EFFECT OF YARN NUMBER ON THE STRENGTH AND FAILURE ENVELOPES OF NON-CRIMP GLASS FIBER COMPOSITES

K. Bilge[1], G. Baser[2,3], E. Binbir[3,4] , M. Papila[1*]

[1]*Faculty of Engineering and Natural Sciences, Sabanci University, 34956 Tuzla, İstanbul, Turkey*
[2]*Institute of Science, Polymer Sci. & Tech., Istanbul Technical University Maslak, Istanbul, Turkey*
[3]*Telateks A.Ş.-Metyx Composites®, 34956 Tuzla, İstanbul, Turkey*
[4]*Department of Structural Engineering, Istanbul Technical University, Maslak, Istanbul, Turkey*

**mpapila@sabanciuniv.edu*

Keywords: non-crimp, TEX , strength, composite

ABSTRACT

This study aims to show the effect of fiber yarn number on the strength and mechanical behavior of non-crimp glass fiber (NCGF) vinyl ester matrix composites. Four different NCGF TEX as 300, 600, 1200, 2400 were used for custom made of a constant reinforcement ply areal weight and were impregnated by vinyl ester resin system via vacuum assisted resin transfer molding. Laminates with four different lay-up sequences such as $(0)_8$, $(+45/-45)_{4s}$, $(0/90)_{4s}$, and $(0/+45/-45/90)_s$ were studied. Ply strength parameters (X, X', Y, Y', S) and stiffnesses are determined by the tensile and compressive testing of $(0)_8$ and $(+45/-45)_{4s}$ laminates. The failure mechanisms are investigated with respect to changing yarn number. The last ply failure prediction by degradation factor based Tsai-Wu criterion were carried out and failure envelopes for $(0/90)_{4s}$, and $(0/+45/-45/90)_s$ laminates were generated. Overall results suggested that the fiber yarn number at a given ply areal weight was very influential in the mechanical behavior of vinyl ester based NCGF laminates.

Introduction

Non crimp fabric composites offer fairly good mechanical properties as well as low manufacturing costs achieved by having a reasonable drapeability and by lacking fibre crimping present in conventional woven fabrics [1,2]. Both computational and experimental efforts have been reported on the way to identify the mechanical performance of such composites. Experiment based studies have focused on the behavior of non-crimp fabric composites under different loading conditions [3, 4, 5, 6] or investigated the effect of several fabric properties to the overall performance [1,6]. On the other hand the computational works are mostly concentrated on the explanation of NCFs and associated meso scale characteristics by the means of finite element modeling [7, 8, 9,10,11,12].

The current study investigates the effect of fiber yarn number on the strength of NCGF vinyl ester composites. The tensile, compressive and shear behavior of laminates containing NCGF reinforcements are investigated in detail by paying specific attention to the effect of fiber-bundle width and inter-bundle distance of the fabrics of a fixed areal weights but different yarn number. Additional effort is given to the implementation of Tsai-Wu failure criterion to predict the behavior of laminates. Test based ply strength parameters are used along with the tensile properties of $(0/90)_{4s}$, and $(0/+45/-45/90)_s$ laminates.

2 Experimental Procedure and Characterization

2.1. Materials

Four different non-crimp fabrics each containing glass fibers of either 300, 600, 1200 or 2400 TEX stitched with synthetic yarn were manufactured and provided by Metyx Composites® (Figure 1a-1d). For all of the fabrics the aerial weight was fixed at 300g/m^2. Fiber bundle size and the distance between the individual fiber bundles were different with increasing yarn number (Table 1). All of the dry fabrics were impregnated with Crystic VE-676-03 unsaturated vinyl ester resin supplied by Scott Bader Co. Ltd.

