3rd International Conference
″Advanced Composite Materials Engineering ″
COMAT 2010
27- 29 October 2010, Brasov, Romania

WATER ADSORPTION INFLUENCE ON CFRP INTEGRITY

Raimond Grimberg[1], Adriana Savin[1], Ioan Curtu[2], Mariana Domnica Stanciu[2], Paul Doru Barsanescu[3], Felipe Silva[4], Petrica-Daniel Salavastru[3*], Rozina Steigmann[1]
[1]National Institute of Research and Development for Technical Physics, Iasi, Romania
[2] Transilvania University, Brasov, Romania
[3] Technical University Gh.Asachi Iasi, Romania
[4]School of Engineering, University of Minho, Guimarães,Portugal

Abstract: *This paper presents the method of transformation of a lamina with biaxial anisotropy into a succession of laminas with uniaxial anisotropy, so that the Tsai Wu criterion shall be applied, for the case of composites that have suffered degradation due to water adsorption.*
Key words*: CFRP, water adsorption, failure criterion, Tsai-Wu number*

1. INTRODUCTION

The standard fiber composite analyses concern laminates from unidirectional reinforced layers. Many composites components, however, are manufactured using the widely available woven fabric reinforcements, thanks to their good formability characteristics, very often these components are thin walled, for which Kirchhoff's hypothesis for bending of thin plates is valid and hence, for which the classical laminate theory (CLT) is a suitable description [1], [2].
An orthogonal woven fabric reinforced layer can generally be characterized on macroscopic level as an orthotropic material with nine independently elastic engineering constants (E_1, E_2, E_3, υ_1, υ_2, υ_3, G_{12}, G_{13}, G_{23}) [3]. For the sake of clarity, the analyses presented here is restricted to fabrics with orthogonal fiber orientation, leaving the effects of skew deformation due to the composite forming process out of consideration. This implies that the fiber directions are normal to planes of material symmetry, and that a shear-extension coupling in the fiber direction will be absent. The fiber directions define the principal material axes, where the directions of the warp yarns is indicated with "1", the direction of the weft or fill yarns with "2", whereas "3" is the direction normal to the plane of the laminate.
In structural problems for composite materials, where the structural response should be determined beyond the initiation of nonlinear material behavior, material failure is of profound importance for the determination of the integrity of the structure. On the other hand, due to the lack of globally accepted failure criterion, the determination of the structure's damage is still under intensive research.
The Tsai-Wu failure criterion [4] is a phenomenological failure theory which is widely used for anisotropic composite materials which have different strengths in tension and compression. The Tsai-Wu criterion can not be used in the case of composites with laminas that present biaxial anisotropy how is the case of those with woven fabric reinforcements.
This paper presents the method of transformation of a lamina with biaxial anisotropy into a succession of laminas with uniaxial anisotropy, so that the Tsai Wu criterion shall be applied, for the case of composites that have suffered degradation due to water absorption.

2. UNIDIRECTIONAL APPROXIMATION OF A WOVEN FABRIC PLY

Six basic ply material properties are necessary for the characterization of woven fabric ply $\{E_1, E_3, \upsilon_{12}, \upsilon_{13}, G_{12}, G_{13}\}^{WF}$. For the characterization of unidirectional layers are necessary only five elastic parameters $\{E_1, E_2, \upsilon_{12}, \upsilon_{23}, G_{12}\}^{UD}$ because

$$E_3^{UD} = E_2^{UD}; \quad G_{13}^{UD} = G_{12}^{UD}; \quad \upsilon_{13}^{UD} = \upsilon_{12}^{UD} \tag{1}$$

Using the method presented in [3], a regular system of five equations is obtained when the transverse shear terms are omitted, leaving

$$\begin{aligned}
&\left(\frac{2}{E_1}\frac{E_1\left[E_1+\left(1-\upsilon_{12}^2\right)E_2-\upsilon_{12}^2E_2^2\right]}{E_1\left(E_1+2E_2\right)+\left(1+2\upsilon_{12}^2\right)E_2^2}\right)^{UD} = \left(\frac{1}{E_1}\right)^{WF}\\
&\left(\frac{4}{E_1}\frac{\upsilon_{12}E_2\left(E_1-\upsilon_{12}^2E_2\right)}{E_1\left(E_1+2E_2\right)+\left(1+2\upsilon_{12}^2\right)E_2^2}\right)^{UD} = \left(\frac{\upsilon_{12}}{E_1}\right)^{WF}\\
&\left(\frac{1}{E_1}\frac{E_1\left(\upsilon_{12}+\upsilon_{23}+\upsilon_{12}\upsilon_{23}\right)+\upsilon_{12}^2E_2}{E_1+\left(1+2\upsilon_{12}\right)E_2}\right)^{UD} = \left(\frac{\upsilon_{13}}{E_1}\right)^{WF}\\
&\left(\frac{\left(1-\upsilon_{23}^2\right)E_1^2+\left(1+2\upsilon_{12}+2\upsilon_{12}\upsilon_{23}\right)E_1E_2-\upsilon_{12}^2E_2^2}{E_1E_2\left[E_1+\left(1+2\upsilon_{12}\right)E_2\right]}\right)^{UD} = \left(\frac{1}{E_1}\right)^{WF}; \quad \left(\frac{1}{G_{12}}\right)^{UD} = \left(\frac{1}{G_{12}}\right)^{WF}
\end{aligned} \tag{2}$$

