EXPERIMENTAL RESULTS FOR BENDING FATIGUE BEHAVIOUR OF GLASS-EPOXY COMPOSITE MATERIALS

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***Abstract**. The paper presents results obtained by bending fatigue tests of specimens obtained from composites plates of ortogomal glass fibers woven and epoxy resin . The samples from plates obtained by hand lay-up method were tested by using a bending fatigue testing machine built in university lab. As a degradation parameter was considered the relative reduction of Young modulus values. The test results revealed a samples fatigue behaviour better as the proportion of fiber oriented along with sample longitudinaral direction is higher. Also from tests results can be pointed out that on the degradation firsts stages have been observed cracks in samples which have fibers with orientation different to longitudinal one, cracks which we consider are related to the inherent defects due to the used fabrication method for composite plates, too.*

***Keywords:** bending fatigue, composite material, degradation*

1. INTRODUCTION

The fiber reinforced composite materials fracture mechanism are more complex in comparison with the mechanism which characterized isotropic and homogeneous materials fracture.

So in fiber reinforced composite the fatigue degradation modifies the stiffness value even in the first fatigue stages.

The change of elastic modulus is due to microcracks formed in the polymer matrix, fiber-matrix decohesion, delamination and the final break can be done to either fiber rupture (in the case of stress applied mainly in the fiber direction) or to the decohesion and delamination (in the case of samples stressed mainly in direction different to fibers direction)[1,2].

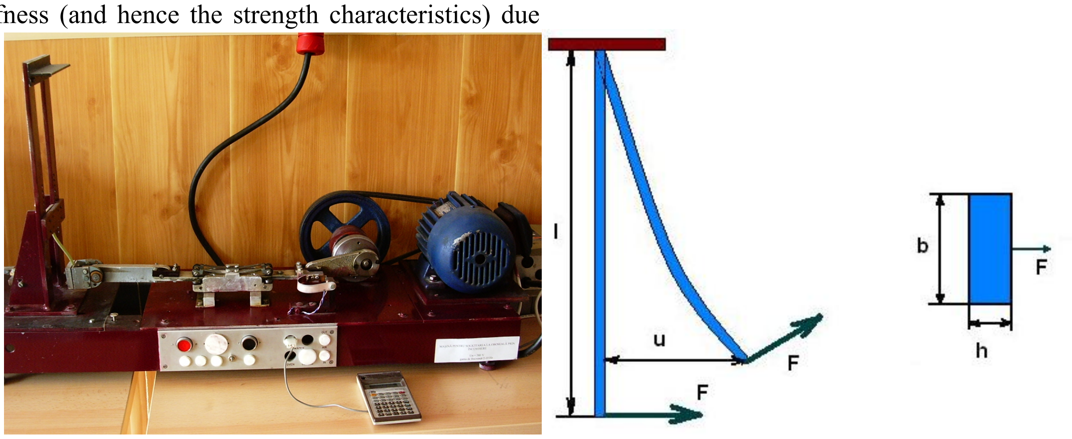
If the composite material is obtained by impregnating fiber bundles manually, stratification will contain embedded air bubbles, defects which are areas of propagation of fatigue cracks and accelerates the sample breaking.

The bending fatigue determines the continuous reduction of stiffness (and hence the strength characteristics) due to progressive accumulation of defects. Because the significant defects influence on material stiffness, the elastic modulus is a material characteristic which can be used as global material degradation parameter.

The degradation evolution in bending tests as function of number of cycles can be expressed as the relative reduction in elastic modulus [3] or as relative changes in bending moment [4].

The overall behaviour of fiber reinforced composite materials during fatigue tests has three different stages in elastic modulus values evolution [5]:

- an initial small decrease of E due to the first defects appearance in material,
- the second stage is characterized by linear decreasing of E due to accumulation of defects and local loss of fiber-matrix cohesion,
- in the third stage apparently the degradation rate becomes smaller in comparison to the second one, even during this stage occurs the final rupture



a b

Figure 1. Overview of bending fatigue testing machine (a) respectively, specimen geometry and loading mode during fatigue tests (b)

2. EXPERIMENTAL CONDITIONS

The bending fatigue testing machine (Fig. 1) tests the specimen (a fixed beam with a rectangular section) by cyclic bending with constant deflection.

The used bending specimens had constant cross section along length (approximate size 140 x 15 x 3 mm) and length l = 80mm.