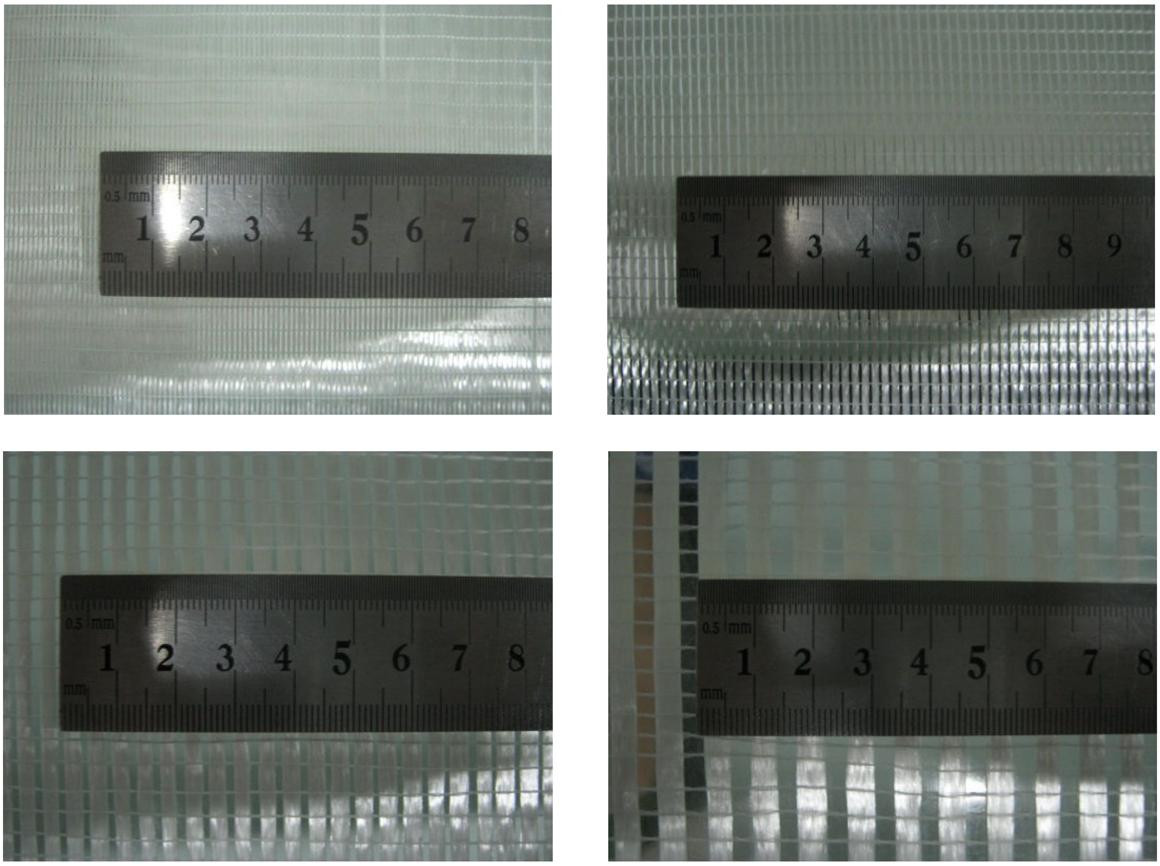

Figure 1. a) 300TEX NCGF Fabric b) 600TEX NCGF Fabric c) 1200 TEX NCGF Fabric d) 2400 TEX NCGF Fabric

	300 TEX	600 TEX	1200 TEX	2400 TEX
Fiber Diameter (µm)	14	15	16,5	17,5
Bundle Width (µm)	100	200	300	400
Bundle-Bundle Distance (µm)	50	80	120	400

Table 1. Fabric properties for different TEX number

2.2. *Laminate Manufacturing*

Vinyl ester based NCGF composite laminates having 8 layers of dry fabric were manufactured in different lay-up sequences (as in Table 2) via vacuum assisted resin transfer molding technique. Vacuum bagging and curing were done at room temperature 0,9 bar vacuum pressure. Laminates were post cured at 80˚C for 3 hours. The fiber volume fractions of the obtained laminates were determined by burn-out tests (Table 3).

