Effect of Thermal Cycling on Stiffness and Strength Degradation of Polymeric Composite Materials

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ABSTRACT
Thermal Fatigue (TF) is a process of damage origination and growth in machine parts and structural components. Thermal fatigue is caused when thermal deformation is restricted. It can be divided in two sub-categories [1]: i) TF due to external constraints, ii) TF due to internal constraints. Fig. 1 shows a classical example of TF Type i.

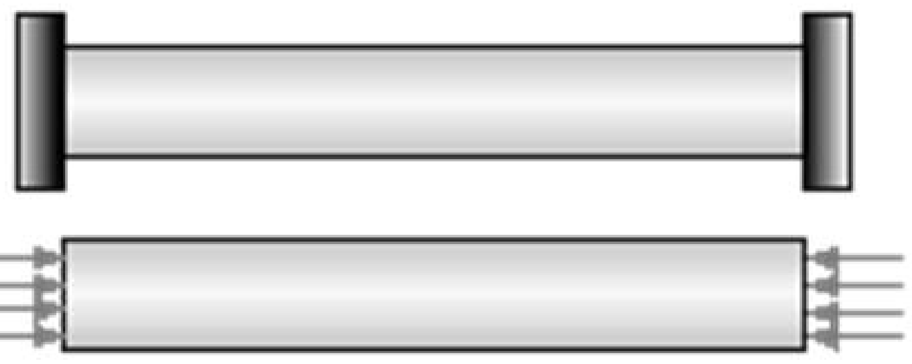

Fig. 1. Thermal fatigue due to external constraints

This study is focused on the degradation of the mechanical properties of FRP's when they are exposed to thermal shock conditions. Such events can occur frequently during the life-time of a composite; e.g. during manufacturing (cooling from curing temperature to environment) or during operation (external temperature of aircrafts can change from -50oC to +150oC, during landing, within seconds). The residual properties studied were the elasticity modulus in bending (flexural modulus – E) and the respective maximum stress (flexural strength - σmax) developed within the specimens. The experimental results are compared with the results given by a simple semi-empirical model, developed to predict the residual properties of a material subjected to a specific damage. The same model predicts, also successfully, the behavior of a system being subjected to impact, hygrothermal or thermal fatigue, erosion, etc.

THERMAL STRESSES

As a first approach to the subject, simple laminate structures will be considered and studied. Fig. 2 shows such a simple two-layer unidirectional (UD) cross-ply laminate The analysis of thermal effects should be made in two scales: i) Considering laminae and interlaminar stresses, and ii) more microscopically, considering stresses and damage in fiber-matrix level.

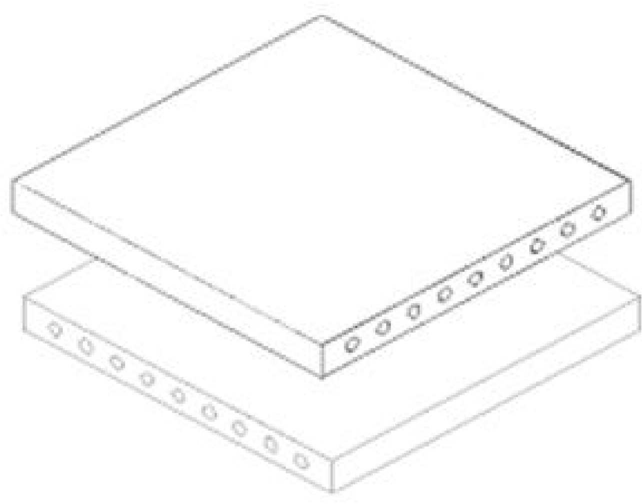

Fig. 2. Simple laminate

The first approach is based on the Classical Lamination Theory (C.L.T.). It can be proved that the equation that connects the temperature change with the corresponding thermal stresses is [2, 3]:

σi(k) = Qij(k) (εj – αj(k) ΔT) {1}

Where,
k is the index referring to the kth lamina, Qij is the stiffness matrix, εi is the total strain of the laminate along the i-direction αi is the CTE along the i-direction, ΔT is the change of temperature, i is the direction index (i = x, y, s)

MATERIALS AND EXPERIMENTAL PROCEDURE

It is obvious that if the relation between temperature (T) and time (t) is known, then the thermal stresses can be easily calculated through equation 1. A series of thermal fatigue tests took place, in order to investigate the degradation of the FRP's properties.
The experiments were focused mostly on materials widely used in the aerospace industry, and the selection of the temperature range/rate was determined by aeronautical applications. With the available lab equipment, a temperature range from -27oC to +200oC could be set.
The minimum temperature was set to be -27oC and the maximum one -designated by Tg- was set to (Tg) ± 20%. The exact temperature change is shown in Fig. 3.

