Composite Structures 149 (2016) 106–113

Contents lists available at ScienceDirect

Composite Structures

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

Three dimensional finite element study of the behaviour and failure mechanism of non-crimp fabric composites under in-plane compression

Luis Miguel Ferreira *, Enrique Graciani, Federico París

Grupo de Elasticidad y Resistencia de Materiales, Escuela Técnica Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

ARTICLE INFO

Article history:
Received 10 July 2014
Revised 25 February 2016
Accepted 8 April 2016
Available online 9 April 2016

Keywords:
Composites
Non-crimp fabric (NCF)
Finite element model (FEM)
Compressive behaviour
Failure mechanism

ABSTRACT

The compressive behaviour and the mechanism responsible for failure of a $[0,90]_n$ non-crimp fabric (NCF) laminate are studied using a 3D finite element (FE) model of the representative unit cell at the mesoscopic scale. The tows of the unit cell were generated using a straight FE mesh taking into account the waviness of the fibres with the definition of the mechanical properties of each element according to the actual direction of the fibres. A parametric study has been carried out to evaluate the influence of the non-linear behaviour of the tows and of the fibre crimp on the compressive failure mechanism of the laminate. The numerical predictions are discussed and compared with experimental data. The results lead to think that the mechanism of failure of a $[0,90]_n$ NCF laminate under a pure compressive load is controlled by the shear strains that appear in the crimp part of the 0° tows. It is also found that the non-linear behaviour of the tows and the fibre crimp substantially contribute to the development of the potential failure initiation mechanism. A satisfactory agreement between the numerical and experimental compressive stress–strain curves is obtained for the highest fibre crimp angles considered.

1. Introduction

The need to combine the excellent in-plane behaviour of the composites made from unidirectional layers of pre-impregnated tapes with the lower cost and better out-of-plane behaviour of the woven fabric composites led to the appearance of the non-crimp fabric (NCF) composites [1]. These composites are made from dry preforms which are produced in a continuous process by sequentially laying groups of fibre tows, or tows for short, at a specific orientation, sequentially on a conveyor system. Once the tows are laid at all the orientations required, they are held in position by a stitching yarn creating, in theory, a fabric without fibre crimp. In practice, however, some geometrical features are introduced at the manufacturing stage of the preforms and others later on at the moulding stage, such as resin pockets between the tows and some mesoscopic fibre crimp, (Fig. 1 [2]); the latter has particular interest for this study since it is strongly related to the compressive performance of NCF composites [3–5].

Due to the complex internal structure of the NCF composites, performing representative studies using Finite Element (FE) models becomes a complicated task. Some representative studies have been performed using a 2D approach [3,6,7]. However, the complex mesoscopic architecture of these materials may not be completely represented by a 2D FE model [5], since it is highly irregular along all directions of the material. Moreover, this approach does not allow the stresses and strains at the 3D mesomechanical level to be calculated. These limitations motivated the development of parametric mesoscopic 3D FE models capable of reproducing the complex 3D structure of a NCF laminate.

The study presented in this paper, of the compressive behaviour and failure mechanism of NCF composites, has been achieved using 3D FE models of the representative unit cell of a $[0,90]_n$ NCF laminate, represented in Section 2.1. The stiffness properties of the constituents and the boundary conditions imposed are described in Sections 2.2 and 2.3, respectively. The compressive behaviour results, which are presented in Section 3, emphasize the shear stresses/strains components associated with the mechanism of failure and how the non-linear behaviour of the tows and the fibre crimp affect the compressive performance of the NCF laminate. In Section 4, the numerical predictions are discussed and compared with the experimental evidence obtained from the work carried out on the FALCOM Project (Failure Performance and Processing Prediction for Enhanced Design with Non-Crimp Fabric Composites). The numerical analysis has been carried out using a FE model

---

* Corresponding author at: Higher Colleges of Technology, Abu Dhabi Men's College, P.O. Box 25035, Abu Dhabi, United Arab Emirates.

E-mail addresses: lferreira@hct.ac.ae (L.M. Ferreira), egraciani@us.es (E. Graciani), fparis@us.es (F. París).

http://dx.doi.org/10.1016/j.compstruct.2016.04.022

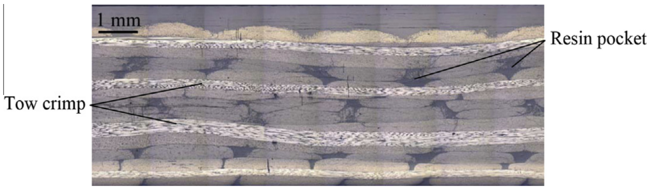


Fig. 1. Cross-section of a typical NCF composite.

with straight mesh, following the modelling approach presented in [8]. In Section 5, the results obtained with the FE models with a straight mesh are compared with those obtained with the *Classical Modelling Approach* (using a curved mesh) to show the better performance of the FE models with a straight mesh. Finally, the conclusions are set out in Section 6.

