TESTING OF CARBON/EPOXY NCF STRENGTH UNDER MIXED IN-PLANE LOADING

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Abstract

The measured stiffness and strength of a carbon/epoxy unidirectional NCF system in shear, tension and compression are compared with test results for the pure resin and for impregnated bundle material under various combinations of in-plane compressive and tensile loading. The study is a part of a project to develop mesomechanics models to predict failure of NCF materials under triaxial loading by use of data for the pure resin and for bundles impregnated by resin. A simplified analytical rule-of-mixtures model is suggested for stiffness and strength of the NCF material. Good agreement is shown for shear and tension along and transverse to the bundles. Compressive strengths are significantly underestimated, apparently due to deficiencies in the compressive test method used for the bundle material.

1 Introduction

The strive to reduce cycle times and material costs of composites in e.g. aircraft and automotive structures has resulted in an increasing interest in replacing prepreg layups by impregnation of dry fibre preforms, which also facilitates manufacture of more complex geometries. Textile based preforms provide flexibility and ease of handling, and are relatively cheap. The in-plane mechanical performance of textile based composites is, however, reduced in comparison to unidirectional (UD) prepreg, due to the inherent fibre waviness and a lower fibre volume fraction [1], although damage tolerance may be improved.

Textile based composites consist of impregnated fibre bundles surrounded by pockets of a homogeneous matrix, and are fairly homogeneous on a microscopic level (i.e. within bundles or resin pockets), but are highly inhomogeneous on the meso level (i.e. within plies). The bundles in textile composites are transversely isotropic, but the composite is orthotropic, and hence a large number of tests are required for material characterisation. Furthermore, the inhomogeneous mesostructure results in stress concentrations and strength values which depend on the specific layup and fibre architecture.

Non Crimp Fabrics (NCF) consist of fairly straight fibre bundles knitted or stitched together by a binder yarn and provide a higher in-plane mechanical performance than conventional weaves, in some respects comparable to UD prepreg. ReFACT is a project aimed to develop homogenised ply failure criteria for NCF composite plies under triaxial loading. Figure 1 shows the dry NCF fabric considered in the present study, and a cross-section of a resulting quasi-isotropic layup. In the figure areas with white "stripes" correspond to 0° plies, areas with dots are 45° plies (lighter) and 90° plies (darker) and grey areas are resin pockets.

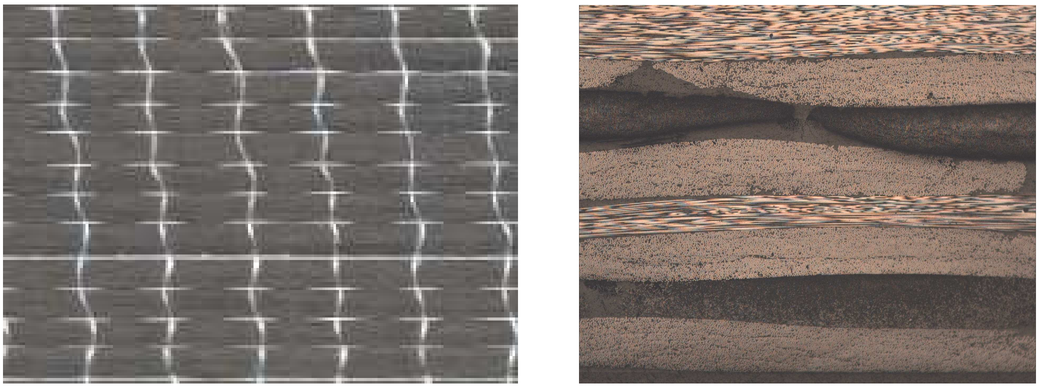

Figure 1. Dry NCF fabric and a cross-section of a quasi-isotropic laminate after RTM processing

In theory the strength of textile composites may be determined by micromechanical models based on the properties of the matrix and fibres, Fig. 2. In practice this approach faces several problems due to; (a) random distribution of fibres in bundles [2], (b) uncertainties in the appropriate matrix failure criterion (dilatational versus distortional failure criteria) [3-4] and (c) volumetric influence of matrix strength values [5]. For this reason the approach taken by ReFACT is to develop a mesomechanical strength model based on a description of the meso-geometry and separate characterisation of the resin and the impregnated fibre bundles, Fig. 2, i.e. excluding the modelling components shaded in grey.

