Effect of Hygrothermal Fatique on the Mechanical Behaviour of Polymeric Composite Laminates and Sandwich Structures

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The present study is aimed to investigate the effect of damage due to hygrothermal fatigue on the mechanical behaviour of CFRP (Carbon Fiber Reinforced Polymer) laminates as well as on the skin-core interfacial stress field in sandwich structures having CFRP laminates as core material and aluminum as skin. The above behaviour was both experimentally and analytically studied using a model recently developed by the CMG group at University of Patras.

Keywords: hygrothermal fatique, polymeric composite laminates, sandwich structures, interfacial phenomena

Polymer composites reinforced with fibers because of their high strength and stiffness to weight ratio, excellent fatigue properties and corrosion resistance, are commonly used in aerospace, sports, automotive and other applications. On the other hand when under humid environmental conditions, polymer composite structures absorb water, which can cause degradation of their mechanical properties. This degradation depends on the environmental conditions, duration and the type of the composite and more precisely the type of the polymer matrix. Epoxy resin is commonly used as matrix, which as it is well known it absorbs moisture from the humid environment. For these reasons, many researchers investigated the mechanisms of water absorption [1-11]. The aim of the present study is to investigate the effect of damage due to hygrothermal fatigue on the mechanical behaviour of CFRP laminates as well as on the skin-core interfacial stress field in sandwich structures having CFRP laminates as core material and aluminum as skin. The above behaviour was both experimentally and analytically studied by using a model developed by the University of Patras CMG group [10].

Experimental part

Component materials

The core material used in this study was a 4 layer twill 6k fabric CFRP (410 gr/m^2, 2 layers at 0°/90° and 2 layers at +/-45°, symmetrical array), 200 mm wide and 2 mm thick. Finally, the adhesive used to bond the face sheets to the core was an LF epoxy resin (lamination resin for aircraft construction). Epoxy resin LF is a bisphenol A resin approved by the German Federal Aviation authorities for the construction of powered aircraft and gliders in conjunction with glass, aramid and carbon fibers. The hardener used for the resin was LF 1 which is a fast amine hardener for smaller components, glued joints, and repairs in aircraft construction. The resin compound cures at room temperature in 24 h. After this preliminary period of curing, aircraft parts must be hot-cured for a further fifteen hours at 50-55 °C.

Fabrication of sandwich beams

A 12 mm wide aluminum skins were machined from a 1 mm thick aluminum sheet. The 12 mm wide CFRP core was machined from a 2 mm thick composite sheet. The face sheets were then bonded to the top and bottom of the CFRP core with LF epoxy adhesive and the assembly was cured under pressure in an oven following the recommended curing cycle for the adhesive. Beams for three – point - flexural testing were 100 mm long for CFRP and 200 mm for sandwich structures. Specimens dimensions are shown in figure 1.

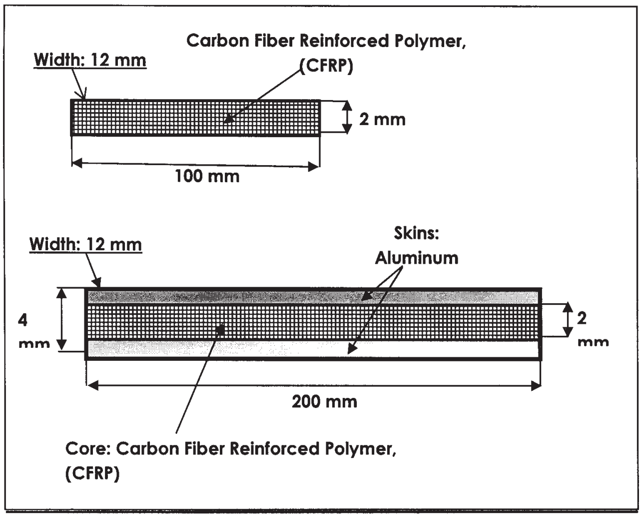

Fig.1. Specimens' dimensions

Mechanical characterization

Three-point bending measurements were carried out with a conventional Instron type tester (INSTRON 4301), at room temperature. Specimens with a gauge length of 63 mm and 180 mm for CFRP and sandwich structure respectively, were tested at a constant strain rate of 1.0 mm/min. The repeatability of results, especially for sandwich structures, confirms the good manufacturing conditions applied.

