Composites Part B 77 (2015) 105–111

Contents lists available at ScienceDirect

Composites Part B

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

Nonlinear response in glass fibre non-crimp fabric reinforced vinylester composites

R.K. Joki [a, b, *], F. Grytten [a], B. Hayman [b]

[a] SINTEF MC, Department of Materials and Nanotechnology, Pb. 124 Blindern, 0314 Oslo, Norway
[b] University of Oslo, Department of Mathematics, Pb 1053 Blindern, 0316 Oslo, Norway

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form
27 February 2015
Accepted 2 March 2015
Available online 11 March 2015

Keywords:
B. Mechanical properties
B. Plastic deformation
C. Finite element analysis (FEA)
D. Mechanical testing

ABSTRACT

This paper addresses the nonlinear stress-strain response in glass fibre non-crimp fabric reinforced vinylester composite laminates subjected to in-plane tensile loading. The nonlinearity is shown to be a combination of brittle and plastic failure. It is argued that the shift from plastic to brittle behaviour in the vinylester is caused by the state of stress triaxiality caused by the interaction between fibre and vinylester. A model combining damage and plasticity is calibrated and evaluated using data from extensive experimental testing. The onset of damage is predicted using the Puck failure criterion, and the evolution of damage is calibrated from the observed softening in plies loaded in transverse tension. Shear loading beyond linear elastic response is observed to result in irreversible strains. A yield criterion is implemented for shear deformation. A strain hardening law is fitted to the stress-strain response observed in shear loaded plies. Experimental results from a selection of laminates with different layups are used to verify the numerical models. A complete set of model parameters for predicting elastic behaviour, strength and post failure softening is presented for glass fibre non-crimped fabric reinforced vinylester. The predicted behaviour from using these model parameters are shown to be in good agreement with experimental results.

1. Introduction

The aim of this study is to improve the prediction of the response of non-crimp fabric (NCF) reinforced polymer composites to in-plane loading beyond the linear elastic range. Failure prediction in fibre reinforced polymer composites has gained attention from a growing community of researchers since the 1960s. After Tsai and Wu proposed their criterion for anisotropic materials in 1971 [1], numerous criteria have been published. In 2004 the first World-Wide Failure Exercise (WWFE) was published [2]. The goal of the exercise was to evaluate the current failure criteria for laminated polymer composites. The organizers of the WWFE concluded with a range of recommendations for designers and researchers [3]. Physically based failure criteria that distinguish between different types of failure mechanisms [4–6] were favoured. Both Puck's [5] and Cuntze's [4] criteria also addressed the apparent stress-strain softening observed between first ply failure (FPF) and ultimate failure by including progressive degradation of material properties. The recommendations advised against simple linear assumptions in applications where significant non-linear response could be anticipated. A robust post-FPF residual analysis should be able to reliably predict significantly non-linear response.

The present study addresses composite laminates based on wet lamination with NCF reinforcement, which offer large potential for application in primary structures as they give excellent performance at lower production costs compared to the equivalent use of pre-impregnated reinforcement (prepregs). The nature of these laminates with resin pockets between somewhat arbitrarily shaped fibre bundles (see Fig. 1) has called into question the use of the modelling and calibration techniques developed by studying more orderly structured laminates from prepreg tapes. During the past decades, several studies have investigated the mechanical properties of the characteristic structure of NCF laminates [7–19]. Nonlinear stress strain response in polymer composites is commonly treated as the evolution of damage [5,13,19–24]. Brittle damage has been observed during the present study. Some laminates, on the other hand, showed additionally irreversible strains when loaded

* Corresponding author. SINTEF MC, Department of Materials and Nanotechnology, Pb. 124 Blindern, 0314 Oslo, Norway. Tel.: +47 909 13 046.
E-mail addresses: reidar.joki@fireco.no (R.K. Joki), Frode.Grytten@sintef.no (F. Grytten), brianha@math.uio.no (B. Hayman).

http://dx.doi.org/10.1016/j.compositesb.2015.03.001
1359-8368/

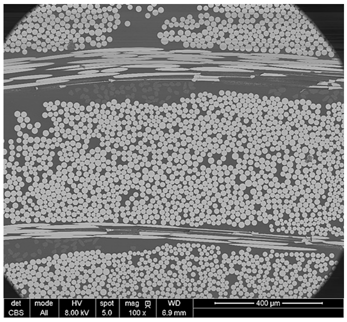

Fig. 1. Cross sectional view of NCF reinforced polymer composite showing fibre bundles and resin pockets.

Table 2
Laminates, orientations and tests.