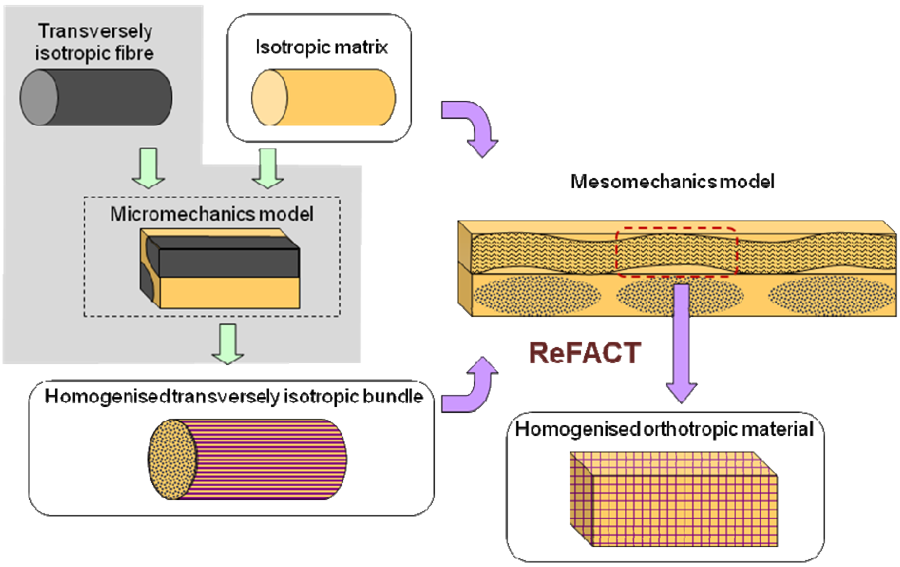

Figure 2. Mesomechanics modelling strategy in the ReFACT project

2 Simplified analytical models

In this paper a simplified analytical model is suggested for estimating the stiffness and strength of the NCF plies. A more accurate material model based on a 3D finite element (FE) mesomechanical model of homogenised bundles and the surrounding resin pockets is also developed within the project ReFACT, and will be presented later in a separate paper.

The simplified analytical model of a UD NCF ply neglects bundle waviness and stress concentrations. The fundamental parameters of the model are illustrated in Fig. 3.

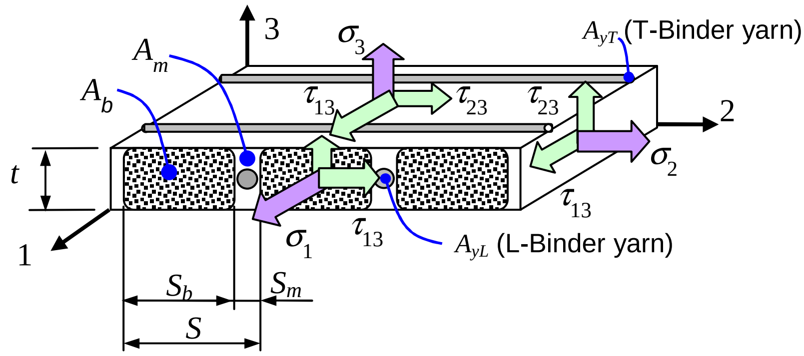

Figure 3. Parameters for analytical mesomechanics model

Assuming longitudinal and transverse binder yarn fractions v_{yL} and v_{yT} the volume fractions of bundles and matrix v_b and v_m are obtained as follows:

$$\mathrm{v}_b = V_b/V = A_b/(tS) \qquad \mathrm{v}_m = V_m/V = (A_m - A_{yL})/(tS) = 1 - \mathrm{v}_b - \mathrm{v}_{yL} \tag{1}$$