The bending machine can apply assymetric or alternating bending with preseted deflection value and cycle frequency.

During the bending fatigue the bending forces as function of number of cycles are recorded.

If specimen dimensions and deflection during the bending cycle are known, the bending force value is enough in order to calculate the elastic modulus of the specimen.

As a measure of fatigue effect, the damage variable D used to analyze experimental data is the relative decreasing of longitudinal elastic modulus [3].

$$D = \frac{\Delta E}{E_0} = \frac{E_0 - E}{E_0} \qquad (1)$$

E_0 – initial Young modulus of specimen (calculated from the first bending cycle);

E – Young modulus after damage level D.

A stratified composite plate (epoxy resin reinforced with six layers of orthogonal woven glass fiber, 300g/m^2) with approximate size 250x400mm and thickness of 3 mm was subject to the bending fatigue behavior analysis. The layers of glass fibers have the same orientation in composite, so that this material can be assimilated with a symmetrical and balanced stratified, with about the same proportion of fiber oriented in each orthogonal plate axes.

The plate was made by hand lay-up method, and due to difficulties in impregnation of fiber bundles with resin, the material had fabrication defects such as air voids, defects inherent after this type of processing procedure. The dimensions of defects not exceeded 0.6 mm.

In order to estimate the influence of the manufacturing route and stress direction on the bending fatigue behavior of composite plates, were tested four types of specimens cut at 0^0, 15^0, 25^0 and 45^0 with respect to fibers direction, specimens marked E0÷E45.

3. EXPERIMENTAL RESULTS

Specimens from each category (E0÷E45) were subjected to bending. The changes in bending force was monitored as function of number of cycles and after that was calculated the variation of material elastic modulus (Fig. 2). Also using modulus values during the composite degradation was calculated the damage parameter D (1) and its dependence to the number of cycles (Fig.5).

In Fig.2 is shown the pronounced reduction of the specimen longitudinal modulus value when number of loading cycles increases, respectively, in Fig.5 the continuous increasing of material damage coefficient D .

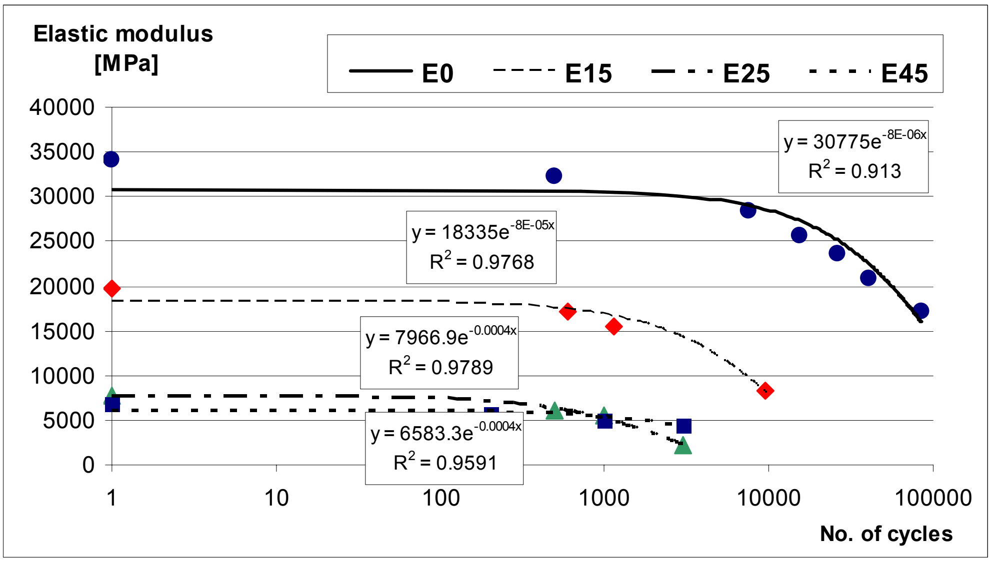


Figure 2. Evolution of Young modulus with number of cycles

The intersections of curves with ordinate axe have the significance of initial elastic modulus of material (measured for the first cycle of bending fatigue loading). It can be seen that the modulus is high dependent on the orientation of the reinforcement elements in composite materials. Thus for E0, specimen cut out in the direction of fiber, modulus is four times bigger than for the specimen E45 which is cut out at 45^0 with respect to fibers direction.