Hydrothermal fatigue

Hydrothermal fatigue took place in a bath with distilled water at 40°C for 0, 2, 4, 8, 24, 28, 32, 48, 52, 56, 120, 240, 480, 960 and 1920 h for CFRP specimens and for 0, 2, 4, 8, 24, 28, 32, 48, 52, 56, 120, 240, 336, 480, 960, 1920 and 3120 h for sandwich structures (Al- CFRP composite - Al).

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A standard procedure for water uptake was followed. Before placing the test specimens into the water bath they dried in an oven at 50 °C, until their weight was stabilized. The dried specimens were then placed in a high vacuum for 24 h to create full-dried specimens and their weights were measured with an analytical balance. Then the specimens were immersed in distilled-water bath at constant temperature of 40°C, controlled to ± 0.5 °C. The specimens, conditioned in water, were then removed at the already mentioned immersion times, wiped, air dried for 5 minutes, and then weighed. All specimens were weighted before and after the water absorption procedure with ± 0.001 gr accuracy. The thus conditioned specimens were then subjected to bending experiments.

Results and discussions

The percentage of water uptake M (t) of the materials tested, or percentage mass-gain, may be defined as the difference in masses of the wet (m_0) and dry (m) materials, normalized to m_0 according to relation: $M(\%) = \frac{m - m_0}{m_0} \cdot 100$

Figure 2 depicts the variation of percentage of water absorption with immersion time for both core and sandwich structures. At the initial stage of the hygrothermal fatigue, a sharp increase in water absorption is observed (first 480 h for core and 120 h for the sandwich structures). After exposure for 980 and 960 h for core and sandwich structures respectively, specimens reached full saturation of water absorption. From the comparison between respective results for the core and the sandwich structure, it is clear that the percentage of water absorbed by the sandwich structure is always lower than the one absorbed by the core and this is due to the existence of metal skins, which limit the amount of water absorbed.

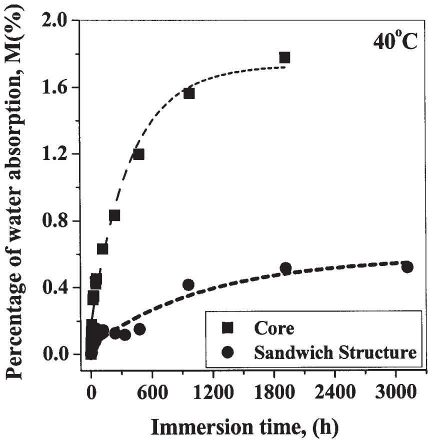


Fig.2. Variation of percentage of water absorption with the immersion time for both core and sandwich structures

Figure 3 shows the variation of reduced bending modulus with immersion time for the core and the sandwich structures. It is clear that the reduced bending modulus values for the core material are higher than the respective ones for the sandwich structure. In addition, it can be observed that the modulus variation for the core material, increases with immersion time until 1260 h and then decreases tending to an equilibrium value after 1900 h of immersion into water. On the contrary, the respective variation for the sandwich structure is quite different than the respective one observed for the core. More precisely, in the case of sandwich structure, bending reduced modulus increases continuously with immersion time reaching a plateau after 960 h of immersion time. The already observed behaviour can be explained on the basis of structural considerations. One of the main parameters controlling the water absorption mechanism in a sandwich structure is the skin – core interfacial adhesion. Hygrothermal fatigue degrades the skin-core interfacial adhesion and as immersion time increases a skin-core debonding takes place till the complete failure of the bond. Thus, the sandwich structure shows always lower bending modulus values in comparison to the core material. At high immersion times, due to the complete skin-core debonding there is an equilibrium value for reduced bending modulus value which for both materials is almost the same.