Laminate	Lay-up	Testing orientation	Property
6R1	$[0]_6$	0°	Tensile
6R1	$[0]_6$	90°	Tensile
6R2	$[0/90]_6$	45°	Shear
6R2	$[0/90]_6$	0°	Tensile
6R2	$[0/90]_6$	0°	Compression
6R2	$[0/90]_6$	0°	Shear
6R3	$[0_2/45/-45]_6$	0°	Tensile
6R3	$[0_2/45/-45]_6$	90°	Tensile
6R3	$[0_2/45/-45]_6$	0°	Compression
6R4	$[0/90/45/+45]_6$	0°	Tensile
6R4	$[0/90/45/+45]_6$	0°	Compression

beyond the linear elastic limit. Similar observations have been reported by others [18,20–22,25–28]. It seems that plies deformed beyond the linear elastic limit in shear, with respect to the principal axis of orthotropy, exhibit such irreversible strains. However, the same plies exhibit insignificant irreversible strains after normal tensile deformations in the principal directions of orthotropy. Finite element modelling (FEM) is a good tool for investigating the effects of different failure mechanisms. The interaction between brittle and ductile response as sources for the observed nonlinear stress strain behaviour observed in NCF laminates are investigated in this paper using FEM. A constitutive model based on the observed response of these NCF laminates is therefore developed, implemented in the LS-DYNA finite element code, characterized and validated for tensile loading. The next section gives a description of the investigated NCF laminates. The following section introduces the constitutive models. The final two sections are devoted to results and concluding remarks.

2. Laminate and test specifications

The NCF fabrics are made of E-glass and produced by Devold AMT. They are embedded in a Reichhold Dion 9102 vinylester matrix. Four different NCF mats are used to construct four laminate lay-ups. The specifications of reinforcements, laminates and tests are listed in Table 1, Table 2 and Table 3, respectively. It should be noted that for some of the laminates small quantities of fibres are oriented in additional directions to the main orientations indicated by the laminate name. Table 1 lists all fibre orientations. All tests were conducted in accordance with the prevailing standard specified by the American Society for Testing and Materials (ASTM). The strength measured on unidirectional laminates was somewhat lower than that obtained by back-calculating [29] from embedded plies in multidirectional laminates. Embedded plies have been reported to show higher strengths than that measured on unidirectional laminate [20,30]. It is thought that for embedded plies the neighbouring plies with different fibre orientations act as micro-crack stoppers, whereas similar micro-cracks in unidirectional laminates are free to grow in the thickness direction. The strength properties obtained from back-calculated response of embedded plies are therefore used here.

Table 1
Reinforcement weight and orientations.

Laminate	Fibre orientation	Reinforcement weight [g/m2] and fibre direction pr. ply (nominal values)			
		0°	90°	+45°	−45°
6R1	$[0]_6$	827	43	–	–
6R2	$[0/90]_6$	388	388	9	–
6R3	$[0_2/45/-45]_6$	413	9	199	199
6R4	$[0/90/45/+45]_6$	236	199	199	199

All tabs were bonded using 3M DP 490 epoxy adhesive. Flatness and parallelity of the tabs were ensured using a large, heated plate press. The average pressure on the tabs was approximately 0.7 MPa and the plate temperature was 45 °C. Tests where failure initiated in the vicinity of the tabs were discarded. The ASTM D 6641 test standard recommends a width of 12 mm [31]. However, the coarse structure of the reinforcement can introduce large scatter in the results. Therefore, a specimen width of 25 mm was used. The ASTM D 7078 V-notched rail shear test specimen had a cross section width of 31 mm between the notches [32]. The notches were machined with a tool radius of 1.3 mm. Tests with invalid failure were disregarded. The material properties found are listed in Table 4. In the absence of experimental results, the shear modulus, G_{23}, and Poisson's ratio, ν_{23} for the transverse plane of isotropy were determined using the micro-mechanical relations defined by Hess and Himmel [14]:

$$G_{23} = \frac{E_{22}}{2(1+\nu_{23})},$$
$$\nu_{23} = \nu_{f21}V_f + \left(1 - V_f\right)\nu_m \frac{\left(1 + \nu_m - \nu_{21}\frac{E_m}{E_{11}}\right)}{\left(1 - \nu_m^2 + \nu_m\nu_{21}\frac{E_m}{E_{11}}\right)}, \quad (1)$$

where $\nu_{21,f}$ is the Poisson's ratio of the fibres, V_f is the fibre volume fraction, and ν_m and E_m are the Poisson's ratio and Young's modulus for the vinylester, respectively. The fibre volume fraction was obtained using a standard ignition loss test [33]. The values for $\nu_{21,f}$, ν_m and E_m were provided by the respective material manufacturers.

3. Constitutive model

The constitutive models are applied at the ply level. Two constitutive models are defined and named model 1 and 2. All nonlinearity is treated as damage in model 1. In model 2, non-linear shear deformation with respect to the principal axes of orthotropy is treated as a combination of plasticity and damage. It is commonly known that matrix associated failure develops in a progressive manner, whereas fibre failure occurs in an abrupt and sudden manner often resulting in ultimate failure [4,5,22]. The gradual evolution of damage associated with the matrix material is therefore thought to be the main contributor to the observed global softening [34]. Damage is treated within the framework of continuum damage mechanics (CDM) [22,24,28,35].

The notations used in the two constitutive models are as follows: E represents Young's modulus, G shear modulus, ν Poisson's ratio and S strength. The numerical notation refers to the