During the experimental data processing we can noted that between the value of elastic modulus and the number of loading cycles is a dependence as follows:

$$E_n = A \cdot e^{-m \cdot n} \quad (2)$$

E_n – elastic modulus of the specimen after n bending cycles,

A, *m*-experimental parameters.

Mathematical modeling of composite material stiffness during bending fatigue test as function of the reinforcement direction and number of loading cycles can be achieved if are known parameters A and m of the model described by equation (2).

Parameters A and m can be computed by using the data summarized in Table 1.

Table 1. Corellation coefficients for dependence between elastic modulus and the number of cycles for the four types of tested specimens

Sample	Equation	A	m
E0	E = 30775e-8E-06n	30775	$8 \cdot 10^{-6}$
E15	E = 18335e-8E-05n	18335	$8 \cdot 10^{-5}$
E25	E = 7966.9e-0.0004n	7966	$4 \cdot 10^{-4}$
E45	E = 6583.3e-0.0004n	6583	$4 \cdot 10^{-4}$

Parameter A has the significance of E for n = 0 , being the initial elastic modulus of specimen. Parameter A value is mainly a function of angle between the reinforcement direction and the loading directions.

The parameter *m* values are also dependent on the specimen cut out direction. The best correlation between coefficient m and the angle between the direction of specimen and fibers direction, expressed in radians, is shown in Figure 3.

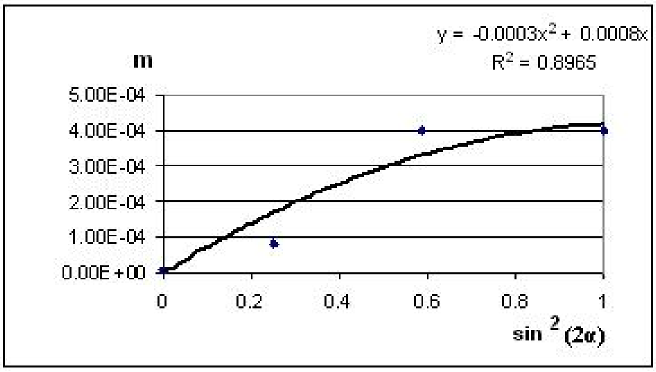


Figure 3. Exponent value m from equation (2) as function of angle between the cut out direction of specimen and reinforcement direction

In Fig.4 are shown simulated curves according to previous presented model in comparison with curves experimentally obtained. There is a good correspondence with the model in the low number of cycles zone, but in the final stages of degradation, for specimens E0 and E15 the model provides elastic modulus values lower than experimental ones (in fact model suggests a more rapid degradation).

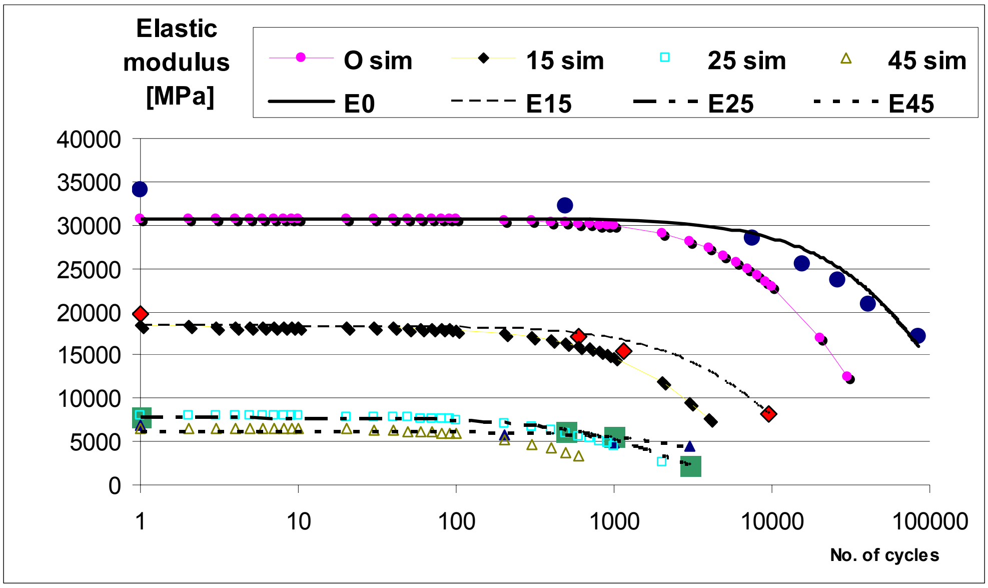


Figure 4. Comparison between experimental curves and model with calculated parameter m