Laminate Coding	300 TEX	600 TEX	1200 TEX	2400 TEX
$(0^\circ)_8$	UD 300	UD 300	UD 1200	UD 2400
$(+45^\circ/-45^\circ)_{4s}$	X 300	X 600	X 1200	X 2400
$(0^\circ / 90)_{4s}$	LT 300	LT 600	LT 1200	LT 2400
$(0^\circ / +45^\circ / -45^\circ / 90^\circ)_s$	Q 300	Q 600	Q 1200	Q 2400

Table 2. Lamination sequences and laminate coding

Fiber Volume Fractions	UD	X	LT	Q
300	52 %	50 %	52,5 %	52 %
600	52,5 %	53 %	50 %	51 %
1200	50 %	52 %	49 %	48 %
2400	51 %	49 %	48 %	47 %

Table 3. Fiber volume fractions out of burning tests

Volume fractions of the laminates were between 47 % and 52,5 % . Each laminate was cut with water-jet to obtain the test specimens.

2.3 Mechanical Testing

Tensile test of cut composite specimens were performed as described in ASTM D3039 test standards. Test specimens were subjected to uni-axial tension with a constant displacement rate of 2mm/min and corresponding stress-strain values were recorded for maximum tensile strength and elastic modulus determination both in transverse and longitudinal directions with respect to fiber orientation. Corresponding shear strength and modulus of the laminates were determined out of tensile tests according to ASTM D3518 test standard. A micro-extensometer was used for displacement measurement. ASTM D695 test standard was considered for compression tests. Constant displacement rate was set to 1.3 mm/min. Compressive strength and modulus of the laminates were recorded.

3. Results and Discussion

3.1 Effect on Longitudinal and Transverse Tensile Strength of Composite Laminates

The failure of $(0)_8$ laminates was often proceded by splitting of plies into parallel strips which was mostly initiated from the resin rich inter-bundle regions and caused the final failure of the laminates. Failure of the laminates have occurred after maximum tensile strength was achieved and was differentiated by the sudden load drop observed at the end of testing (Figure 1a-1b). The longitudinal tensile strength of L2400 test coupons was lower due to bigger inter-bundle distance. However, L600 test specimens showed the highest tensile performance rather than the L300 specimens (Table 4). The superior behavior of L1200 laminates with respect to L300 and L2400, suggested that the inter-bundle distance could be tuned for better performance rather than choosing the extremes.

