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In-plane shear investigation of biaxial carbon non-crimp fabrics with experimental tests and finite element modeling

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ABSTRACT

In-plane shear is one of the basic deformation mechanisms in forming fabrics on complicated shapes. In this paper, the in-plane shear behavior of non-crimp fabrics (NCFs), including NCFs based on T300 carbon fibers with chain or tricot-chain stitches, was characterized by picture frame and bias extension tests. It was found that the stitching yarns' strained condition depending on loading direction influences the shear behavior of NCFs. Further, the results of these two tests were compared by normalizing the shear force. It was observed that the normalized results of these two tests for shear force are consistent with each other in the direction of shear of the stitching, while deviations in other directions are attributed to the different strain mechanisms, as a result of the clamping way of the sample in the test. Finally, a mesoscopic finite element (FE) model was established to simulate the picture frame and bias extension tests for the selected T300 NCF with chain stitches. The model's validity was checked by comparing the simulated results with the experimental ones. Although some improvements are still needed, the model provides encouraging results and good foundations to predict the shear behavior for NCFs' forming.

1. Introduction

NCFs consist of unidirectional plies arranged in a number of designed orientations relative to the fabric warp direction, which are kept together by the stitching yarns. This structure enables the combination of the dimensional stability and the excellent shear deformation properties and the conservation of mechanical characteristics of the fibers in the final part [1–5]. Hence, these fabrics are applied in many areas of composites industry [6–8]. The fabrication of composites from NCFs usually involves a step in which the reinforcements are deformed into a designed shape by automatic and/or manual manipulations. Resin is subsequently injected to the lay-up, and then cured in an oven [9,10]. However, the deformation process may change the fiber angle in the fabrics and cause wrinkling or fiber breakage. Due to in-plane shear, the local fiber volume fraction and the permeability of the preform change, thus affecting the resin impregnation flow [11–14]. As a result, the final quality of the components is impacted. Therefore, advanced deformation simulation methods of NCFs are developed to optimize the forming process to improve the fabricating quality of preforms. In-plane shear deformation of these fabrics, as the basic mechanism for forming and the basic input data for simulations, should be deeply understood to improve the accuracy of the simulation, guaranteeing the final quality of the composite components [15,16].

Studies on the in-plane shear behavior of the NCFs have been conducted by many research groups. Two popular methods—the picture frame test and bias extension test, are used to characterize the in-place shear behavior of textile reinforcements. Lomov et al. [17] investigated the in-plane shear behavior of biaxial T700 NCFs with chain, tricot or tricot-chain stitches, using the picture frame test. The fabric shear angle was registered by full-field optical measurements and the thickness of sheared fabric was also measured. Further, full-field strain measurements were used to study the distribution of local deformation (e.g., local shear angles) of a NCF reinforcement with picture frame test. It was found that the difference between the shear of the fabric and the pure shear prescribed by the frame are normally negligible [18,19].

Kong et al. [20] experimentally investigated the deformation resistance and mechanisms of biaxial and triaxial glass non-crimp fabrics under bias extension loading. It was shown that the amount, the line-tension and the location of the warp-knitted stitches used to bind non-crimp fabrics have a major influence on the bias deformation resistance. Samir and Hamid [21] developed a method to determine the in-plane shear rigidity modulus of NCFs from bias-extension test. Bel [22,23] observed the sliding between the two plies of the reinforcement in bias extension tests, which was very different from the deformation kinematics of woven fabric; thus the sliding should be taken into consideration

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when simulating performing. Creech and Pickett [24] presented a meso-modeling approach for draping simulation of a biaxial NCF with a tricot stitch, in which some input data was determined from the picture frame and bias extension tests and used to validate the adopted deformation mechanisms. Generally, a mesoscopic mechanical FE model can represent the non-linear behavior of fabrics accurately and reproduce the boundary conditions of forming processes realistically [15,25,26].

Previous studies have rarely compared the shear results of both the two tests for NCFs and did not fully consider the role that the stitching plays in the fabrics' deformation mechanisms. Thus, in order for a deep understanding of the deformation mechanisms of NCFs, we herein characterize the in-plane shear behavior of biaxial NCFs with chain or tricot-chain stitches, using both the picture frame and bias extension tests. The influences of the stitching on the shear deformation and wrinkling of NCFs are discussed. The test results of the picture frame and bias extension tests are compared with each other after normalizing the results. Finally, a mesoscopic finite element model of T300 NCF having a chain stitch is presented to predict the shear behavior, which is validated by comparing the simulated results with the experimental results of picture frame and bias extension tests.

2. Materials

NCFs with chain stitches and tricot-chain stitches were used in this study; the fabric parameters, as specified by manufacturer, are shown in Table 1. In all case, the fabrics are stitched by polyester (PET) yarns with a weight of 33 dtex; the stitching spacing and the needle spacing are 2 mm and 5 mm, respectively. Toray T300 (3 K) carbon NCFs are provided by Changzhou Hongfa Zhongheng New Materials Co., Ltd, China. The photographs of chain or tricot-chain stitching NCFs are illustrated in Fig. 1.