It is noted significant differences in evolution of degradation mode, due to differences in reinforcement orientation (glass fibers). Thus, specimens cut out at angles of 15^0, 25^0, 45^0 to the fibers direction show significant degradation (up to 0.6; 60% reduction in longitudinal modulus value) and breaking after 10,000 cycles applied. In case of E45 specimen, rupture occurred before 30% reduction in elastic modulus. On the other hand, the specimen E0 shows in the same

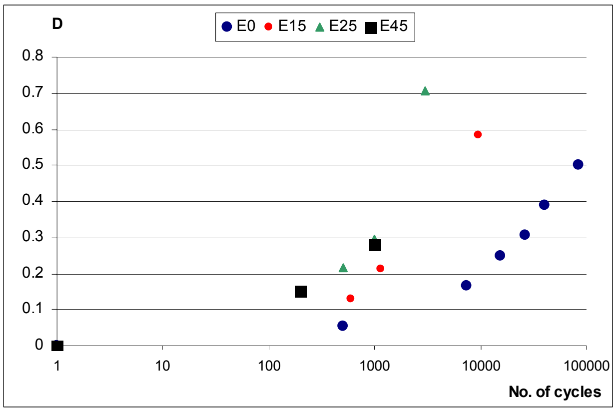


Figure 5. The evolution of composite degradation with number of cycles

loading condition (number of cycles) a degradation of only 20%

It is clearly observed that, in bending fatigue degradation with constant deflection, the specimen behavior is better as for the specimens with lower angle between the fiber and loading directions.

The experimental results reported by other authors highlights in the shape curves of variation of degradation with the number of cycles, the presence of three distinct stages of degradation [5]. In case of our specimens tested, curves analyzed show only two distinct stages of degradation: a stage characterized by a sharp decreasing speed of material stiffness, followed by a second stage characterized by a slower reduction rate.

Basically, in our experiments is missing the first stage of the modulus reduction due to slow initiation of defects, because the material has been hand made and has already defects at the beginning of loading cycles.

If consider for each stage of degradation, a linear dependence between degradation variable D with the number of loading cycles (Fig.6), can be highlighted inflection points in the rate of degradation which will be called as the critical number of cycles.

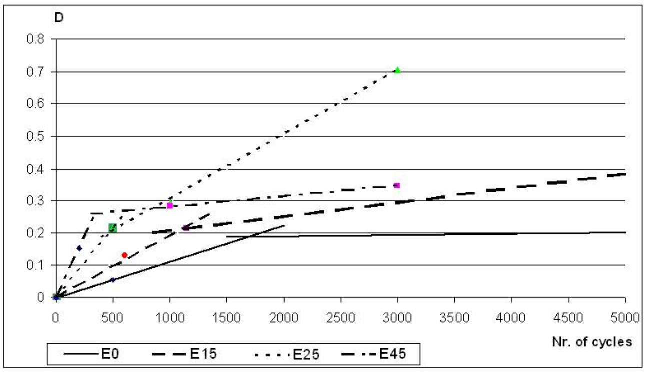


Figure 6. Highlighting the two stages of bending fatigue damage in hand made stratified composites

It is noted that accelerated degradation phase is completed at a lower critical number of cycles if the fiber direction makes a greater angle with respect to specimen direction.

The rate of degradation characteristic for first stage is even greater if the angle between the fiber direction and the direction of specimen is greater. Thus, as can be observed from the slope of the lines shown in Fig.6 (angular coefficients of lines whose equations are presented in Table 2) for E0 specimen with fibers oriented in the direction of loading, the relative reduction rate of longitudinal modulus is 0.0001 / cycle while, in the case of specimen E45 with fibers oriented at 45^0 with respect to loading direction, degradation rate is about 8 times higher (0.0008 / cycle).

The same type of evolution is remarkable in case of the II stage of degradation when degradation rates are lower than in the first stage and having the same dependence to the direction of reinforcement as in the first degradation stage.

An exception is specimen E45, which shows apparently a lower degradation rate than in the case of sample E25 (0,00003 in comparison with 0,0002).

