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A new biaxial tensile shear test method to measure shear behaviour of coated fabrics for architectural use

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ABSTRACT

Shear properties of coated fabrics is poorly understood and the effects of shear stiffness on the behaviour of tensile fabric structures are usually ignored in the current design practice. The paper presents a new test method for the investigation of architectural coated fabric shear properties. The method relies on the biaxial pretension of cruciform specimens, where warp and weft yarns are oriented 45° with respect to the loading directions. Loading protocol is used to generate consecutive shear stress wave with specific biaxial tensile stress aligned with the yarns. An advanced biaxial tensile test system has been developed to implement biaxial loading by either displacement or force control strategy. Biaxial tensile shear tests of PVDF-coated polyester materials have been carried out to validate the new method. The implications of shear deformation, and material's viscosity and plasticity from the experimental results are addressed. The determination of shear stiffness is described and a comparison of results derived from different methods has been made. The advantages of the new biaxial tensile shear test method and some experimental findings are concluded.

1. Introduction

Tensile fabric structures have been used in many landmark buildings, such as airports, stadia, and convention centres, for more than four decades [1,2]. However, the structural analysis and design rules of tensile fabric structures are not as well codified as those of conventional building structures made of masonry, concrete or steel in most countries. Until now only limited technical specification or design guidance is available, and crude assumptions have been made for the material properties of architectural fabrics in the analysis of tensile fabric structures.

Although the important role of material properties in the design of tensile membrane structures has been recognised [3–10], the theory and techniques to determine and utilise these data are far from mature. It is a common practice to neglect the effects of shear behaviour in most analytical tools used by industry [3]. Gosling *et al.* [11] launched a round robin exercise for the analysis and design of membrane structures. The results indicated that the fabric shear property is poorly understood and further work in this area is required. This paper focuses on the development of an experimental method to study the shear behaviour of coated fabrics.

In the last decade, the topic concerning the shear response of the coated-fabrics has attracted growing interest due to the increasingly use of coated fabrics and strong concern about the performance and safety of the tensile fabric structures. Several test methods and test rigs have been developed. Galliot and Luchsinger [12–14] summarised the test methods for the investigation of fabric shear response, including the bias extension test, the picture frame test, the KES-F test [15], and the cylinder shear device [16], biaxial test with T-shape specimen [17] and biaxial test of a cruciform specimen [18].

The only test standard [19] for in-plane shear stiffness of membrane materials, released by Membrane Structures Association of Japan (MSAJ), employed the picture frame method. The inner dimensions of the square frame need to be not less than 16 cm × 16 cm. The square frame of the tester is loaded at a constant tension rate of 10 mm/min to the predetermined displacement, at which the in-plane shear angle is only limited to 1°. The picture frame method requires a small piece of fabrics and the material deformation is homogeneous in the whole sample. However the rigid clamps can produce undesired fibre tensions [12], which may affect the material's shear response.

Blum et al. [20], and Bögner and Blum [21] proposed a shear test method by applying biaxial tension on a cruciform specimen in which yarns are rotated at 45° to the loading directions. The central square of the specimen is 70 cm wide, and three extensometers are required to measure deformations in three directions in order to evaluate the variation of shear angles (0°–15°). In comparison with the picture frame

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method [19], the sample used in this method is much larger and the measurement of shear deformation is more complicated.

Galliot and Luchsinger [13,14] developed a shear ramp method, in which the shear deformation is obtained by linear stress ramps. A cruciform specimen with the central square of 50 cm × 50 cm and four arms, divided into five strips, was used. Unlike Blum's method [20], the yarns do not rotate but are aligned with the loading directions. This makes it possible to use a single specimen to carry out both biaxial extension and shear tests. However, the theoretical stress ramp can only be approximately satisfied by five steps because the load is applied by five actuators on each arm.

Jackson et al. [22] and Colman et al. [23] proposed a shear loading procedure for the picture frame method. The cruciform specimen with a central square and four arms was first loaded on the biaxial test rig. Then the picture was fitted around and clamped the specimen with the biaxial stress level maintained. Finally the picture frame and the test specimen were removed from the biaxial test rig and installed in a uniaxial test machine for shearing. This procedure allows investigating shear behaviour at various biaxial stress levels. In their test, a 30 × 30 cm biaxial cruciform specimen was used and the shear deformation is within ± 15°. Their picture frame test has an issue in accurately evaluating the shear force from the applied biaxial load because the friction in the frame hinges is difficult to determine.

The bias extension and the picture frame tests are probably the most popular methods to characterise shear behaviour of coated fabrics, but the biaxial tests have been increasingly used recently because the same test rig can also be used to evaluate the membrane's tensile behaviour, and a biaxial pre-tension of the specimen can be applied before the shear loading.