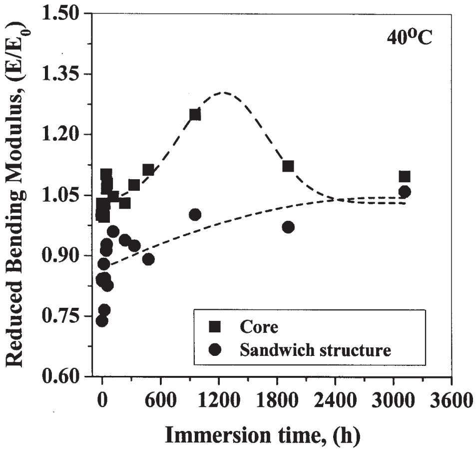


Fig.3. Variation of reduced bending modulus with immersion time for the core and the sandwich structures

Theoretical Approach

Interfacial Phenomena

Knowledge of the interface characteristics is important for both fundamental and practical adhesion aspects. Indeed, the interfacial discontinuities in the boarder of two different materials which are in contact, determine the final overall properties of the composite systems (adhesion, corrosion resistance and durability). In the sequence of the present investigation, the effect of hygrothermal fatigue on the skin-core interfacial stress filed will be studied by means of an analytical model recently developed by [10].

Skin-Core Interfacial Stress Distribution

To elucidate the significance of the interface stiffness concept on the skin-core interface load distribution in FRP-metal laminate beams the researchers [11] proposed a shear lag model, which can be used for the determination of the load distribution along the skin-core interface length of FRP-metal laminates subjected to in – plane tension. The model introduces a basic hypothesis according to which, the interface stiffness depends on the difference in shear moduli of the constituent materials as well as on the degree of adhesion which, in turn, depends on the abrupt jump in shear moduli at the skin–core boundary. According to the model, the interfacial axial force developed along the length of the core material is given by:

$$N_C = \frac{P}{\left(\frac{1}{E_S A_S} + \frac{1}{E_C A_C}\right)} \cdot \frac{1}{\sinh nL} \cdot \left[(\sinh nx) + \sinh n(L - x)\right] \cdot \left(\frac{f}{E_C A_C} - \frac{(1-f)}{E_S A_S}\right) + \frac{\sinh(nL)}{E_S A_S} \tag{1}$$

where:

P is the external force applied to the beam;

E_S - skin modulus;

E_C - core modulus;

Table 1

SPECIMENS' DIMENSIONS AND THEIR MECHANICAL PROPERTIES

Bending load (P)	200 N
Total core cross-area (A_C)	24.22 mm^2
Total facing cross-area (A_S)	24.22 mm^2
Total Length (L)	100.00 mm
Beam width (b)	12.11 mm
Beam height (2h)	4.0 mm

A_S - total facing cross-area;
A_C - total core cross-area;
L - total length;
f - a constant (0<f<1) representing the percentage of the force P transferred to the facing, as well as to the core;
n -a constant calculated as follows:

$$n^2 = K\left(\frac{1}{E_C A_C} + \frac{1}{E_S A_S}\right).$$

Next, the shear load per unit length can be calculated as follows:

$$t = \frac{dN_c}{dx} = \frac{Pn}{\left(\frac{1}{E_S A_S} + \frac{1}{E_C A_C}\right)} \cdot$$

$$\frac{1}{\sinh nL}\left[\left(\cosh nx - \cosh n(L-x)\right) \cdot \left(\frac{f}{E_C A_C} - \frac{(1-f)}{E_S A_S}\right)\right] \qquad (2)$$

Finally, the axial interfacial force along the length of the facings is given by:

$$N_S = P\left[1 - \frac{1}{\left(\frac{1}{E_S A_S} + \frac{1}{E_C A_C}\right) \cdot \sinh(nL)} \cdot \left[\sinh(nx) + \sinh n(L-x)\right] \cdot \right.$$

$$\left. \cdot \left[\frac{f}{E_C A_C} - \frac{1-f}{E_S A_S}\right] + \frac{\sinh(nL)}{E_S A_S}\right] \qquad (3)$$

Application of the interface model

After hygrothermal fatigue for sandwich structures, the above theoretical model was applied. Table 1 shows input experimental data used for the application of the model.

