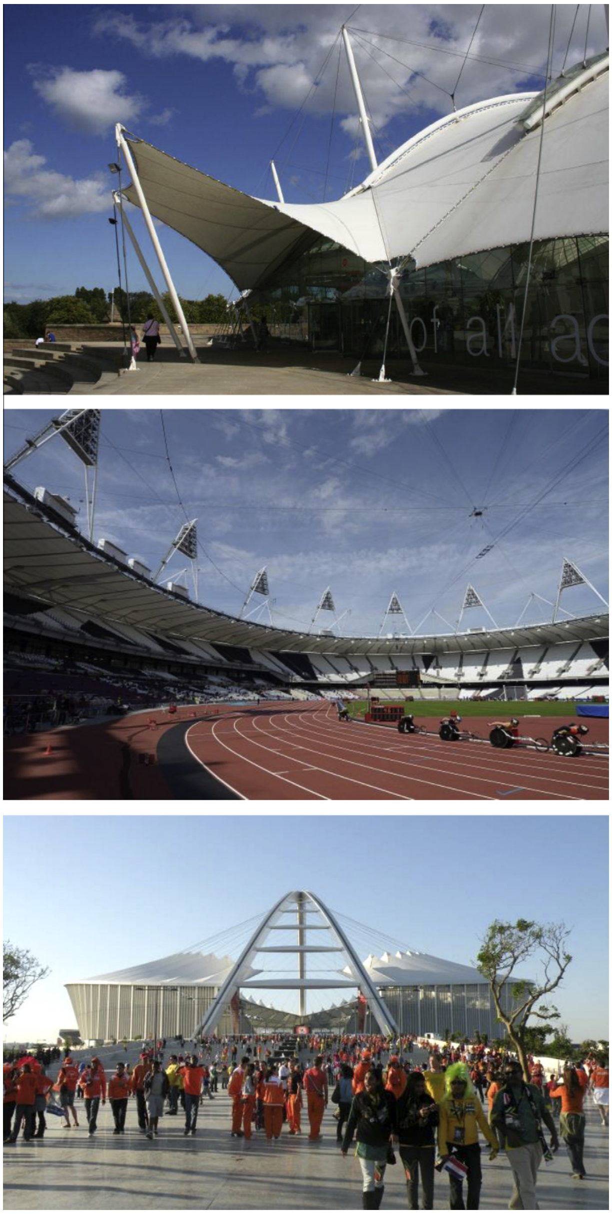

Fig. 1. (From top to bottom) Dynamic Earth Centre, Edinburgh ©Ben Bridgens; 2012 Olympic Stadium, London ©London 2012; and Moses Mabhida Stadium, Durban ©Schlaich Bergermann und Partner/Knut Göppert. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

standard practice to define stiffness values in 'kN/m width' with no reference to the fabric thickness [10].

The shear stiffness of architectural fabrics is predominantly governed by the protective polymeric coating [11] and is routinely assumed to be linear [2,4,12]. It is important to distinguish between shear of fabrics with and without yarn rotation. Typically, shear of woven fabrics refers to a change in angle between perpendicular yarn sets. However, shear can also occur with no change in angle between perpendicular yarn directions. The latter circumstance is observed when strain occurs in the perpendicular yarn directions and the strain in one direction does not equal that in the other. Fig. 2a shows 15° of shear deformation with yarn rotation and Fig. 2b shows 15° of shear deformation without yarn rotation. When this happens, shear resistance mechanisms of the coating are mobilised and the biaxial and shear behaviours will be linked. This paper is concerned with shear deformation that results in a change in angle between the yarns, as it is this type of shear deformation that is required to develop a curved surface from flat panels during installation. Note also that shear of woven fabrics is pure shear (Fig. 2c) with constant side lengths, as opposed to simple or 'engineering' shear (Fig 2d) which maintains a constant area.

1.3. Shear testing

The only standardised methodology for the shear characterisation of architectural fabrics has been produced by the Membrane Structures Association of Japan [13]. Therefore, further development of test equipment and methodologies must look to this standard, previously published experimental works, and industry best practice. Much of the available literature related to shear testing of fabrics concerns uncoated fabrics for use in composite forming [14–21]. This work is useful in the development of methodologies for the testing of architectural fabrics, but it is important to recognise that key differences exist when considering shear of *coated* fabrics. Uncoated fabrics are typically tested to large angles of shear and have low shear stiffness, compared to architectural fabrics that are tested at smaller angles and have relatively high shear stiffness (Table 1).

Methodologies for shear testing of woven materials have been described by Galliot and Luchsinger [26]. To accurately simulate the *in situ* behaviour of an architectural fabric it is necessary to simultaneously apply predetermined biaxial tension and shear deformation. Furthermore, it is desirable to apply a homogenous strain field to the fabric specimen as this allows simple calculation of the stresses resulting from the applied load. Assumptions regarding homogeneity of strain fields in during shear deformation must be validated [16]. The KES-F shear test [27,28], T-shaped specimen test [22] and extensively used bias extension test [14–18,21] cannot apply biaxial tension whilst shearing the specimen. The biaxial cruciform test with 45° yarns [23,29] applies biaxial tension, but the level of tension varies with shear deformation, and cannot be independently controlled. This method also requires a specimen that is difficult to prepare and can only apply 1:1 biaxial stress ratios. The inflated cylinder test [30] does allow independent control of biaxial tension and shear (through axial tension, inflation pressure and torsion, respectively), but no procedure to quantify the influence of the seam is presented. Galliot and Luchsinger [25,26] have developed an alternative methodology, the 'shear ramp', which produces a non-homogeneous shear strain field and consequently a non-homogeneous shear stress field. Therefore, the complex calculation of a correction factor is required to analyse the test results. Recently, Harrison et al. [31] developed a biaxially stressed bias test, by applying a load to each side of a bias test specimen by means of an arrangement of clamps and weights. However, in its present form the approach cannot control the load applied by the weights and no assessment of homogeneity of the strain field has been undertaken.

The picture frame shear test [14,15,18,21,32–36] allows application of biaxial prestress, which, subject to stress relaxation, can be maintained during a subsequent shear test by clamping the shear specimen along its edges. The frame subjects the specimen to a uniform deformation that should result in a homogenous state of pure shear. Homogenous deformation allows for calculation of the shear stress–strain relationship and definition of the shear stiffness. A further benefit of this method is that the fabric can be biaxially mechanically conditioned [8] prior to shear testing, to enable medium to long term fabric behaviour to be explored. For these reasons this test method has been adopted for this research.