2. Mesoscopic approach of the NCF laminate

Before presenting the mesoscopic scale 3D FE models developed for this study, it is necessary to define the concept of the representative unit cell (RUC): a repeatable cell which allows any part of the NCF laminate to be generated just by assembling multiple RUC's. This concept is illustrated in Fig. 2 using a $[0,90]_2$ NCF laminate.

At the mesoscopic level, an NCF laminate can be thought of as a stack of layers of fibre tows (in different orientations) with homogeneous transversely isotropic behaviour, the isotropic plane normal to the fibres being surrounded by an homogeneous isotropic matrix.

2.1. Numerical models

A mesoscopic scale 3D FE model of the RUC of a $[0,90]_n$ NCF laminate with fibre crimp, due to nesting of the tows, was generated using structural solid element SOLID45 from ANSYS® FE code [9]. The unit cell is composed of 4 laminas (0°, 90°, 0°, 90°) and each lamina contains two half-tows with a resin pocket between them, see Fig. 3(a) and (b). Notice that the resin has been removed to better understand the tows' shape and orientation. Some of the geometrical parameters, which appear in Fig. 3, will be defined later.

The curvature of the tows has not been included in the geometry of the model, however the waviness of the fibres has been taken into consideration, see Fig. 4(a), following the modelling approach presented in [8]. This approach obviously allows a straight FE mesh, as represented in Fig. 4(b), to be used. An isolated element with the appropriate orientation of the fibres in shown in Fig. 4 (c). Notice that α is the angle between the fibre direction 1 and the ideal longitudinal direction of the tow (x in the 0° tows and y in the 90° tows) and will be referred to as the *misorientation angle* from now on. β is an angular parameter that corresponds to the maximum misorientation angle and thus represents the maximum fibre crimp of the tow, that is: $\beta = \max(\alpha)$.

A maximum fibre crimp angle of 9° was chosen for the initial studies, based on the fact that previous results showed a satisfactory agreement between the apparent in-plane stiffness properties and the experimental evidence for angles in the range of 9° to 12° [4,10]. In what follows, the fibre crimp was parametrically varied (in a range of 0° to 12°) in order to reveal the influence of this geo-

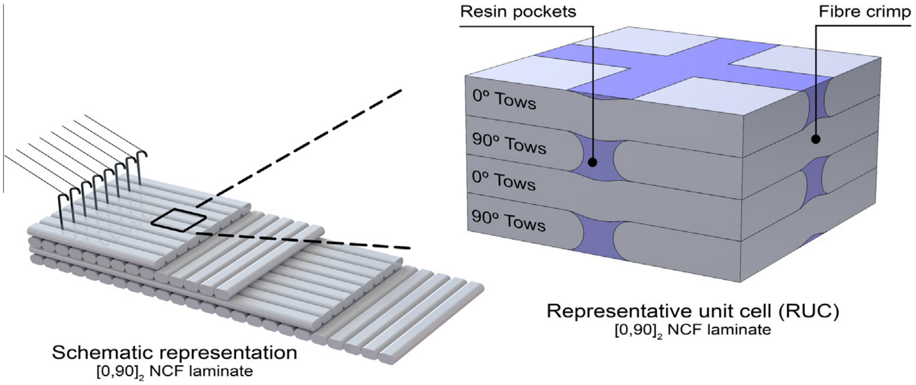
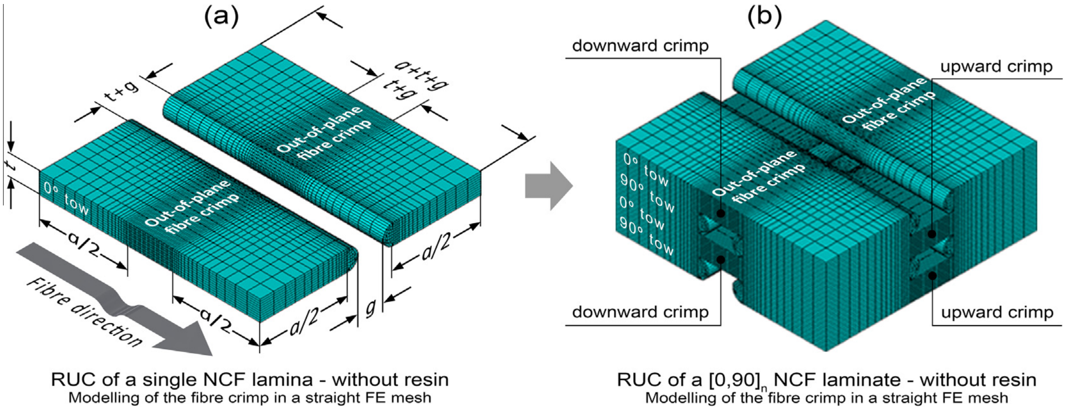


Fig. 2. Process used to obtain the representative unit cell of a $[0,90]_2$ NCF laminate.



RUC of a single NCF lamina - without resin
Modelling of the fibre crimp in a straight FE mesh

RUC of a $[0,90]_n$ NCF laminate - without resin
Modelling of the fibre crimp in a straight FE mesh

Fig. 3. 3D FE model of the representative unit cell without resin.