Figure 4 shows the skin-core interfacial axial force distribution developed along the length of the core material of the sandwich structures for different immersion times. As one can observe, axial force is maximum at both ends of the specimen and minimum at the centre of the beam. Also, Nc is always higher for higher immersion times. The lower values for the axial force in the core are observed for the undamaged specimen and the maximum after 336 h of immersion into distilled water. The difference between the maximum Nc value after 336 h of immersion and the respective one for the dry specimen is 11.2 %. In addition, figure 4 depicts the variation of the skin axial force, N_S along the skin-core interfacial length of the specimen for nine different immersion periods. In contrast to the previously described variation, the respective axial force distribution for the skin is maximum at the centre of the beam and minimum at both ends of it. In general, Ns decreases with immersion time. As immersion time decreases, the rate of Ns variation is increasing. The difference between the maximum Ns-value for the dry and the respective maximum Ns-value for the wet specimen as measured after 336h of immersion (damaged) is only 6.5 %.

Scanning electron microscopy (S.E.M.)

In order to obtain a clear view of the internal structure of the sandwich structures after 0, 336 and 3120 h hygrothermal fatigue, photomicrographs (figs. 5-8) have been taken by means of a scanning electron microscope.

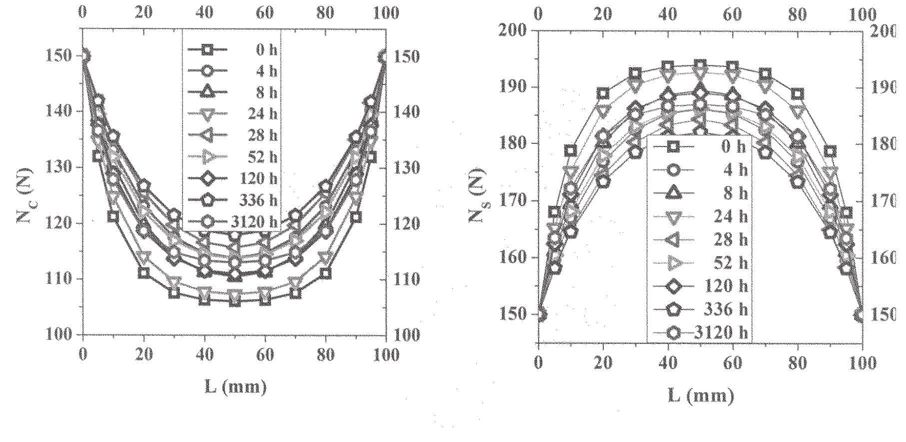
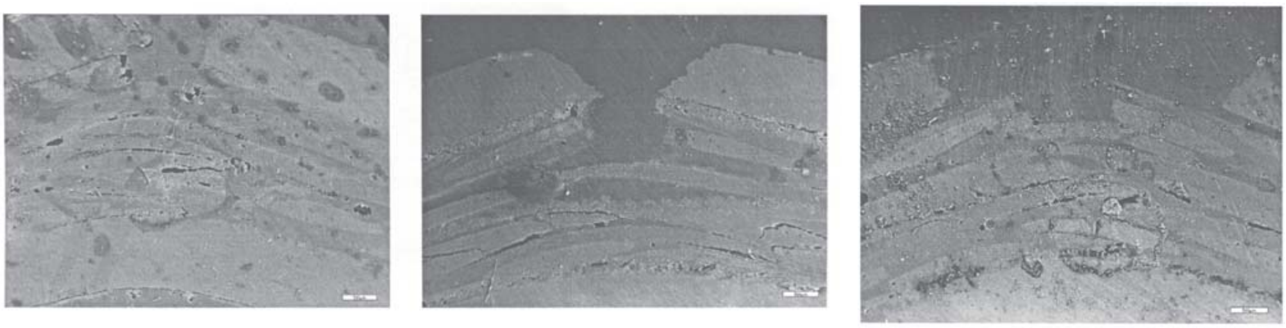


