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Frictional behaviour of non-crimp fabrics (NCFs) in contact with a forming tool

Evangelos I. Avgoulas [a], Daniel M. Mulvihill [b], Andreas Endruweit [c], Michael P.F. Sutcliffe [a,*], Nicholas A. Warrior [c], Davide S.A. De Focatiis [c], Andrew C. Long [c]

[a] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom
[b] School of Engineering, James Watt South Building, University of Glasgow, Glasgow, G12 8QQ, United Kingdom
[c] Composites Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

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ABSTRACT

Microscopic observation and analysis are used to examine the role that contact conditions play in determining the frictional behaviour of non-crimp fabrics (NCFs). The true fibre contact length is measured over a range of normal pressures. For the NCF considered, the contact length is 67% lower than for a corresponding unidirectional tow-on-tool contact at a pressure of 240 kPa. The difference in contact behaviour is associated with the fabric architecture, specifically stitching and gaps between tows. These microscopic observations are used to predict friction using a constant interface shear strength model. These predictions are found to compare well with macroscopic friction measurements taken using a sliding sled arrangement, once the roughness of the sled tool is taken into account.

1. Introduction

The use of carbon fibre reinforced plastics (CFRP) is growing in the automotive, aerospace and marine industries, meeting the need to produce lightweight and geometrically complex parts and allowing lower stiffness to weight ratios than traditional metal based structures. A variety of forming techniques can be used to produce these parts from either dry fibre preforms or prepregs. Non-crimp fabric (NCF) composites are reinforced with multiple layers of straight (i.e. non-crimped) fibrous yarns stitched together using polyester thread, aramid or glass yarn [1]. Compared to woven fabrics, NCFs could offer better mechanical performance, shorter process cycles with lower resin consumption, and thus reduced manufacturing costs. Therefore, NCFs are increasingly being considered by the aircraft industry, as well as in automotive applications, wind turbine blades, yachts and other complex structural components [2–4].

Where liquid composite moulding (LCM) processes are employed for component manufacture, a dry preforming process typically precedes the resin infusion stage. The optimum setup of this preforming process to avoid wrinkling and buckling is typically determined by an inefficient trial and error approach. An accurate description of the forces induced in the fabric during preforming is needed to inform predictive models and accurately anticipate deformation including defects such as wrinkling and buckling. A key parameter required to determine the forces acting on the system is the friction in the system, for example for fibre-tool and fibre-fibre contact. Lee et al. [5] used a finite element analysis to show that non-isothermal stamping of woven composites is sensitive to the assumed friction law, predicting significant changes in load and local deformations, a result confirmed by Gorczyca et al. [6]. Hence there is a strong need for better models of friction in composites forming. However such models are held back by a lack of understanding of the mechanisms controlling friction. The aim of this paper is to uncover the mechanisms controlling friction in NCFs, and to make the link between microscopic contact conditions and macroscopic friction.

To better comprehend friction forces, it is important to understand the true fibre-tool and fibre-fibre contact area. In contacts between a fibrous material and any other material, the friction behaviour does not follow the direct proportionality between friction force F and normal force W given by Amontons' first law of friction [7]:

$$F = \mu W \tag{1}$$

where μ is the coefficient of friction. Instead, a more general power law formula has been proposed [8]:

* Corresponding author.
E-mail address: mpfs@eng.cam.ac.uk (M.P.F. Sutcliffe).

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$$F = kW^n \quad (2)$$

where k and n are constants. This general description (with n usually less than unity) has been experimentally observed for individual fibres [9–11], multi-fibre arrangements [12,13] and carbon fibre tows [14]. To understand the reasons behind this behaviour, it is helpful first to consider contacts between metal surfaces. The work of Bowden and Tabor [15], Archard [16] and Greenwood and Williamson [17] explained why metal surfaces follow the direct proportionality (i.e. $n = 1$) in Amontons' first law: namely, a constant interface shear strength acts over a 'real area of contact' which is only a fraction of the nominal contact area, but which is usually directly proportional to the applied normal load. However, contact involving fibrous materials deviates from the behaviour associated with metals because the real contact area is generally not linearly proportional to normal load owing to the differing details of the fibre contacts.

To explore the details of the contact behaviour for fibrous material, Smerdova and Sutcliffe [18,19] developed an optical technique to measure the true fibre contact length in woven fabric-tool contact. This was extended by Mulvihill et al. [14] to study the contact of fibrous tows. A key finding of these studies was that the real fibre contact length is actually much smaller than the maximum contact length that would be predicted by an idealised packing of parallel touching fibres, and that the contact length is especially small and sensitive to load at low pressures (i.e. less than 50 kPa, which is representative of pre-forming). Moreover there is a continuous increase in real fibre contact length with normal pressure which occurs as a fibrous tow is compacted by a flat surface [14].

Mulvihill et al. [14] also introduced a new rig to measure friction and fibre contact length concurrently at a small scale. Although real contact area varies non-linearly with normal load in the case of fibrous materials, Mulvihill et al. [14] found that tows obey a constant interface model of friction where friction and real contact area are proportional through a constant of proportionality representing the interfacial shear strength of the fibre contacts. Roselman and Tabor [11] investigated the contact of a carbon filament with a range of rough metal surfaces. They noted an increase in friction with decreasing surface roughness. This effect was also observed by Mulvihill and Sutcliffe for tow-on-metal contact [20]. This was explained by noting that smoother surfaces allow greater tow conformance with the surface and hence greater contact area and friction.

