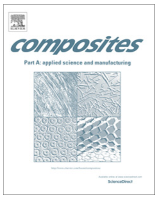
Composites: Part A 82 (2016) 159–169

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa



Experimental measurement of wrinkle formation during draping of non-crimp fabric

S.E. Arnold, M.P.F. Sutcliffe *, W.L.A. Oram

Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 12 December 2015
Accepted 19 December 2015
Available online 30 December 2015

Keywords:
A. Carbon fibre
A. Fabrics/textiles
E. Preforming
Wrinkling

ABSTRACT

A rig and image analysis methodology is described to characterise wrinkle formation during draping of non-crimp fabrics. The circular fabric blank is draped over a male hemispherical mould, partly constrained by a circular clamping ring around the periphery of the blank. The three-dimensional shape of the fabric is derived from a shape-from-focus analysis of a stack of photographs of the deformed blank. Wrinkles are identified from the deviation of the shape from a smoothed shape. Wrinkle formation is strongly dependent on the fabric architecture and increases progressively with increased punch displacement. Triaxial fabrics have the highest wrinkle amplitude, unidirectional and 0/90° biaxial fabrics the lowest amplitude. The clamping force reduces the wrinkling for some fabrics but, for the maximum force applied, is not effective at eliminating wrinkling.

1. Introduction

Non crimp fabrics (NCF) are attractive in a range of composite applications because of their good mechanical performance, handling characteristics, and because multi-axial tows can be stitched together to form a heavier-weight fabric [1,2]. Typically the dry fabric will be pre-formed at low pressure, perhaps using a blank holder to control the fabric movement, and then resin will be injected in a resin transfer moulding stage. Such a process route lends itself to automation with applications, for example, in the aerospace and automotive industries [2–4]. At present the selection of an appropriate fabric type which will work for a given geometry and draping process relies on experience and testing. Although simulations have been developed to model draping, development of defects and wrinkles remains an area of concern [5,6].

Drape modelling for woven fabrics has become reasonably mature, with a range of models of varying complexity used to predict the deformation behaviour [7]. The simplest kinematic pin-jointed net model can give a reasonable prediction of in-plane shear deformation [5]. Wrinkling is commonly supposed to occur when the tows 'lock-up' as shear in the fabric reaches some critical value [8]. However this over-simplifies the picture when modelling the effect of membrane stresses and out-of-plane wrinkle deformations, with more sophisticated models and associated experiments highlighting the importance of the in-plane and bending components of the fabric forces in determining wrinkling [8–10]. Once these factors are included, such drape models give a reasonable prediction of wrinkling behaviour of woven fabrics, as well as the associated shear deformation [11].

The difference in tow architecture and the introduction of stitches in NCFs means that a simple pin-jointed network approach for drape modelling is no longer able to predict the deformation mechanism and wrinkle development accurately. Instead more sophisticated material models are needed to capture the drape behaviour [1,12–14]. Both experiments and simulations highlight the effect of blank holder forces on wrinkle deformation [6,13]. While these simulations are encouraging, particularly in terms of the shear deformation modelling, the comparison and validation of models of wrinkling with experiments is somewhat limited, with ad hoc comparisons of the pattern and wrinkle height for a given geometry. Such models would benefit from a richer study of the way that such wrinkles develop, including more data on the location and geometry of the wrinkles, to improve the confidence in the quantitative predictions.

It appears that a hindrance to understanding of wrinkle development is a relative sparsity of good data characterising these features, particularly for NCFs. Al-gaadi et al. [15] used a laser set-up to re-construct the profile of draped cotton fabrics, characterising the wrinkles formed by the amplitude of deviations of the shape from a mean value. Lee et al. [6] measured wrinkling in a formed NCF fabric via the effect such wrinkles have on scattering of laser light. Although the information gained about the wrinkle geometry

---

* Corresponding author. Tel.: +44 1223 332996; fax: +44 1223 332662.
E-mail address: mpfs@eng.cam.ac.uk (M.P.F. Sutcliffe).

http://dx.doi.org/10.1016/j.compositesa.2015.12.011

is somewhat limited in this approach, the method nevertheless provides a quantitative way of demonstrating the reduction of wrinkling with increased blank holder force. Domskienė et al. [16] described a more rudimentary approach, again using the effect of wrinkles on scattering of light, to quantify wrinkle formation. More recently Christ et al. [17] used a laser triangulation sensor and camera set-up to measure the shape of the draped fabric, in a system which is available commercially by Textechno. Ouagne et al. [18] measured tow buckling when draping a plain weave flax over a tetrahedron using a camera system. Finally three dimensional (3D) shape reconstruction using two cameras is now a well-established technique which has been applied to textile deformation (see for example [19]) and in principle this could also be used to measure wrinkles. So, while there is a range of techniques which can adequately measure wrinkling in fabrics, it appears that there is a significant overhead associated with adopting any of these measurement techniques, limiting their more widespread use.