Fig.4. Variation of N_C and N_S along the FRP metal laminate interfacial length for nine different immersion times at 40°C in distilled water

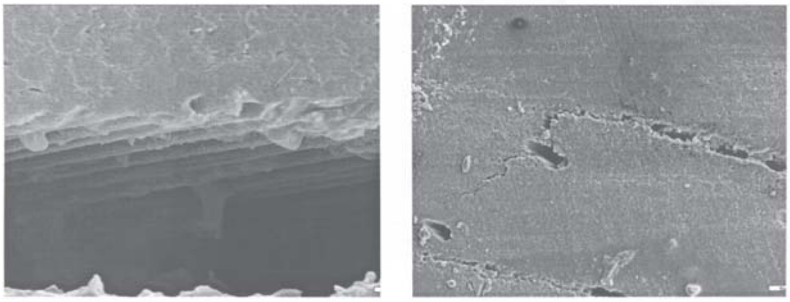


(a) 500μm

(b) 500μm

(c) 500μm

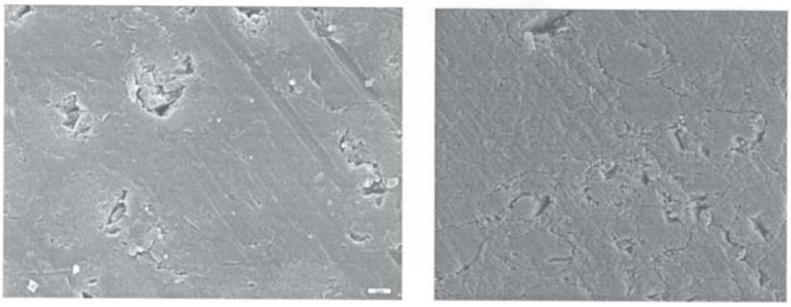
Fig.5. Vertical option of fracture surface of sandwich structures after: (a) 0 h, (b) 336 h and (c) 3120 h of hydrothermal fatigue in distilled water at 40°C



(a) 5μm

(b) 50 μm

Fig.6. Crack propagation regions in the dry sandwich specimens created into the core material during manufacturing procedure