The above findings illustrate how friction in fibrous fabrics is governed by the details of the fibre contact. The present paper applies the methods developed by Smerdova and Mulvihill for woven fabrics and individual tows to determine the mechanisms controlling friction in NCF-on-tool contacts. The hypothesis is that the stitching and tow geometry in NCFs will change the details of the true fibre contact and friction. Sliding sled tests are used to measure macro-scale friction for the same materials which have undergone microscopic analysis. This allows the link to be made for the first time for such fabrics between microscopic contact conditions and macroscopic friction tests.

2. Experimental methodology

2.1. NCF-on-tool contact tests

The experimental methodology described by Smerdova and Mulvihill [14,18,19] is briefly summarised in this section. Fabric is compressed by a glass slide in a loading rig while under a microscope, allowing visualization of the true contact area between the fabric and a flat tool surface (Fig. 1). The rig is able to apply normal loads W to the NCF via glass plates and to enable concurrent measurement of the true contact length L of carbon fibres in contact with the plate over the range of these normal loads. A key feature of the rig is use of a special semi-reflective coating on one surface of the upper glass plate [18], which enhances the contrast of the contacting fibres. Roughness measurements of the upper and lower contact plates were carried out [14] using a stylus profilometer with measured values of R_a of 0.0044 µm and 0.0042 µm, for the upper coated plate and lower platform, respectively.

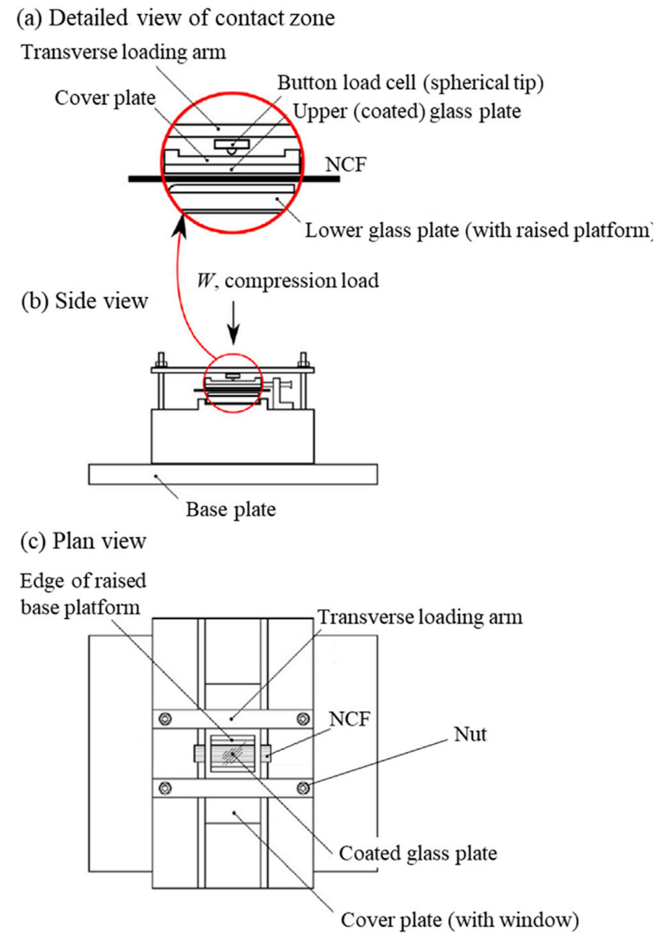

Fig. 1. Schematic drawing of the experimental rig for NCF-on-tool testing. (a) Detailed view of contact zone, (b) side view and (c) plan view, (modified from Ref. [14]).

The biaxial NCF used (FCIM591, supplied by Hexcel, Leicester) is made from 12K carbon tows, weighs 300 g per square metre and contains two tow layers orientated at −45°/+45°. The NCF is tricot stitched. This type of NCF was chosen because it is made from the same tow, T700SC-12k-60E, tested by Mulvihill et al. [14], and thus comparison of the contact area results can be made between single tow and NCF measurements. In each test, a layer of the NCF material was cut from the roll and clamped between the lower glass plate and the upper coated glass plate (see Fig. 1). The upper plate was balanced on the top of the NCF fabric with the coating touching the fibres on the triangular tricot stitched side of the NCF. A range of normal loads was applied by tightening the four nuts, with the resulting load measured by two button load cells. Five tests were carried out in total, and each consisted of 14 normal loading steps between 4 N and 200 N. Normal load was taken as the sum of the recorded output of the two button load cells (LBS-25, Interface force measurements, Arizona USA). A new NCF specimen was used for each test as fibre disruption or damage might have occurred during each test. Thus, five separate specimens were tested under the same conditions to give an indication of repeatability. The applied normal load was converted to a nominal pressure p using the nominal contact area of 25 mm × 25 mm.

The load cells were connected through a full bridge amplifier to a desktop PC via a data acquisition device (National Instruments NI USB-6009) and a Lab-VIEW program was written to acquire and output the