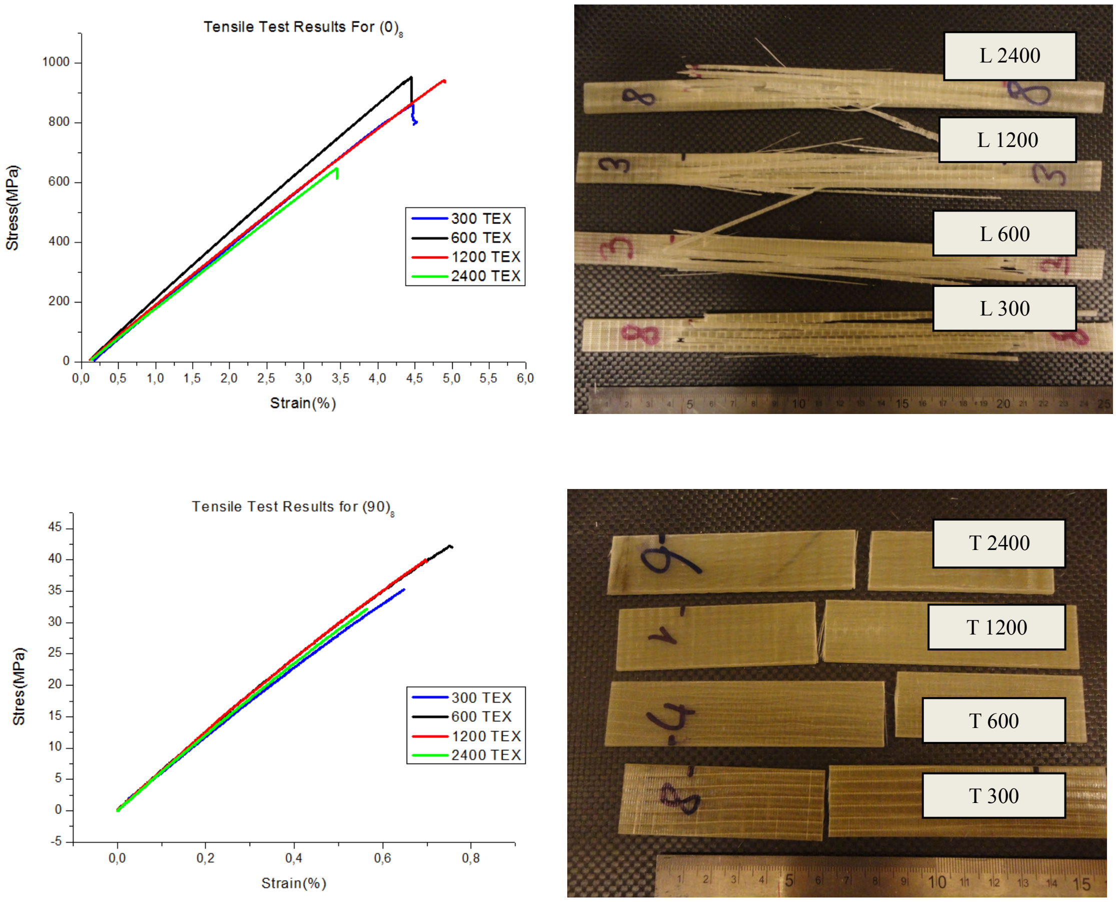

Figure 2. a) Stress-Strain curves of $(0)_8$ laminates b) Fractured $(0)_8$ laminates c) Stress-Strain curves of $(90)_8$ laminates d) Fractured $(90)_8$ laminates

Critical matrix cracking of T2400 specimens supported the fact that the inter-bundle region played a significant role in the failure. The fiber reinforcement effect was nearly negligible for the transversal loadings, the low performance of T2400 specimens attributed to the residual stresses occurred during curing process in the resin rich regions which were ideal places for transverse crack initiation.

Tex	Longitudinal Tensile Strength (MPa)	Longitudinal Elastic Modulus (GPa)	Transversal Tensile Strength (MPa)	Transversal Elastic Modulus (GPa)
300	830,89	42,58	39,28	5,35
600	924,71	44,88	44,35	5,86
1200	918,35	41,50	41,76	5,83
2400	655,82	39,90	33,13	5,6

Table 4. Tensile Test Results for $(0)_8$ and $(90)_8$ specimens

3.2 Effect on the In-Plane Shear Strength of Composite Laminates

The characteristic failure of $[+45/-45]_{4S}$ laminates under uniaxial tension was dominated by a non-linear behavior which was formed of an initial elastic region followed by plastic region. This behavior under shear loading was previously reported on several works in the literature [12,13,14,15,16]. Similar to the works of Van Paepegem the fracture of all the laminates had occurred from the midsection and with an angle of 45˚, as a typical shear failure. In the scope of current work, the non-linearity of the stress-stain curves (Figure 3.a) was observed to be very sensitive to TEX number of the reinforcement. We believe This behavior was due to the tendence of fiber bundles to move in-situ, towards the loading direction. For X300 test specimens where the additional plastic deformation for bundle alignment was low and a continuous load increase on plastic region was observed.

