Residual Tensile Strength after Impact of Woven Glass/Polyester Reinforced Composites

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Impact damage in structures made of composite materials is a major concern since such damage can be introduced during the life of the structure, and its mechanical properties can be dramatically reduced as a result. Many efforts have been made in order to predict the damage and residual properties after impact. In the present paper a previously verified model is used in order to evaluate the residual tensile strength of woven fabric laminated composites. The model takes into account the number of plies; the impact energy and the stacking sequence. The effect of the thickness on the residual tensile strength as well as on the impact energy threshold was also examined. The predicted values seem to be a very good approximation of the experimental results.

Keywords: Laminate, reinforcement, impact device, residual stiffness, uniaxial tension

All structures and components made of composite parts are subjected to impacts during their service. Composite materials, especially fiber reinforced polymer composites, are very susceptible to accidental impact damage.

Impact damage is a combination of delamination, matrix cracking and fiber breakage. Among all these modes of impact damage the effect of delamination on the degradation of composite strength and stiffness has been found to be of greatest importance [1].

Evaluation of residual strength and stiffness after impact loading is a major aspect in the study of the behaviour of laminated composite materials. It appears also to be important in assessing damage tolerant materials and improving the crashworthiness of composite structures.

The evaluation of both impact damage and residual strength after impact has been the subject of many investigators [2-3]. Several investigators suggested that the behavior of impact damaged laminates is similar to that of a laminate with a clean hole or a crack of same size [4].

El-Zein et al [5] modeled impact damage as an elliptical inclusion in an anisotropic layer in order to predict the residual tensile strength.

Caprino [6] considered the residual strength of impact damaged laminates and assumed that strength reduction due to impact damage was equivalent to that of a notch of size c. The size of the equivalent notch was assumed to be connected to the total impact energy.

All the above investigations into the impact behaviour of composites have shown that parameters such as impact energy stacking sequence and thickness of the examined material play significant role in the prediction of damage and residual strength.

It has been experimentally found that the damage threshold for an impacted laminate is strongly dependent on the thickness [7]. Increasing laminate thickness the damage threshold increases. In the same work it was also reported that residual strength after impact is dependent on the laminate thickness.

Choi et al [8] have studied the effect of stacking sequence, thickness and impactor's mass on the impact induced damage in graphite - epoxy composites.

Liu [9] found that the degree of delamination between two adjacent layers is strongly dependent on their relative difference in fiber orientation, i.e. on the specific stacking sequence.

The theoretical model used in the present work is based on a previously verified approach [10]. In fact this is an attempt to extend the use of the model in order to evaluate the residual tensile strength for woven laminated composites.

The above model has already extended to predict the residual strength after impact for non-fibrous composite materials and especially for a polymer-polymer composite [11].

Theoretical background

The model developed by Papanicolaou et al [10] is based on the assumption that degradation of flexural stiffness matrix term, D_{xx}, is related to the residual tensile strength as follows:

$$\frac{\sigma_r}{\sigma_0} = \frac{D_{xx,r}}{D_{xx,0}} \qquad (1)$$

where:

σ_r represents the residual tensile strength of the impacted material,

σ_0 is the strength of the unimpacted material,

$D_{xx,0}$ is the flexural stiffness matrix term of the unimpacted material,

$D_{xx,r}$ is the respective flexural stiffness matrix term of the impacted material.

Through the analysis presented by the authors the final form of the model is given by the expression:

$$\frac{\sigma_r}{\sigma_0} = \frac{\frac{d}{U^\alpha}\sum_{\kappa=1}^{n}\left(\overline{M_\kappa}\right)_0\left[Q_{xx,\kappa}\left(z_\kappa^3 - z_{\kappa-1}^3\right)\right]}{\sum_{\kappa=1}^{n}\left[Q_{xx,\kappa}\left(z_\kappa^3 - z_{\kappa-1}^3\right)\right]} = m\frac{d}{U^\alpha} \qquad (2)$$

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where:

U is the impact energy,

α is an energy absorption capacity factor, which depends on the capacity of the material to absorb impact energy,

d is a factor depending on the material properties and test conditions,

m is the ratio of summations.

$$m = \frac{\sum_{\kappa=1}^{n} \left(\overline{M_\kappa}\right)_0 [Q_{xx,\kappa}(z_\kappa^{\,3} - z_{\kappa-1}^{\,3})]}{\sum_{\kappa=1}^{n} [Q_{xx,\kappa}(z_\kappa^{\,3} - z_{\kappa-1}^{\,3})]} \qquad (3)$$

In the above equation, $\left(\overline{M_\kappa}\right)_0$ is the mean value for the bending stiffness mismatching coefficient of the k-lamina [9], $Q_{xx,k}$ is the x-direction stiffness matrix term, z_k is the distance of the k-lamina from the middle plane of the laminate and n is the total number of plies in the laminate.