Table 2. Critical number of cycles and the equations of degradation curves

Sample	Critical number of cycles	StageI	Stage II
E0	1886	y = 0.0001x - 1E-05	y = 4E-06x + 0.1811
E15	1016	y = 0.0002x	y = 4E-05x + 0.1626
E25	534	y = 0.0004x	y = 0.0002x + 0.1069
E45	325	y = 0.0008x - 0.0007	y = 3E-05x + 0.25

An explanation of this type of behavior could be the very intense initial reduction of modulus for E45 specimen. In fact, modulus decreases so much due to the loss of cohesion between fibers and matrix in the final stages of fatigue loading cycle and the specimen shows even a permanent deformation (Fig. 8).

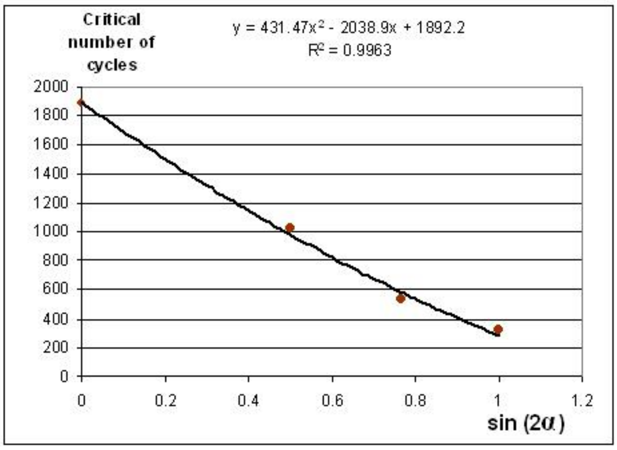


Figure 7. Correlation between the critical number of cycles and the direction of cut out specimens

It may be revealed an obvious correlation between the type of specimen orientation (reinforcement orientation) and the critical number of cycles.

Critical number of cycles is correlated to the angle α between the direction of fibers and specimen sampling direction, according to a relation with following form:

$$n_{cr} = 431{,}47 \sin^2(2\alpha) - 2038{,}9 \sin(2\alpha) + 1892 \quad (5)$$

We can conclude that the behavior of the stratified composite material in bending fatigue is dependent on the strength of fibers in the maximum stressing area and fiber-matrix decohesion (the decohesion is produced by propagation of small defects and their accumulation under further loading cycles, having as overall effect the final delamination).

The defects, inherent in hand made composite, have a significant effect on crack propagation rate and to the degradation rate.

Tests performed on hand made stratified composite reinforced with glass fiber woven formed highlighted the important influence of manufacturing defects on the evolution of degradation.

4. CONCLUSIONS:

1. Bending fatigue experiments were performed with a machine designed in University Valahia of Targoviste lab.

2. Tested specimens were cut out from epoxy resin / orthogonal glass fiber fabric stratified composite plates.

3. Breaking fatigue phenomena are preceded by a preliminary degradation strongly dependent on the type and dimensions of defects generated in the specimen, due to on the one hand to manufacturing processing and, to the another hand to the fiber orientation with respect to longitudinal direction of tested specimen (loading direction).

4. Stratified composite materials have a better fatigue behaviour if the angle of fiber direction and the direction of the specimen is lower.

5. During the bending fatigue tests of composites obtained by hand lay-up method can be highlighted two distinct areas for variation of damage with the number of cycles in comparison with composite obtained by other methods, by which is not expected the appearance of air bubbles or another kind of fabrication defects and which have three distinct stages of damage variation.

6. Critical number of cycles (which marks the transition from one damage stage to another) is also dependent on the orientation of the reinforcing elements.

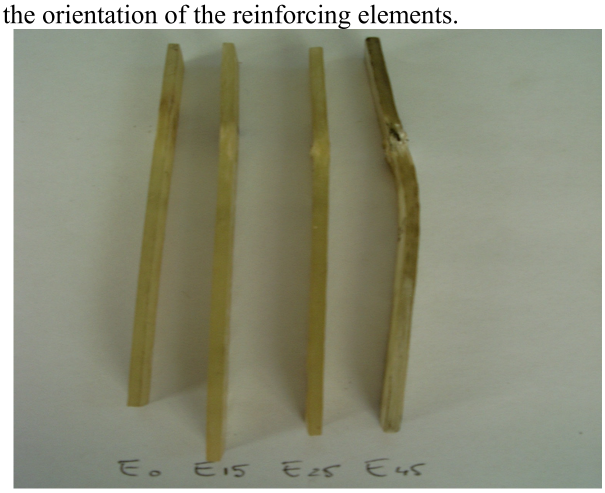


Figure 8. Specimens appearance after bending fatigue loading

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