The aim of the research is to develop a simple and repeatable way to measure the formation of wrinkling defects during draping of fabric. The method is used to investigate wrinkle formation during pre-forming of non crimp fabrics, where the wide range of tow orientations and stitch patterns available means that a simple drape assessment tool is critical to effective process development. As well as providing a simple tool to identify which fabrics would be appropriate for a given application, the development of a more complete method for characterising wrinkle evolution can provide insights into the key elements needed in a model for wrinkle development and a comprehensive set of validation data for such a model.

2. Experimental method

Fig. 1 shows a schematic of the experimental rig used to investigate wrinkle formation. In order to be able to view wrinkle evolution during draping, initially-flat fabric was formed over a male-only hemispherical mould, in conjunction with a blank holder clamping ring. It is supposed that the mode of wrinkle formation in this process would also be typical of a matched mould process, albeit in the latter case that the constraint of the two moulds could limit the extent of wrinkle formation. An imaging methodology was developed to characterise the evolution of wrinkles, based on a ‘shape-from-focus’ method, chosen because of its relatively simplicity. In this approach a ‘*z*-stack’ of images is used to build up the 3D geometry. Details of the materials, mechanical design, draping procedure and image analysis methodology are given below.

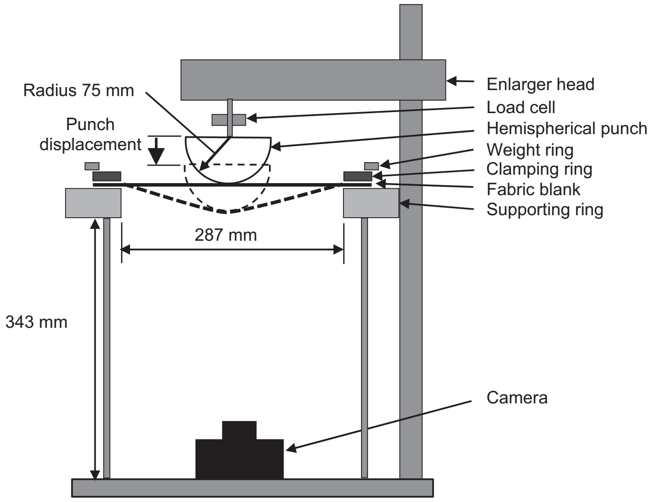


Fig. 1. Schematic of rig.

2.1. Materials

A range of non-crimp carbon fabrics was tested as detailed in Table 1, comprising a unidirectional fabric, ±45°, ±60° and 0/90° biaxial fabrics and two triaxial fabrics of differing weights, termed here light and heavy triaxial. The ±60° biaxial fabric contained powder binder. In all cases the stitching direction runs in the 0° direction so that all the fabrics are symmetrical about this stitching direction. Manufacturer’s data sheets are included in a data repository [20].

2.2. Draping rig

The draping rig is based on the testing rig described by Christ et al. [17], in which fabric is formed over a convex axisymmetric male tool, held in place by a transparent clamping ring. The realisation of this concept in our study is illustrated in Fig. 1. The design is built around a photographic enlarger head which provides the basic frame and mechanism for vertical travel. The male punch, manufactured out of modelling board, has a 75 mm radius hemispherical shape. The circular fabric blank of diameter 380 mm is held between a supporting ring, again made of modelling board, and a transparent perspex clamping ring. The inner and outer diameters of the clamping ring are 287 and 383 mm. Pressure is applied to the fabric through the clamping ring via a relatively stiff aluminium weight ring sitting on top of the clamping ring, on which deadweight loads are distributed at four locations around the ring, up to a total maximum weight of 8 kg. To this is added the 1.4 kg weight of the clamping and weight rings, even in the absence of additional weights. A simple beam bending calculation predicts that the deflections associated with uneven loading through the weight ring would be 20 μm at the maximum clamping load of 8 kg, assuming that the weights are reacted by point loads from the fabric mid-way between the weight locations. The actual deformations will be significantly less than this, since the reaction from the fabric will be more evenly distributed. This calculation indicates that such deflections will not lead to uneven loading, as such small deflections can be taken up by the compliance of the fabric.

Further modifications to the enlarger head include insertion of a load cell between the frame and the punch, and mounting of a stepper motor and gearbox on the side of the enlarger head, connected to the rack and pinion mechanism on the enlarger head. The stepper motor is controlled through a custom-built motor controller unit by Labview software, driven by a laptop PC through an NI USB-6009 interface. The speed of the punch is controlled via a software loop in Labview. Although this method of controlling the forming speed is not very accurate, as it depends on the PC clock speed, this is not considered to be a critical factor for the dry fabrics being tested. Gearbox backlash and flexure of the rig limit the accuracy of the displacement control, with an error of approximately ±0.5 mm. The NI interface device is also used to log the signal from the load cell, via a strain bridge amplifier. Digital filtering is used to remove noise in the logged signal, applying a low-pass Butterworth filter using a Matlab programme. Calibration of the load cell is performed using deadweight loading. The full set of load data for the different materials has been deposited in the online data depository.

2.3. Imaging

In the testing rig described by Christ et al. [17], two cameras and a laser triangulation sensor were used to characterise the shape of