Through the same anlysis, parameters α, d were related to the amount of plies with $\pm 45^o$ fiber orientation and they can be easily estimated using a characteristic nomogram for each kind of material.

Materials and experiment

All materials used in the present work were constructed by COMOTI S. A. The laminated plates comprised a polyesteric matrix (NESTRAPOL 220) and one of two types of E-Glass woven fabrics (FER3 and FER5), and they were fabricated using the hand lay-up technique. Table 1 summarizes the mechanical properties of the involved matrix and fiber materials while table 2 shows the configuration for each material system. The lay-up of the laminates is also shown in figure 1.

Table 1

MECHANICAL PROPERTIES OF THE COMPOSITE

Material	Young modulus [GPa]	Tensile strength [MPa]	Poisson's ratio
Nestrapol 220	3.9	50	0.35
E- glass fibers	73.82 (22°C)	3515	0.17

Table 2

CONFIGURATION OF MATERIAL SYSTEM

Material	Lay-up	Thickness [mm]
Nestrapol+FER5	6 plies	4.5
Nestrapol+FER5	3 plies	2.25
Nestrapol+FER3	3 plies	2.25

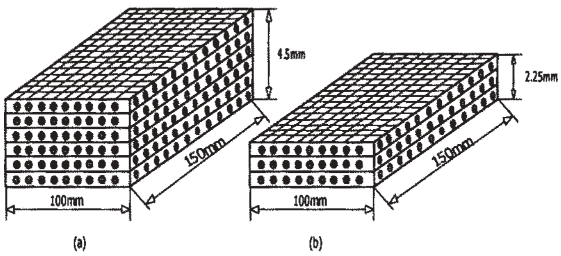

Fig.1. Lay-up of the laminates

Falling weight impact procedure is the most commonly used method in order to simulate a real impact event. To perform the falling impact tests an impact device has been realized according to the IGC 04.26.383 standard for low velocity impact testing (fig. 2).

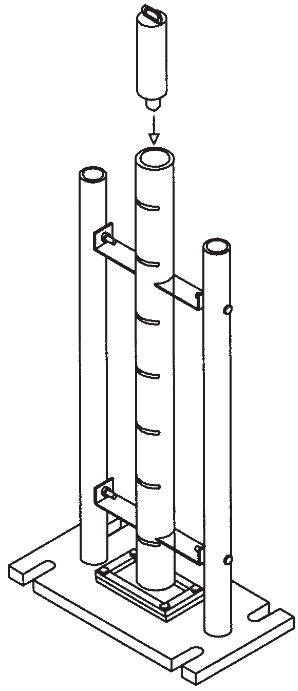

Fig.2. Impact device

The compact device construction consists of a steel plate support with a rectangular window 125 . 75 mm^2 in the middle. A metallic frame is used in order to fix the specimens over the window. The impact is produced by a cylindrical falling weight guided inside a tube.

Rectangular, plate specimens 150 . 100mm^2 were cut from the initial plates. Cylindrical steel impactors with a hemispherical tup 16 mm in diameter and approximately 3 Kg in weight were used to produce impact. Varying the falling height of the impactor (max 1.65m) the impact energy varied from 5 Joules up to 50 Joules.

Finally, the impacted specimens were subjected to static tensile loading until ultimate failure, to determine their residual tensile strength. For the tensile tests a 30mm width sheet was isolated from the initial specimen so as to contain the impact zone. The static tensile tests were carried out with a FPZ 100 universal-testing machine with a 4 load cell. The cross - head speed was 5 mm/min.

Results and discussions

Considering that woven laminates belong to particular kind of composite materials and no amount of plies with $\pm 45^o$ fiber orientation exists, the model must be reassigned to the experimental results in order to evaluate the parameters *a* and *md*.

To this effect Equation (2) can be written alternatively as follows:

$$\log\left(\frac{\sigma_r}{\sigma_0}\right) = -\alpha \log U + \log(md) \qquad (4)$$

Using the experimental results for the fraction of tensile strength v. impact energy along with equation (4), the coefficient *a* and constant log (*md*) can be estimated, using least squares. Figure 3 shows the log (σ_r/σ_0) vs. log (U) plot for the NESTRAPOL + FER3 laminate together with fitting results.