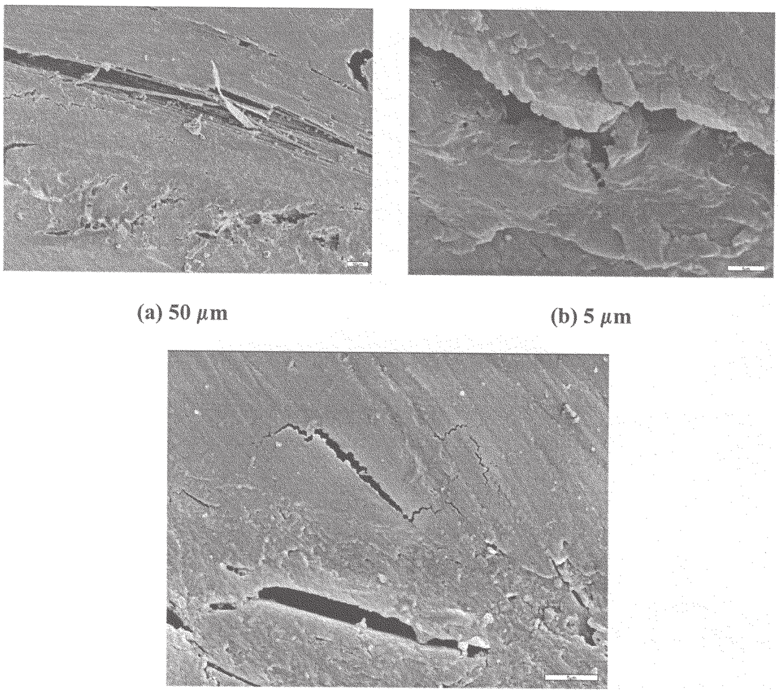
(a) 2 μm

(b) 5 μm

Fig.7. The adhesive mass in sandwich structures for: (a) 0 h and (b) 336 h of immersion times

The above immersion times were selected on the basis of our experimental results, which as mentioned above have shown that after 336 h of immersion in hot water, the highest difference in mechanical properties were observed while after 3120 h of immersion, the respective difference tends to zero. Figures 5 a,b,c, show clearly that for higher immersion times, extent of internal damage increases too. figure 5b, shows the necking effect developed on the aluminum skins as well as the type that CFRP laminates have failed and delaminated. In figure 5c, which was taken after 3120 h of immersion, voids, impurities, delaminations and interlaminar cracks can be observed**.** The most important point coming out from these figures is the skin – core adhesion quality observation which is evident when comparing figures 5a-c. This comparison clearly shows the good quality of skin-core adhesion bond in the case of undamaged specimens in contrast to the bad adhesion quality observed in the wet specimens. Figure 6 shows crack propagation regions for the dry sandwich specimen created into the core material during manufacturing procedure. These cracks are mainly due to voids, other impurities and manufacturing's damages in core.

After high periods of immersion, water molecules penetrated into the voids, and due to swelling cracks started to propagate into the core. In figure 7a, one can observe voids and delamination areas developed into the core material while figure 7b shows a crack propagating into the skin-core interfacial area which is an area of minimum energy. As expected, the damage extent (crack formation and propagation, voids, delamination, etc.) into the core increases with increasing immersion time. This is better observed if one compares the extent of damage created at higher times of immersion as illustrated in figures 8a,b and c (3120 h immersion time) with respective damage extent shown in figures 7a and b (336 h immersion time).



(a) 50 μm

(b) 5 μm

(c) 5 μm

Fig.8. Cracks, bending and delaminations in sandwich structure after 336 h immersion time (a) and (b) as well as after 3120 h of immersion time (3)

Conclusions

In the present investigation, the hygrothermal fatigue behaviour of sandwich structures with aluminium skins and CFRP core material was studied. The same subject was approached by other researchers in [12,13]. In order to specify with higher accuracy the performance of damaged and undamaged polymer composite, a simple analytical model for the estimation of the skin-core interface stress distribution and its variation with immersion time in Al-CFRP sandwich structures was developed and applied by the authors.

The main conclusions are:

- a sharp increase in water absorption at the initial stage (first 480 h for core and 120 h for the sandwich structures) is observed. After exposure for 980 and 960 h for core and sandwich structures respectively, specimens reached full saturation;
- percentages of water absorption for sandwich structures are always lower than those of the core material.
- experimental values for the core reduced bending modulus are higher than those of the sandwich structures;
- both core and sandwich structure occur the same equilibrium value for the reduced bending modulus;
- for higher immersion times, the development and propagation of cracks into both the core material and the skin-core interface are more intense;
- the interface model is a simple analytical model, applied for the determination of the skin-core interfacial stress distribution and its variation with immersion times. It was found that hygrothermal fatigue strongly affects the skin-core degree of adhesion by reducing its strength and this, in turn, is responsible for the finally observed decrease in stiffness of the whole sandwich structure with immersion periods. This, in turn, is followed by a decrease of the maximum value of the interfacial shear flow developed along the specimens' length, with immersion times.

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Manuscript received: 17.05.2010