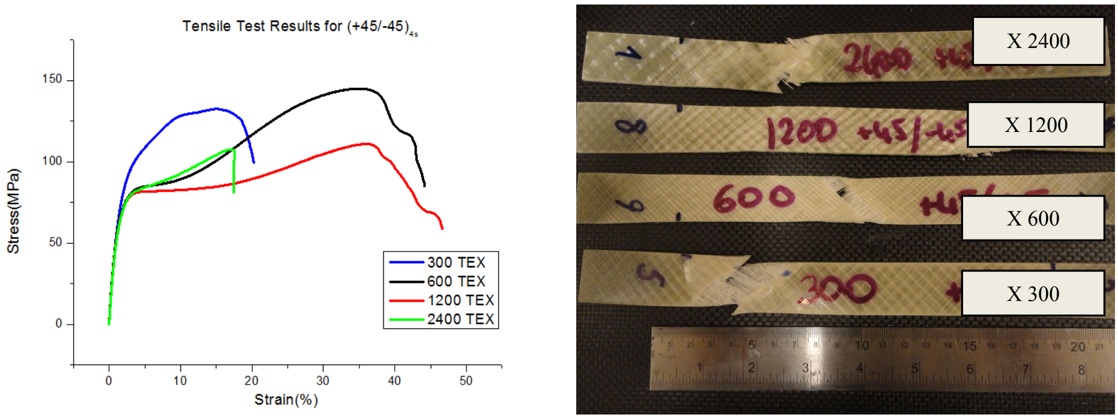

Figure 3. a) Stress-Strain curves of $(+45/-45)_{4s}$ laminates b) Fractured $(+45/-45)_{4s}$ laminates

The early failure of X2400 specimens occurred due to the appearance of high shear stresses that may not be transferred efficiently between fiber bundles. For X1200 and X600 specimens maximum bundle alignment was achieved and the final fracture occurred just after necking.

Tex	Shear Strength (MPa)	Shear Modulus (GPa)
300	68,35	6.81
600	74,8	7.66
1200	57	6.78
2400	55,3	6.49

Table 5. Tensile Test Results for $(+45/-45)_{4s}$ specimens in accordance with ASTM D3518

3.3 Effect on the Longitudinal and Transversal Compression

Longitudinal and transversal compression tests of UD laminate were conducted in order to complete all of the ply strength parameters required for the creation of Tsai-Wu failure envelopes. The failure of $(0)_8$ test specimens was initiated by fiber kinking and the ultimate fracture had occurred due to the fiber fracture at the kinking region (Figure 4.a, 4.b). Kinking behavior was differentiated by the deformation pattern during testing. The transversal direction the fracture occurred due to the matrix cracking.