Supplementary, we can use also

$$\frac{1}{G_{13}^{WF}} = \left(\frac{1+\upsilon_{23}}{E_2}+\frac{1}{2G_{12}}\right)^{UD} \tag{3}$$

The problem that is set is how much repetitive sequences [0^0, 90^0] are necessarily for the simulation of a woven fabric ply. This problem can be solved imposing the condition that the flexural rigidity of the woven fabric ply shall be approximate equal with those of the repetition sequence [0^0, 90^0]. According to [5], this might happen if the number of repetitive sequences is at least 6.

3. TSAI-WU FAILURE CRITERION

Tsai-Wu theory is a quadratic failure criterion for anisotropic materials. It is stated as

$$f_i\sigma_i + f_{ij}\sigma_i\sigma_j \le 1, \quad i,j = 1,2,...,6 \tag{4}$$

If the failure surface is to be closed and connex, the interaction terms F_{ij} must satisfy

$$F_{ii}F_{jj} - F_{ij}^2 \ge 0 \tag{5}$$

which implies that all the F_{ii} terms must be positive.

For plane –stress condition (4) can be write as

$$F_1\sigma_1 + F_2\sigma_2 + F_6\sigma_6 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 + 2F_{16}\sigma_1\sigma_6 + 2F_{26}\sigma_2\sigma_6 \le 1 \tag{6}$$

Shear strength is independent of sign of the shear stress, therefore all linear stress terms must vanish. Therefore we get

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 \le 1 \tag{7}$$

The constants that appear in (7) can be determined as follows: longitudinal tension and compression tests $F_1 = \frac{1}{\sigma_{1t}} - \frac{1}{\sigma_{1c}}$; $F_{11} = \frac{1}{\sigma_{1t}+\sigma_{1c}}$; transverse tension and compression test - $F_2 = \frac{1}{\sigma_{2t}} - \frac{1}{\sigma_{2c}}$; $F_{22} = \frac{1}{\sigma_{2t}+\sigma_{2c}}$; shear tests $F_{66} = \frac{1}{\tau_{12}}$. σ_{1t}, σ_{2t} and σ_{1c}, σ_{2c} are the failure strengths in uniaxial tension and compression, respectively. τ_{12} represents the shear strength in plane 1-2.

4. THE EXPERIMENTAL METHODOLOGY

Samples from composite materials, CFRP type with 12 ply biaxial woven fabric 5H satin type have been taken into study. Fiber designation is Tarayca T300 3K. The matrix is from polyphenylene sulphide designation Ticona Fortron. The thickness of the composite is 4.2mm and the volume ratio is 0.5.

The composite is made by TenCate Cetex [3]. The properties of one lamina indicated by the producer are [3] σ_{1t}=730MPa; σ_{2t}=646MPa; σ_{1c}=558MPa; σ_{2c}=526MPa; in plane shear strength=108MPa; E_1=57GPa; E_2=53GPa;

G_{13}=58GPa; G_{23}=45GPa; G_{12}=2.65GPa.
The elastic properties of composites were determined as following: E_1, E_2 and E_3 using Dynamic Mechanical Analyzer DMA 242C –Netzsch Germany; Poisson coefficients υ_{12} and υ_{21} by measuring phase velocity of Lamb waves with 65kHz frequency generated in composite by Hertzian contact, S_0 mode - using transducers with Hertzian contact, P111-01-P3.1 Introscope coupled at Pulser Receiver 5077PR Panametrics USA, the digitization being assured by LeCroy Wave Runner 64Xi digital oscilloscope which allows the measuring of time intervals with 10^{-10}S precision; $\upsilon_{13}=\upsilon_{23}$ by measuring the propagation velocity of compressional and shear ultrasonic waves with frequency of 5MHz and 4MHz respectively using US transducers for compressional waves, type G5KB GE and MB4Y-GE type for transversal waves. The Pulser Receiver was 5073PR type, Panametrics USA and the same oscilloscope.
Immersed in water, the composite absorbs a certain quantity of water depending on immersion time. The time dependency of adsorbed water is presented in Figure 1, being determined through weighing with analytical balance with ±1μg precision. In Figure 2 are presented the studied samples.