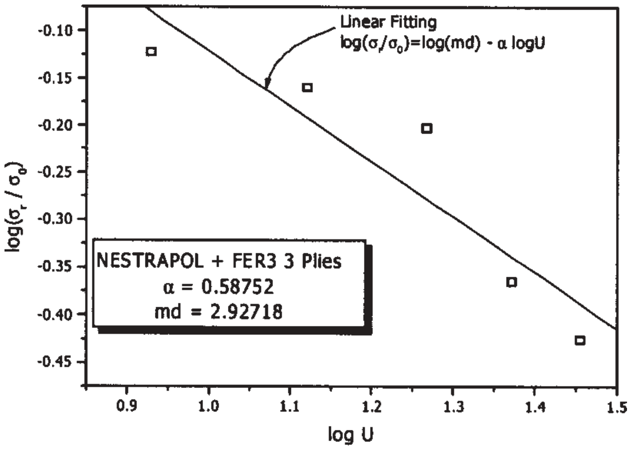

Fig. 3. Log(σ_r/σ_0) vs. log(U) plot for the evaluation of the model parameters

Following the above procedure the parameters for all the laminates were calculated (table 3).

Once α and *md* were calculated the impact energy threshold can be predicted setting $\sigma_r/\sigma_0 = 1$ in equation 2:

$$U_0 = (md)^{1/\alpha} \qquad (5)$$

where U_0 represents the impact energy below that no damage occurs on the material.

A graphic comparison of the model parameters for the different material systems is shown in figures 4 and 5.

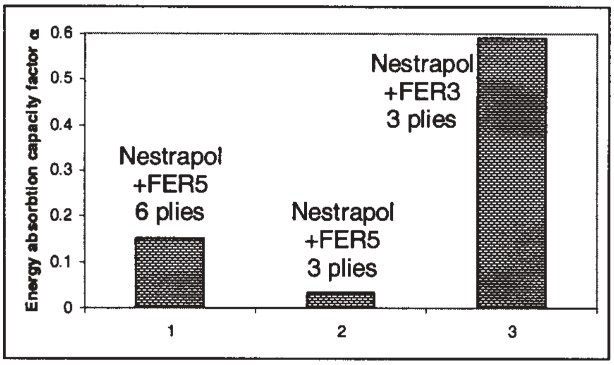

Fig. 4. Comparison of α values for different material systems

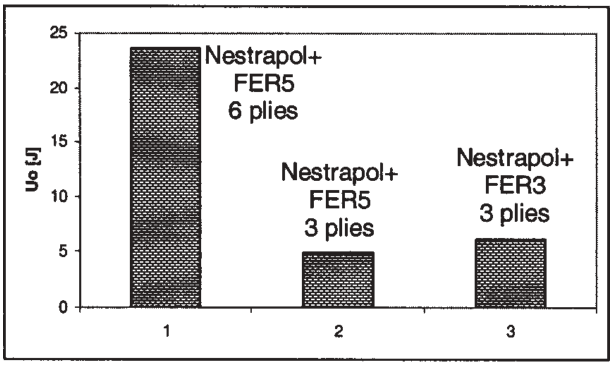

Fig. 5. Comparison of impact energy threshold U_0 values for different material systems

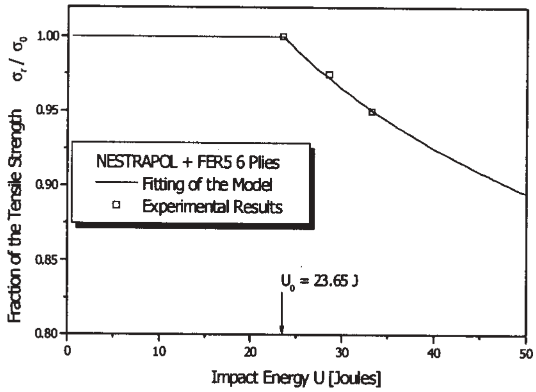

Fig. 6. Fraction of Tensile Strength (σ_r/σ_0) vs. U plot for NESTRAPOL+FER5 6 Plies

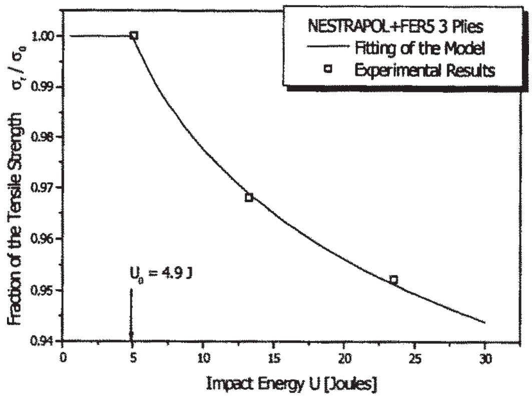

Fig. 7. Fraction of Tensile Strength (σ_r/σ_0) vs. U plot for NESTRAPOL+FER5 3 Plies