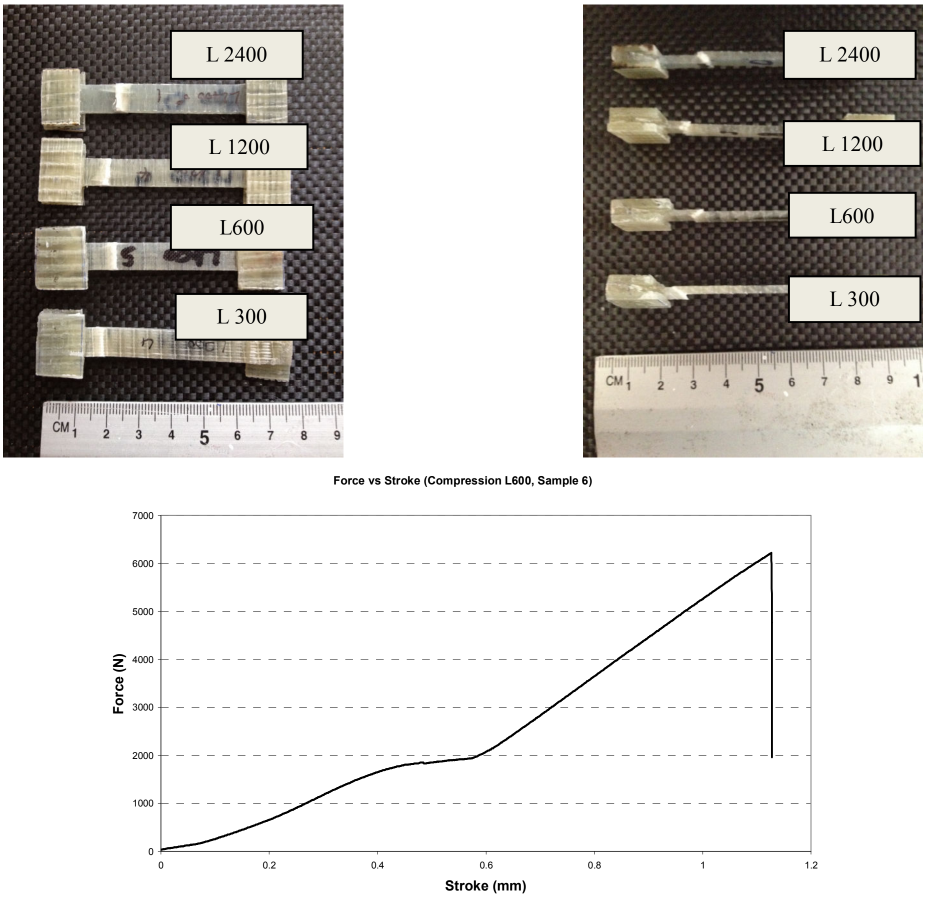

Figure 4. a) Fractured $(0)_8$ laminates b) Side-view of fractured $(0)_8$ laminates
c) Force-displacement curve for a $(0)_8$ laminate

Different from the tensile test results, the longitudinal compressive strength of L600 specimens were lower than the other ones whereas L2400 specimens showed the highest compressive strength. Detailed analysis for the compressive failure is still ongoing.

Tex	Longitudinal Compressive Strength (MPa)	Longitudinal Compresion Modulus (GPa)	Transversal Compressive Strength (MPa)	Transversal Compresion Modulus (GPa)
300	350,86	33,82	128,40	10,14
600	324,69	35,02	131,9	10,52
1200	331,2	28,3	126,16	9,37
2400	377,3	32,03	123,42	9,26

Table 6. Compression Test Results for $(0)_8$ and $(90)_8$ specimens

3.4 Tsai-Wu Failure Envelopes and Correction Cases

The ply strength parameters (X, X',Y,Y'S) and stiffness parameters that were extracted out from the previously mentioned tensile and compressive tests were used in Tsai-Wu failure envelopes of a cross ply laminate $(0/90)_{4S}$ and a quasi-isotropic laminate $(0/+45/-45/90)_S$. The tensile tests of those laminates were determined and results were compared with the predicted strength values. For the creation of failure envelopes a degradation factor based last ply failure analysis was carried out by MicMac [17]. Last ply failure envelopes for the two laminates are given at figures 5a, 5b, 5c and 5d.