Elastic properties of the ply are predicted by conventional models for unidirectional fibre composites, with the properties of fibres replaced by the homogenised properties of the bundles, i.e. the rule of mixtures for ν_{12} and the modulus along the bundles E_1 and the Halpin-Tsai relations [6] for the transverse modulus E_2 and shear modulus G_{12}, modified by a rule of mixture model accounting for the transverse load carried by the transverse binder yarn:

$$\nu_{12} = \mathrm{v}_b \nu_{b12} + \mathrm{v}_m \nu_m + \mathrm{v}_{yL} \nu_y \qquad E_1 = \mathrm{v}_b E_{bL} + \mathrm{v}_m E_m + \mathrm{v}_{yL} E_y$$

$$E_2 = \mathrm{v}_{yT} E_y + (1 - \mathrm{v}_{yT}) E_m \frac{(1 + \xi_E \eta_E \mathrm{v}_b)}{(1 - \eta_E \mathrm{v}_b)} \qquad G_{12} = G_m \frac{(1 + \xi_G \eta_G \mathrm{v}_b)}{(1 - \eta_G \mathrm{v}_b)} \tag{2}$$

$$\text{where} \quad \eta_E = (E_{bT}/E_m - 1)/(E_{bT}/E_m + \xi_E) \quad \eta_G = (G_{bLT}/G_m - 1)/(G_{bLT}/G_m + \xi_G)$$

where ν_{b12}, ν_m and ν_y are the Poisson's ratio of the bundles, matrix and binder yarn, E_{bL} and E_{bT} are the longitudinal and transverse Young's moduli of the bundles, G_{bLT} is the shear modulus of the bundles for shearing in longitudinal planes, E_y the Young's modulus of the yarn and E_m and G_m are the Young's modulus and shear modulus of the matrix. The ξ_i parameters were set to ξ_E=2 and ξ_G=1.

For prediction of strength it is assumed that failure is controlled by fibre failure during loading along the bundles and by matrix cracking within the bundles during shearing and loading transverse to the bundles. Thus, the bundles are considered as the "weakest link", which is in agreement with previous experimental observations [1] and the current measurements on fibre bundle material and pure resin.

The axial strengths X_i of the ply are predicted by a constant strain model:

$$X_i = \sigma_{bLi} \left[\mathrm{v}_b + \mathrm{v}_m \, E_m/E_{bL} + \mathrm{v}_{yL} \, E_y/E_{bL} \right] \tag{3}$$

where i=t or c for tensile or compressive loading and σ_{bLi} is the bundle failure stress.

The ply transverse strengths Y_i and shear strength XY are predicted by a constant stress model:

$$Y_i = \left[1 - v_{yT} + v_{yT}\, E_y / E_{bT}\right] \sigma_{bTi} \qquad XY = \tau_{bLT} \tag{4}$$

where σ_{bTt} and σ_{bTc} are the transverse tensile and compressive strengths of the bundle and τ_{bLT} is the shear strength of the bundle.

For the strength of UD NCF laminates it is necessary to consider that at least one resin pocket will be present through the thickness, Fig. 4a, unless all bundles have been aligned perfectly on top of each other. For laminates with large bundle fractions (i.e. narrow resin pockets) this upper limit is also a reasonable approximation of the strength, as the likelihood for two resin pockets exactly on top of each other is small. By assuming a constant strain through the laminate the transverse strength and shear strength of $n \geq 2$ stacked NCF plies are given by:

$$Y_{lam} = Y \cdot \left(n - 1 + E_m / E_{bT}\right) / n \qquad XY_{lam} = XY \cdot \left(n - 1 + G_m / G_{bLT}\right) / n \tag{5}$$

The lowest strengths are obtained for a two ply laminate, and the strengths then asymptotically approach the values for a single ply.