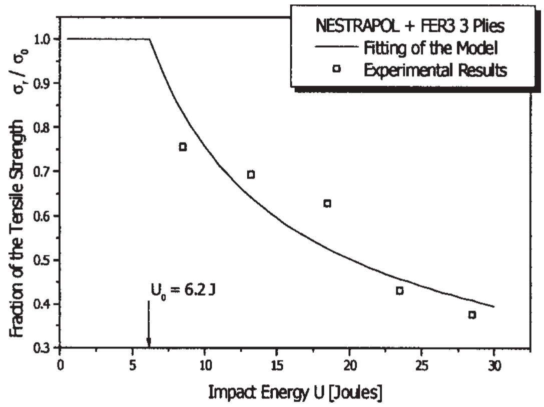

Fig. 8. Fraction of Tensile Strength (σ_r/σ_0) vs. U plot for NESTRAPOL+FER3 3 Plies

It is obvious that an increase of thickness for the NESTRAPOL + FER5 laminate results to an increase of α parameter. So, as material thickness increases the capacity to absorb energy during impact becomes higher. Duplicated the thickness for the specific material an increase up to 515% for the impact energy threshold was also noticed.

Using the above values the residual tensile strength can be calculated according to the model. Experimental results

Table 3
MODEL PARAMETERS

Material	α	md	U_0 [J]
Nestrapol+FER 5 (6 plies)	0.15	1.57	23.65
Nestrapol+FER 5 (3 plies)	0.032	1.05	4.9
Nestrapol+FER 3 (3 plies)	0.59	2.93	6.2

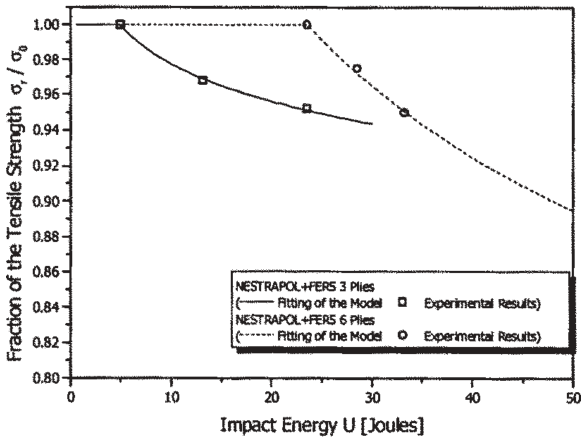

Fig. 9. Effect of laminate thickness on the fraction of Tensile Strength (σ_{rr}/σ_0) - Experimental results along with predicted curves

Table 4
EFFECT OF FIBER TYPE ON THE RESIDUAL RENSILE STRENGTH

Nestrapol + FER5			Nestrapol + FER3		
h = 2,25 mm			h = 2,25 mm		
σ_0 = 260 MPa			σ_0 = 188 MPa		
U_0 = 6,2 J			U_0 = 4,9 J		
U [J]	**σ_r/σ_0 Expec.**	**σ_r/σ_0 Pred.**	**U [J]**	**σ_r/σ_0 Expec.**	**σ_r/σ_0 Pred.**
13,2	0,692	0,647	13,2	0,968	0,969
23,5	0,431	0,458	23,5	0,952	0,951

together with the theoretical predictions are shown in figures 6, 7 and 8.

In figure 9 the experimental and theoretical values for NESTRAPOL + FER5 materials are presented. It is obvious that increasing the thickness better impact behaviour for the specific material was achieved. These observations seem to agree with [12] wherein the authors concluded that the residual strength as well as the damage energy threshold increases with increasing the laminate thickness.

The effect of fiber type is clearly shown in table 4.

For the same laminate thickness big differences in the behaviour of NESTRAPOL + FER5 and NESTRAPOL + FER3 were noticed. For a 13.2Joules impact loading the decrease of the tensile strength for NESTRAPOL + FER3 material is greater than for NESTRAPOL + FER5 with the same lay-up and thickness. In table 4 the theoretical values for the residual tensile strength are also presented. The agreement with the experimental is satisfactory.

Conclusions

In the present work an existing theoretical model for the prediction of the residual strength after impact of laminated composites was adopted in order to study the tensile behaviour of impacted woven laminates. The theoretical model approximates very well all experimental data.

The influence of laminate thickness on the residual tensile strength was also examined. Increasing thickness an increase on the residual tensile strength was noticed as well as on the impact energy threshold. Finally, the use of different types of E-Glass woven fabrics (FER5, FER3) seems to affect significantly the material's impact performance.

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