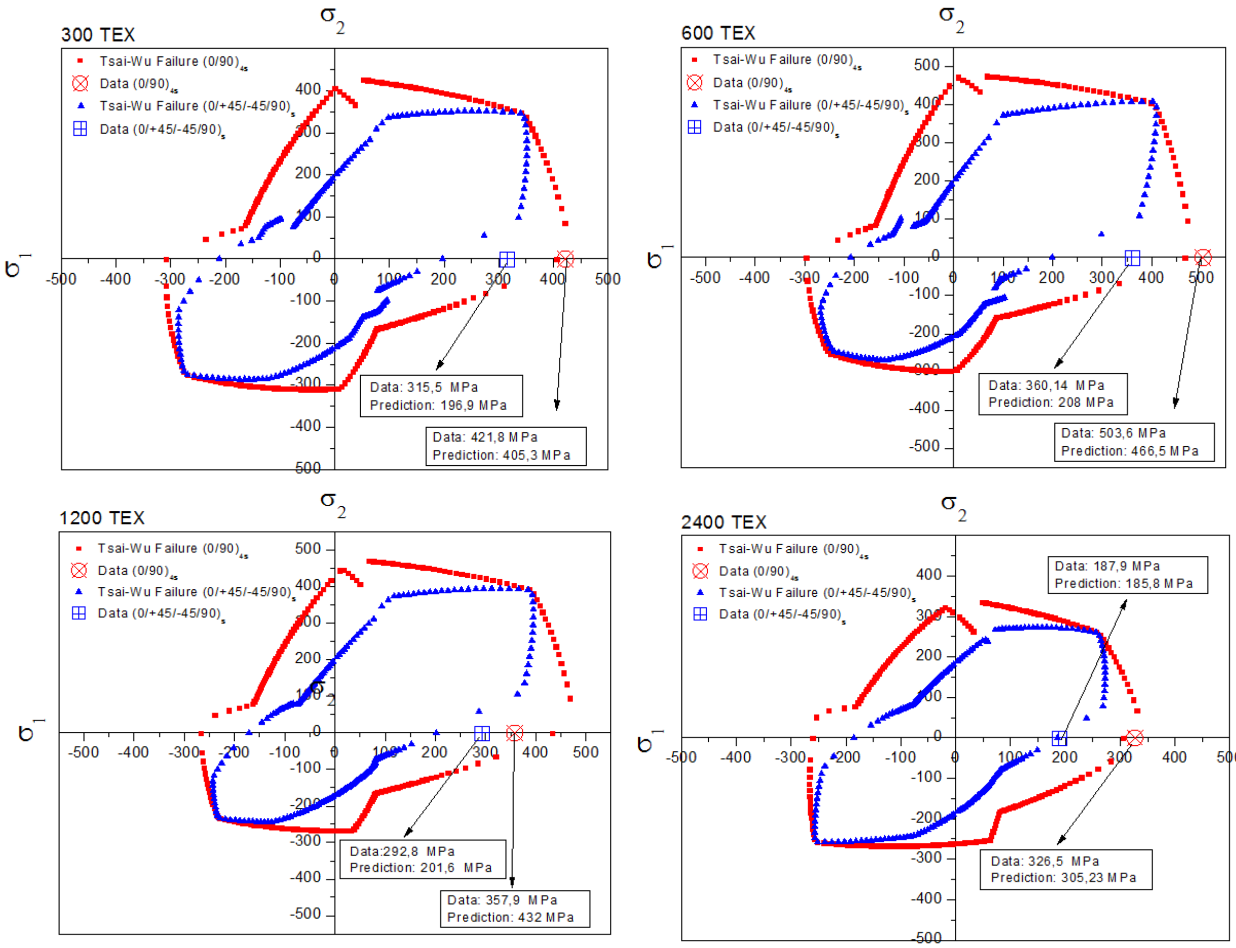

Figure 5. Failure envelopes for a) LT-Q 300 b) LT- Q 600 c) LT-Q 1200 d) LT-Q 2400 laminates

Tex	$(0/90)_{4s}$ Strength (MPa)	Tsai-Wu Failure Prediction $(0/90)_{4s}$ (MPa)	Difference (%)	$(0/+45/-45/90)_s$ Strength (MPa)	Tsai-Wu Failure Prediction $(0/+45/-45/90)_s$ (MPa)	Difference (%)
300	421,8	405,3	-3,9	315,5	197	-37,6
600	503,6	466,5	-7,4	360,1	208	-42,2
1200	357,9	432	20,7	292,8	201,6	-31,1
2400	326,5	305,2	-6,5	187,9	185,8	-1,1

Table 7. Test Results and Predicted Strength

References

[1] D.Mattsson, R.Joffe, J. Varna, Damage in NCF composites under tension: Effect of layer stacking sequence, *Engineering Fracture Mechanics*, **Vol. 75**, pp. 2666–268 (2008)