3 Materials and specimens

The materials in this study involved (1) NCF material consisting of Tenax HTS 12k carbon fibre roving impregnated by RTM 6 resin, (2) pure RTM 6 resin, (3) transversely isotropic material representative of the impregnated bundles.

3.1 NCF specimens

The NCF material was produced by resin transfer moulding (RTM) of a dry NCF fibre preform using RTM 6 resin. The ratio between volume fractions v_y of binder yarn and carbon fibres was v_{yL}/v_f =0.023 in the bundle direction, and v_{yT}/v_f =0.009 transverse to the bundles. Eight layers of dry UD NCF preforms were placed between two steel plates with a fixed distance of approximately 2 mm, and resin was infused under elevated pressure. Microscopy confirmed a total average thickness of 2.01 mm consisting of eight plies with a thickness of 0.234 mm/ply covered by pure resin surface layers of 0.069 mm on each side of the laminate, Fig. 4. C-scan and microscopy confirmed a defect free material with negligible void content (below 1%) except in certain areas, which were discarded. Laminates for Iosipescu specimens were 2.10 mm thick, and hence had a somewhat lower fibre volume fraction.

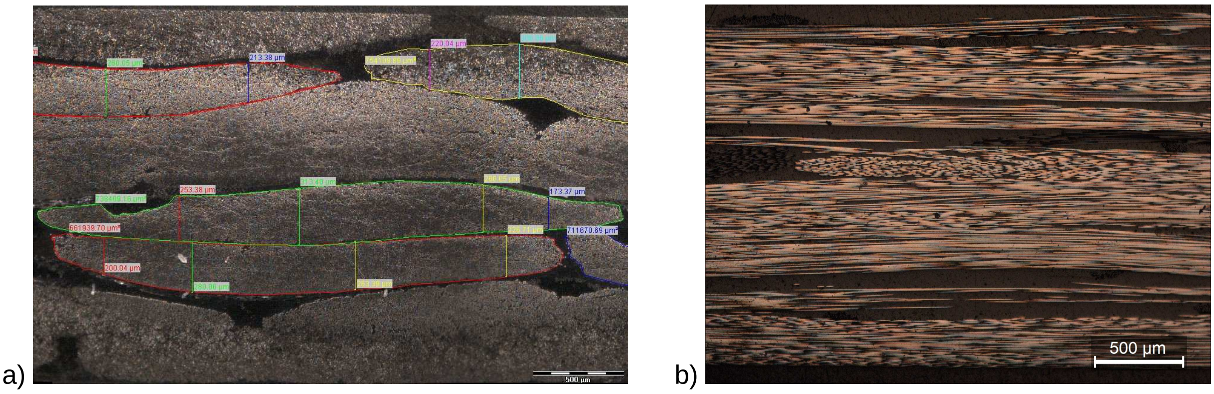

Figure 4. Cross-sections of the UD NCF laminate (a) perpendicular and (b) parallel to the fibre bundles

The estimated carbon fibre volume content of the laminate was v_f^{lam}=0.56 based on measured laminate thickness, areal weight of the dry preform and densities of fibres and matrix. Image analysis of micrographs gave a fibre bundle volume fraction v_b =0.94 in the NCF plies, after exclusion of the pure resin surface layers. The corresponding carbon fibre volume fraction in the bundles is then $v_f^{\,b}$=0.65, i.e. a carbon fibre content of v_f=0.61 in the NCF plies.

3.2 Pure resin specimens

The RTM 6 resin was tested in uniaxial tension and compression. All specimens were manufactured using standard cure cycle: initial cure mould temperature 160 °C for 2 h under an applied pressure of 2 bars, followed by 2 h of post cure at 180 °C. Tension specimens were manufactured according to ASTM D638 (specimen type II) specifications. Compression specimens were cylindrical with height equal to diameter. The results are shown in Table 1.