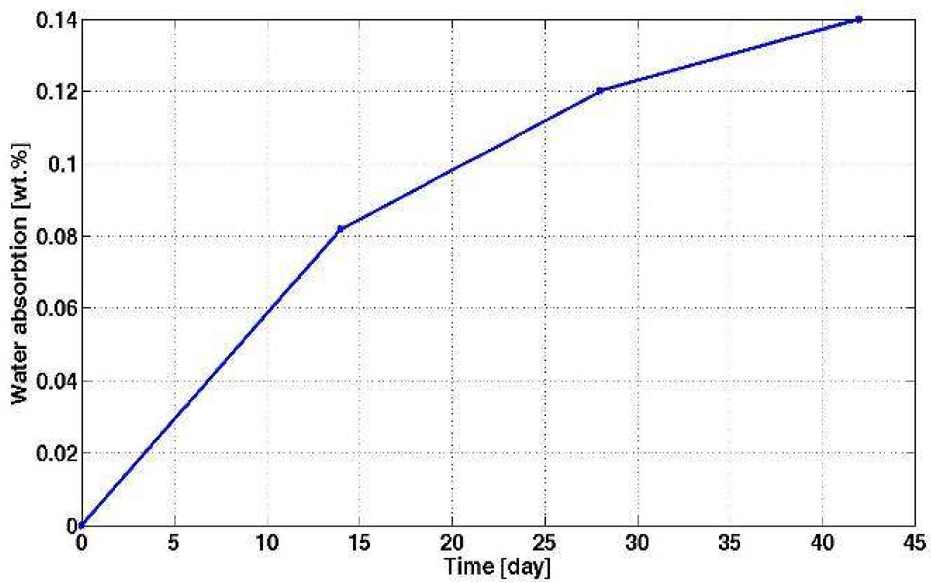

Figure 1: Time dependency of weight adsorbed water percent of the composite at $(20\pm2)^0$C

Figure 2: Studied samples

The effects of water adsorption over the mechanical properties of the composite are presented in Table 1. These data represent the average value obtained on 3 samples.

Table 1: Water effects on elastic characteristics of studied composite

Immersion time [days]	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	υ_{12}	υ_{21}	υ_{13}	G_{12} [GPa]	G_{21} [GPa]	G_{13} [GPa]
0	45	44	11	0.32	0.32	0.03	8.4	8.4	5.5
14	40	29	9	0.31	0.31	0.03	7.7	7.7	4.8
28	34	34	7	0.30	0.30	0.02	6.7	6.7	4.0
42	27	27	6	0.30	0.30	0.02	5.9	5.9	3.1

5. USING TSAI-WU CRITERION FOR PREDICTION OF FAILURE

For applying Tsai-Wu criterion, a numerical code has been developed in Matlab 2009b, based on finite element method (FEM). The finite element chosen was 4 Node-20 Dof Reissner Flat –Shall [6]. The code allows, in the basis of data from lamina and of efforts at which the CFRP plate was supposed, the calculation of Tsai-Wu number and the direction of global coordinate axis reported to the local ones of the lamina that minimizes the Tsai Wu number.

A plate with dimensions $1000x1000x4.2m^3$ from a composite with the elastic properties indicated above has been analyzed. Strengths and moments that assure Tsai-Wu number almost equal with 1 have been searched. In this way, each of the 12 laminas of the composite, with bidirectional anisotropy, has been fictive decomposed in 8 layers with $[0^0, 90^0]$ layout. In CFRP thickness 12x8=96 elements have bee taken, localized on the middle of equivalent laminas. Along x and y directions, 60x60 elements have been choose. The composite plate has been loaded as following σ_x=750MPa, σ_y=700MPa, M_x=800MPa·m, M_y=700MPa·m. The analyses effectuated with FEM code shows that in these conditions, the minimum of Tsai-Wu number is 0.96321 and the optimal angle between the global and local coordinate systems is 67.5^0, Figure 3. If the same composite plate is immersed 14 days in water, considering the same loads, it has been ascertained that the minimum value of Tsai-Wu number is 2.7018 and this value is obtained for the angle 22.5^0, Figure 4.