3. Experiments

For NCF3-1, in-plane shear tests were performed in two ways: with the force applied in the parallel direction to the stitching and in the perpendicular direction to it. In the former case, the stitching was tensioned, while in the latter case the stitching was in compression. For NCF3-2, there should be no difference for the test direction, as the stitching, in the direction of 45° to the force, is always sheared. These three test directions will be referred below as ST (stitching-tension), SC (stitching-compression) and SS (stitching-shear), respectively.

3.1. Picture frame test

The central area of shear deformation was 210 mm × 210 mm, as shown in Fig. 2(a). Before the fabric was fixed in the frame, a pre-tension of approximate 0.013 N/mm was applied by hanging dead weight on the edges of the fabric, trying to make the fiber yarns in the same ply parallel to each other. There was a rubber pad beneath the plates to prevent slippage of the fibers (Fig. 2(b)). The fabric was gripped in the frame by screws in the plate with fibers parallel to the frame sides (Fig. 2(c)). It was recommended to remove the traverse yarns in the arm parts of the sample to eliminate the potential force contribution from these parts and the untimely wrinkling [17,27]. The frame was mounted on an Instron 5967 machine and the test speed equals 20 mm/min for all tests. When the crosshead moves up, the load is applied directly to the upper hinges. The load–displacement diagrams of the tests were recorded during the test. Since there are usually "bad" results in the first shearing cycle because of the variability in pretension of different yarns (see Section 4.1), every fabric has to be cyclically sheared to get reliable results.

Table 1
Parameter of the non-crimp fabrics.

Preform ID	Stitching pattern	Area density/ g/m^2	Number of layers	Orientation of fiber tows
NCF3-1	Chain	332	2	45°, −45°
NCF3-2	Tricot-chain	332	2	0°, 90°

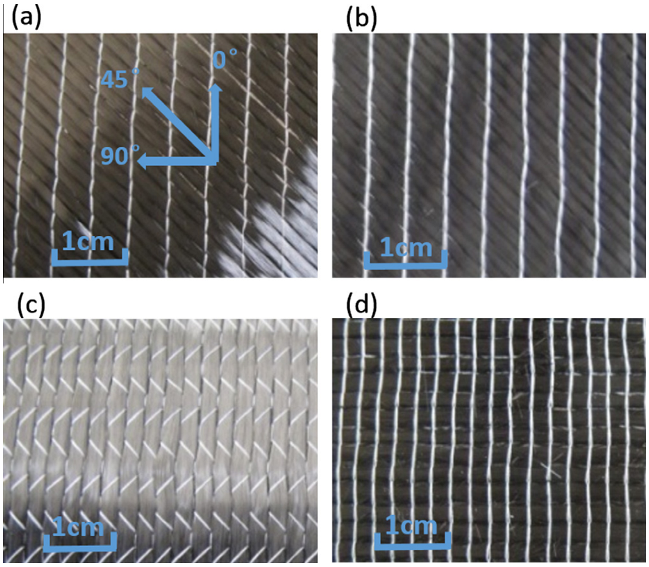

Fig. 1. Photographs of NCFs: face (a) and back (b) of chain stitching, NCF3-1, and face (c) and back (d) of tricot-chain stitching, NCF3-2.

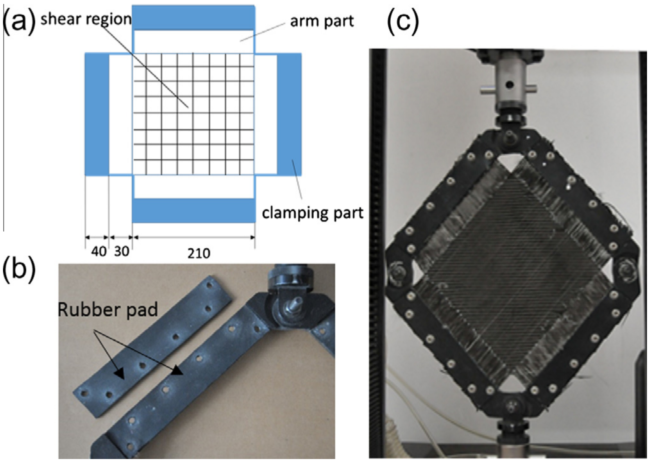

Fig. 2. Picture frame test: (a) dimensions of the sample, (b) grips and (c) mounted sample with fringe fibers taken out in the arm parts.

It was demonstrated that the difference between the theoretical shear angle and the local shear angle is very small especially at the initial deformation stage [17,27]. Hence, the global shear angle calculated from the frame kinematics is used in this paper, to denote the average shear angle of the fabric. Based on the deformed configuration of the fixture, the shear angle of the frame is calculated from the displacement by the following equations

$$\gamma = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} + \frac{d}{2L_{frame}}\right] \tag{1}$$