E	***ν***	**Tensile failure**	**Compressive yield**	**Compressive failure**
3.1 MPa	0.38	82 MPa, ε=3.8%	134 MPa, ε=10%	295 MPa, ε=42%

Table 1. Measured RTM 6 properties (true stress/strain).

3.3 Fibre bundle specimens

The manufacture of a representative bundle material was done by winding roving with a feed of 3.1 mm per round on a 50x500x500 mm aluminium tooling plate covered with a peel ply, resulting in a roving width of about 6 mm. A 4 mm diameter steel bar was placed between the fibres and the tool during winding to compensate for thermal and chemical deformations during processing. The steel bar was removed prior to infusion and curing. After completed winding the plates were covered with a peel ply and a caul plate and placed in a vacuum bag where the resin was infused along the fibres from one edge of the plate to the opposite edge using vacuum. After infusion the laminates were cured at 160°C in 2.5 h + 180°C in 4 h.

The quality of the laminates was inspected using microscopy, which indicated a homogeneous material without distinguishable bundles and a porosity of less than 1%, Fig. 5.

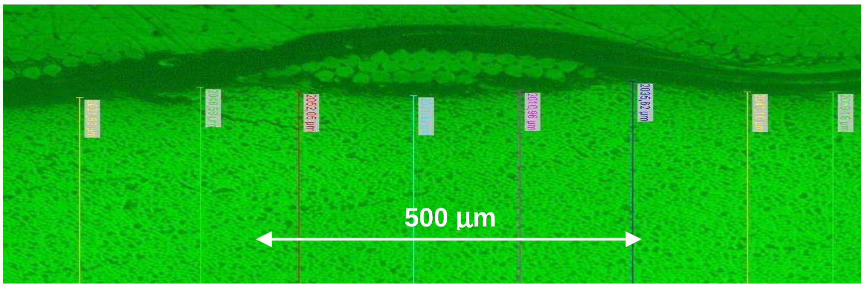

Figure 5. Cross section close to the upper surface of one laminate.

A peel ply bundle with coarser fibres is visible in the upper part of Fig. 5. The peel ply generated a somewhat wavy surface of the specimen. Microscopy was used to determine the local thickness at several positions (shown by vertical lines in the figure) in several specimens. The resulting average thickness was typically 0.06 mm less than the peak-to-peak thickness. The thickness measured by a micrometer was therefore reduced by 0.06 mm, providing an estimated average specimen thickness of 2.14 mm. The thickness and width of the gauge section of each specimen was measured at 2-3 lengthwise positions.

The fibre volume fraction v_f was determined indirectly from the fibre weight fraction by measuring the weight loss of small specimens after removing the matrix by a heat ramp up to 450°C for 1 h followed by 4 h at 450°C, and compensating for the weight loss of the carbon fibres in an accompanying reference tow. The measured value of v_f=0.69 is close to the value

$v_f^{\,b}$=0.65 estimated for bundles in the NCF laminates. Thus, the material was considered representative of the NCF bundle material.

After manufacture of laminates specimens were cut in 0°, 10°, 45° and 90° angle to the fibres of the UD material. To minimise stress concentrations all off-axis specimens (i.e. other than 0° and 90°) were equipped with tabs at an oblique angle, Fig. 6, according to recommendations by Sun and Chung [7]. The angle ø between the edge of the tab end and the loading axis of the specimen is given by the following expression:

$$\cot\phi = -\bar{S}_{16} / \bar{S}_{11} \tag{6}$$

where $\bar{S}_{ij} = \left(\bar{C}_{ij}\right)^{-1}$ are the compliance components of the material in a coordinate system aligned with the load. Specimens were manufactured with a 25° tab angle for 10°-specimens, and 62° for 45°-specimens, based on the *assumed* material properties E_1=155 GPa, E_2=12 GPa, G_{12}=6 GPa, ν_{12} =0.3. All specimens had a free length of 40-50 mm between tabs, satisfying the ASTM D3039 minimum requirement of two specimen widths + one gauge length (12.5 mm for the extensometer, less for strain gauges).