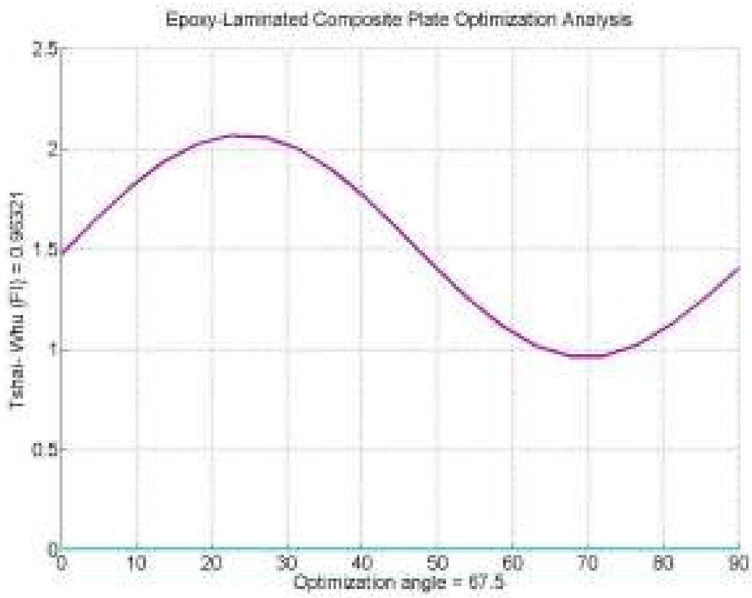

Figure 3: Dependency of Tsai-Wu number by the angle between global and local coordinate systems

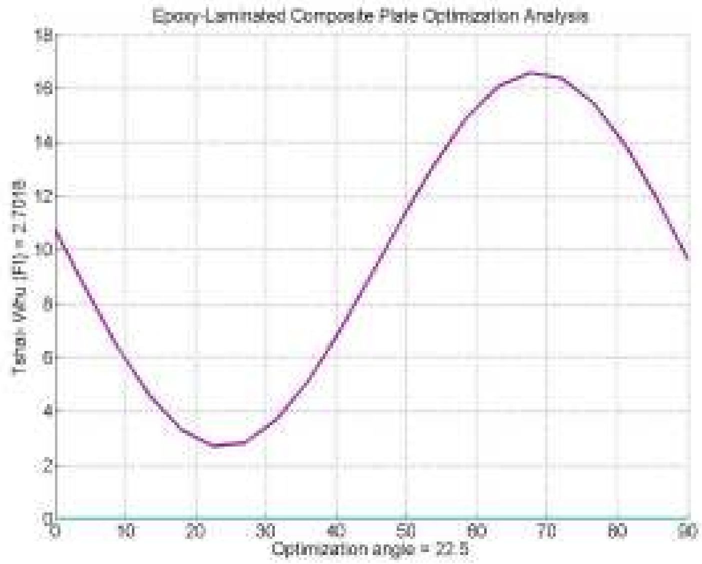

Figure 4: Dependency of Tsai-Wu number by the angle between global and local coordinate systems for the sample with adsorbed water

In this situation, the composite plate failures for the same loads because practically all the elastic parameters are modified due to the action of adsorbed water.

6. CONCLUSION

This paper studies the effect of water adsorption by CFRP having reinforcement from woven fabric from carbon fibers 5H satin type and PPS matrix. The elastic properties of the lamina are delivered by the producer and of the composite in assembly have been determined by dynamic mechanical analyzes and ultrasound procedures. Immersing the samples in water, it has been shown that the material adsorb water, the weight percent of the adsorbed water being proportional with the immersion time. The elastic properties of the immersed samples were determined, being shown that the elastic modulus and shear modulus decrease drastically. To use the Tsai Wu failure criterion, a method of transformation of the laminas with bidirectional anisotropy in [0^0, 90^0] fictive sequences with the same properties was presented. A system of loading was choused so that the reduced angular interval between global and local coordinate system attached to the plies assure a Tsai –Wu number smaller than 1. The composite immersed 14 days in water, at the same loads, failures, the Tsai-Wu number having relative higher values.

ACKNOWLEDGEMENT

This paper was partially supported by the Romanian Ministry of Education, Research, Youth and Sports under National Plan II Program – Contract 71-016/2008 MODIS, Nucleus Program –Contract PN 09430104 and by European Social Fund under Program BRAIN – Investment in Intelligence 2008 – 2nd Year*.

REFERENCES

[1].R.M.Jones, *Mechanics of composite materials*, ScriptaBook Co, Washington DC, 1975
[2].S.W.Tsai, H.T.Hahn, Introduction to composite materials, Technomic Pub, Lancaster, 1980.
[3].R.Akkerman, *Laminate mechanics for balanced woven fabric,* Composites, PartB, Engineering, 37, (2006), pp.108-116
[4].S.W.Tsai, E.M.Wu, *A general theory of strength for anisotropic materials*, J.Comp.Mater,5,(1971), pp.58-80
[5].R.Akkerman, *On the properties of quasi-isotropic laminates*, Composites: Part. B, 33, (2002), pp.133-140
[6].J.R.Xiao, D.F.Gilhooley, J.W.Gillespile, M.A.McCarthg, *Analysis of thick composite laminates using a higher-order shear and normal deformable plate theory (HOSNDPT) and a meshless method,* Elsevier, NY, 2006.