In this paper, a new biaxial test method for the investigation of coated fabrics shear behaviour is proposed. The main differences between the current biaxial test method and Blum et al.'s method [20] are twofold: the sample size and the method to evaluate shear deformation. MSAJ standard [19] for tensile behaviour specifies a minimum cruciform specimen with a central square of 16 cm wide and four arms. In order to be consistent with this dimension and therefore use the same biaxial test rig, this sample size has been adopted for investigating shear behaviour. In order to simplify the measurement of shear deformation, the use of three extensometers has been reduced to two. Accordingly the theory and equations to determine shear deformation are also derived.

2. Methodology

In this section, the specimen and the theory to characterise the shear behaviour of coated fabrics are introduced. The effects of the shear angle on the measurement precision are also describe.

2.1. Cruciform specimen

Cruciform specimens have been extensively used to evaluate the biaxial tensile behaviour of membrane materials [18,24–28]. To perform these tests, special biaxial test machines were developed in different laboratories. In order to utilise the same test rig for the biaxial tensile test, and to minimise the sample size, the minimum cruciform specimen regulated in the MSAJ standard [19] is adopted to carry out further analysis.

Fig. 1 shows a schematic drawing of the cruciform specimen with 45° orientated warp and weft yarns. The width and length of its arms are usually determined by the experimental purpose, and are constrained by the test machine used. The specimen corners are rounded with a radius of 10–15 mm. The specimens are taken from the part of the fabrics which is one tenth of the overall width from each selvage, exempting the portion within 1000 mm from the end.

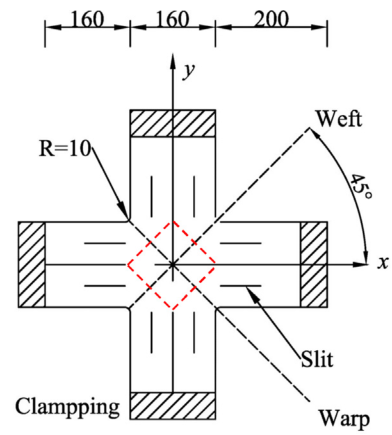

Fig. 1. Cruciform specimen use in a biaxial tensile shear test (Unit: mm).

2.2. Shear strain

When the cruciform specimen shown in Fig. 1 is under unequal biaxial tension, both tensile and shear deformation takes place at the central square. Since this study mainly concerns the shear behaviour, it is reasonable to assume that the deformation of warp and weft yarns in the core area is pure in-plane shear (Fig. 2), and no wrinkling occurs. In Fig. 2, the dash and solid lines represents the original and deformed shapes of warp and weft yarns in the core area, respectively, where α denotes the angle between the warp and the weft directions, and β denotes the angle between the warp and the x-axis in the deformed shape; ΔL_1 and ΔL_2 denote the displacements of the upper corner node and the right corner node, respectively. The relation between α and β is $\beta = \pi/2 - \alpha/2$ and it is derived on the basis of the assumptions that at the pretension stage the warp and weft yarns in the core area are perpendicular to each other, and at the loading stages the rhombus is symmetric to the x-axis and y-axis.

Using the stress tensor theory, Blum et al. [20] and Bögner-Balz and Blum [21] derived the shear strain equation, and for the 45° orientated yarns it becomes

$$\varepsilon_{wf} = \varepsilon_x - \frac{1}{2}(\varepsilon_w + \varepsilon_f) \tag{1}$$

where, ε_{wf} is the engineering shear strain, ε_x is the strain along the x-axis, and ε_w and ε_f are the strains in the warp and weft directions, respectively. The engineering shear strain is usually small, but sometimes large [18,22,23]. As shown in Fig. 2, the shear strain is defined as angular change γ, and it is positive when the diamond is narrowed in the y-axis, and negative when narrowed in the x-axis.

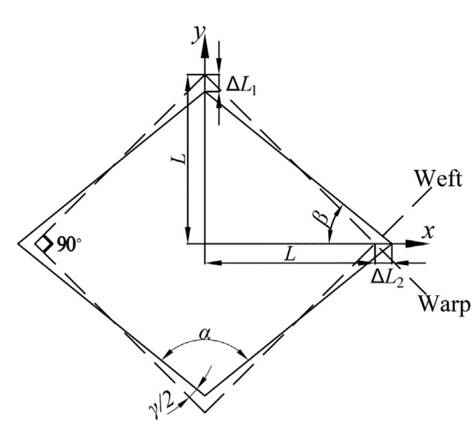

Fig. 2. Shear deformation of the core diamond area of a cruciform specimen under biaxial tension. Broken and solid lines denote undeformed and deformed shapes, respectively.