Figure 6. Examples of test specimens with bundles in 0° and 45° angle.

4 Testing

Tensile testing was performed according to ASTM D3039-07 under displacement control in conventional hydraulic test machines using extensometers for 0° and 90° specimens, and strain gauges for off-axis specimens. Compression testing of the bundle material was performed using strain gauges and similar specimens as in tension, but supported by a Swerea SICOMP in-house anti-buckling rig, consisting of plates with 15 mm diameter central holes for the strain gauges and using Teflon film to minimise friction between the specimen and the anti-buckling plates. Compression testing of the NCF laminates was performed according to ASTM D3410-03 (IITRI) using 12 mm wide specimens.

Shear strength tests were performed using a modified Iosipescu test rig [8] and Iosipescu specimens with bundles in the axial direction (perpendicular to the gauge section) and a notch angle (~140°) modified according to the stiffness scaling recommended in [8]. The shear strength was defined as the onset of shear cracking, as indicated by interruptions in vertical marker lines in the gauge section and observed by a USB-microscope. Onset of shear cracking was found to essentially coincide with the peak shear load.

5 Results and discussion

Three 0° bundle specimens were tested. The axial strengths were σ_{bLt}=2215 MPa (±4%) in tension and σ_{bLc}=925 MPa (±18%) in compression. For tensile strains in the interval 0.1-0.6% the Young's secant modulus of the bundle was E_{bL}=160 GPa (±5%), and the average

Poisson's ratio was ν_{b12}=0.333 (±8%). Measurements on five 90° bundle specimens in the strain interval 0.05-0.3 % yielded E_{bT}=9.14 GPa (±9%). The secant shear modulus was determined by evaluating shear stresses and strains from triaxial strain gauges on two 10° specimens. For shear strains 0.2-0.6% the resulting shear modulus was G_{bLT}=5.52 GPa (±5%).

Figure 7 provides a comparison between measured strengths of the bundle material and the NCF laminates for various combinations of in-plane shear and transverse stresses. The measured strength of the NCF laminates was determined using average stresses based on the total laminate thickness, i.e. including the 0.069 mm resin layers on each surface. A curve showing predictions based on a modified Puck criterion [9] has also been added. The assumed fracture angle 55° was based on fractographic observations after completed compressive tests.

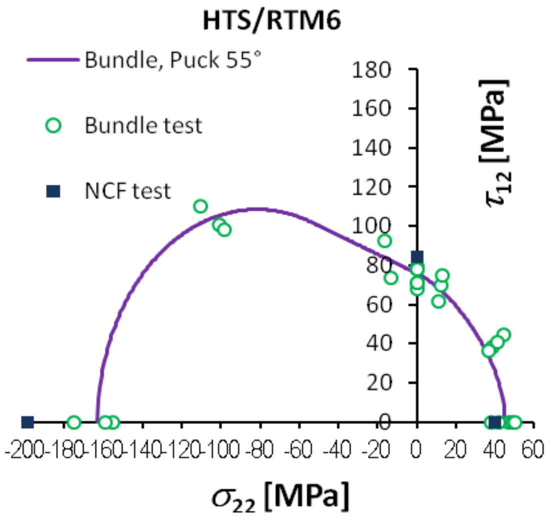

Figure 7. Failure envelopes for various combinations of shear stress and transverse stress.

To compare the theoretical predictions with experimental strength and stiffness values, the moduli and strengths of the structural plies in the NCF were first predicted using the equations in Section 2, assuming E_y=75 GPa and ν_y=0.22 for the glass binder yarn. These values were then combined with experimental values for the pure resin, using laminate theory, to predict the average stress and moduli at failure of the NCF laminates with resin surface layers. The predicted moduli and strengths of the complete NCF laminate are 2-7% lower than for just the structural NCF plies. Table 2 gives a comparison between theoretical predictions of stiffness, based on resin and measured bundle properties (v_f^b=0.69), and experimental data for NCF laminates. A comparison is also included for ply properties scaled according to the estimated fibre volume fraction of v_f^b=0.65 in the bundles of the NCF laminates.