[2] F.L. Edgren, E. Asp, R. Joffe Failure of NCF composites subjected to combined compression and shear loadings, *Compos Sci Technol,* **Vol. 66**, pp. 2865–2877 (2006)

[3] F. Edgren, D. Mattsson, L.E. Asp, J. Varn, Formation of damage and its effects on non-crimp fabric reinforced composites loaded in tension, *Compos Sci Technol*, **Vol.64**, pp. 675–692 (2004)

[4] K. Vallons, A. Behaeghe, S. V. Lomov, I. Verpoest, Impact and post-impact properties of a carbon fibre non-crimp fabric and a twill weave composite, *Composites Part A: Applied Science and Manufacturing*, **Vol. 41**, pp. 1019-1026, (2010)

[5] K.Vallons, S.V. Lomov, I.Verpoest, Fatigue and Post Fatigue behaviour of carbon/epoxy non-crimp fabric composites, *Composites Part A: Applied Science and Manufacturing*, **Vol.40** , pp. 251-259, (2009)

[6] S.V. Lomov, E.B. Belov, T. Bischoff, S.B. Ghosh, T.T. Chi, I. Verpoest, Carbon composites based on multiaxial multiply stitched preforms. Part 1. Geometry of the preform, *Composites Part A*, **Vol. 33**, pp. 1171–1183, (2002)

[7] S. Drapier, M.R. WisnomFinite-element investigation of the compressive strength of non-crimp-fabric-based composites, *Compos Sci Technol*, **Vol.59** ,pp. 1287–1297 (1999)

[8] S. Drapier, M.R. Wisnom A finite-element investigation of the interlaminar shear behaviour of non-crimp-fabric-based composites, *Compos Sci Technol*, **Vol. 59** pp. 2351–2362, (1999)

[9] A. Gonzalez, E.Graciani, F.Paris, Prediction of in-plane stiffness of non-crimp fabric laminates by means of 3D finite element analysis, *Compos Sci Technol*, **Vol.68** pp.121-131, (2008)

[10] H. Heß, N. Himmel, Structurally stitched NCF CFRP laminates. Part 2: Finite element unit cell based prediction of in-plane strength, *Composites Science and Technology*, Vol.71, pp. 569-585, 2011

[11] L.G. Zhao, N.A. Warrior, A.C. Long, Finite element modelling of damage progression in non-crimp fabric reinforced composites, *Composites Science and Technology*, **Vol. 66**, pp.36-50, 2006

[12] H.T Hahn, S.W Tsai, Non-Linear Elastic Behaviour of Unidirectional Composite Laminate, *Journal of Composite Materials,* **Vol. 7**, pp. 102-118, (1973)

[13] W.P. Lin, H-T Hu. , Nonlinear Analysis of Fiber-Reinforced Composite Laminates Subjected to Uniaxial Tensile Load, *Journal of Composite Materials*, **Vol.36** pp.1429-1450, (2002)

[14] J. Cho, J. Fenner, B. Werner, I.M. Daniel, A Constitutive Model for Fiber-reinforced Polymer Composites, *Journal of Composite Materials* 2010 **Vol. 44**, pp. 3133-315

[15] Van Paepegem, W., De Baere, I. and Degrieck, J.. Modelling the non-linear shear stress-strain response of glass fibre reinforced composites. Part I: Experimental results. *Composites Science and Technology*, **Vol.66**, pp.1455-1464, (2006)

[16] Van Paepegem, W., De Baere, I. and Degrieck, J. (2006). Modelling the nonlinear shear stress-strain response of glass fibre-reinforced composites. Part II: Model development and finite element simulations. *Composites Science and Technology* , **Vol. 66**, pp.1465-1478.

[17] S.W.Tsai, Strength and Life of Composites, JEC Composites, 2008