	Axial modulus	Transverse modulus	Shear modulus	Poisson's ratio
Theory v_f^b=0.69 vs Exp.	+12%	-4%	+15%	+7%
Theory v_f^b=0.65 vs Exp.	+6%	-11%	+5%	+7%

Table 2. Ratio between predicted and measured moduli of NCF. Prediction = analytical rule of mixtures model.

The analytical rule-of-mixtures model based on measured bundle moduli yields an overestimation of the axial modulus and shear modulus of the NCF and a slight underestimation of the transverse modulus. The overestimation of the axial modulus and shear modulus are mainly due to a higher fibre volume fraction (v_f=0.69) in the replica bundle material than in the NCF bundles (v_f=0.65). Remaining difference is due to bundle waviness.

Table 3 compares the predicted and measured strengths of the NCF laminate. The strength was defined as the average stress at failure of the structural layers.

	Axial tension	Transv. tension	Shear	Axial compr.	Transv. compr.
Theory vs Exp.	-6%	+6%	-23%	-28%	-24%

Table 3. Ratio between predicted and measured strength of NCF. Prediction = analytical rule of mixtures model.

The analytical rule-of-mixtures model based on measured bundle strength bundle test data provides good agreement with strength test data for the NCF material in axial and transverse tension. The predicted NCF strength for axial and transverse compression is more than 20% *lower* than the values measured for the NCF material, in spite of the fact that the model not accounts for reductions in axial compressive strength caused by bundle waviness in the NCF. This indicates deficiencies in the compression test method used for the bundle material. Future compression tests need to be performed with an improved test method, e.g. the IITRI method used for the NCF material. The differences in predicted and measured shear strength may be due to neglect of shear softening in models and that the Iosipescu shear tests were done on 4% thicker NCF laminates with a correspondingly lower fibre volume fraction.

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References

[1] Asp L.E., Marklund E., Varna J. (2011). *Damage progression in non-crimp fabric composites.* Ch 12 in: “Non-crimp fabric composites: Manufacturing, properties and applications”, Editor Lomov S. Woodhead, Oxford, pp. 289-309 (2011).

[2] Hobbiebrunken T., Hojo M., Jin K.K., Ha S.K. Influence of non-uniform fiber arrangement on microscopic stress and failure initiation in thermally and transversally loaded CF/epoxy laminated composites. *Compos Sci Technol*, **68**, pp. 3107-3113 (2008).

[3] Asp L.E., Berglund L.A., Talreja R. Prediction of matrix-initiated transverse failure in polymer composites. *Compos Sci Technol*, **56**, pp. 1089-1097 (1996).

[4] De Kok J.M.M., Meijer H.E.H. Deformation, yield and fracture of unidirectional composites in transverse loading 1. Influence of fibre volume fraction and temperature. *Compos Part A*, **30**, pp. 905-906 (1996).

[5] Hobbiebrunken T, et al. Experimental determination of the true epoxy resin strength using micro-scaled specimens. *Composites Part A*, **38**, pp. 814-818 (2007).

[6] Halpin J.C. *Primer on composite materials: Analysis*. Technomic, Lancaster PA (1984).

[7] Sun C.T., Chung I. An oblique end-tab design for testing off-axis composite specimens. *Composites*, **24**, pp. 619-623 (1993).

[8] Melin L.N., Neumeister J.M. Measuring constitutive shear behaviour of orthotropic composites and evaluation of the modified Iosipescu test. *Compos Struct*, 7**6**, pp. 106-115 (2006).

[9] Marklund E., Varna J., Asp L.E. *Stiffness and strength modelling of non-crimp fabric composites*. Paper AIAA-2011-1748 in “Proc. *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*”. Denver, USA, (2011).