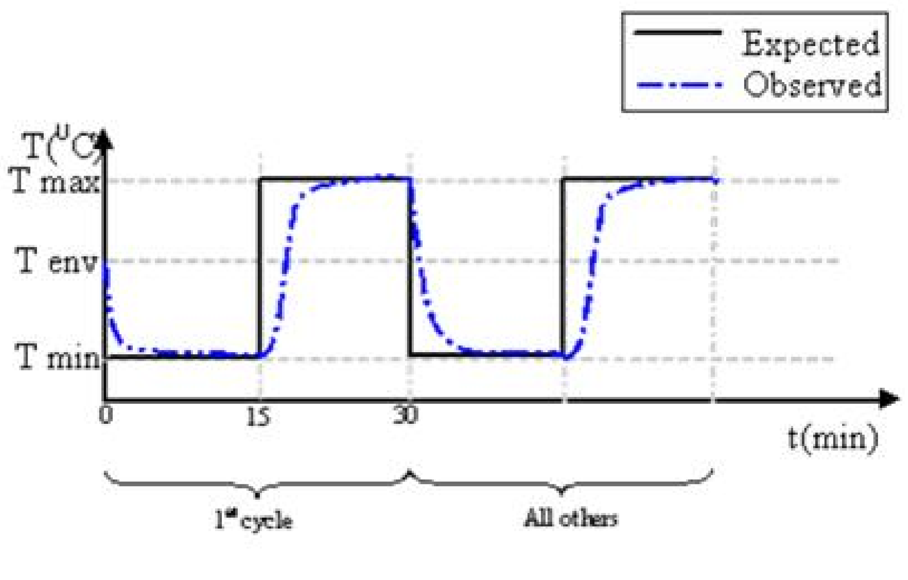

Fig.3. Temperature change during every cycle

The materials used were manufactured by SEAL Co, ITALY, and their respective properties are listed in Table 1. The complete test procedure was:

1.At first, all specimens were placed in freezing environment (-27°C) for 15 minutes.
2.Next the specimens were placed in hot environment for 15 minutes
3.Three specimens were selected and subjected to a three-point-bending test (Fig. 5) on an *Instron 4301* machine (with its own data acquisition system) with a constant displacement rate of 5mm/min. At the same time the rest of the specimens were placed in the freezing environment and the steps were repeated until all specimens were tested
4.After the completion of each bending test the experimental data were analyzed with Mathworks Matlab; flexural modulus and strength were calculated.

Table 1 Material properties

Material 1		E-Glass - Epoxy	
Flexural modulus of the composite E (GPa)	Flexural modulus of the Matrix E_m (GPa)	Maximum stress of the composite σ_{max} (MPa)	Maximum stress of the Matrix $\sigma_{max,c}$ (MPa)
8	3	145	80
Stacking sequence	8 x (E-Glass Fabric reinforced Epoxy) – Satin 8H		
Other information	TEXIPREG ® EE300/ET441		$T_g = 65^0C$
Material 2		E-Glass - Polyester	
Flexural modulus of the composite E (GPa)	Flexural modulus of the Matrix E_m (GPa)	Maximum stress of the composite σ_{max} (MPa)	Maximum stress of the Matrix $\sigma_{max,c}$ (MPa)
7	2	120	30
Stacking sequence	$[0/\pm 45/90]_{2T}$		
Other information			$T_g = 105^0C$
Material 3		Carbon – Epoxy	
Flexural modulus of the composite E (GPa)	Flexural modulus of the Matrix E_m (GPa)	Maximum stress of the composite σ_{max} (MPa)	Maximum stress of the Matrix $\sigma_{max,c}$ (MPa)
125	3	1000	80
Stacking sequence	$[0/90]_{2S}$		
Other information			$T_g = 150^0C$

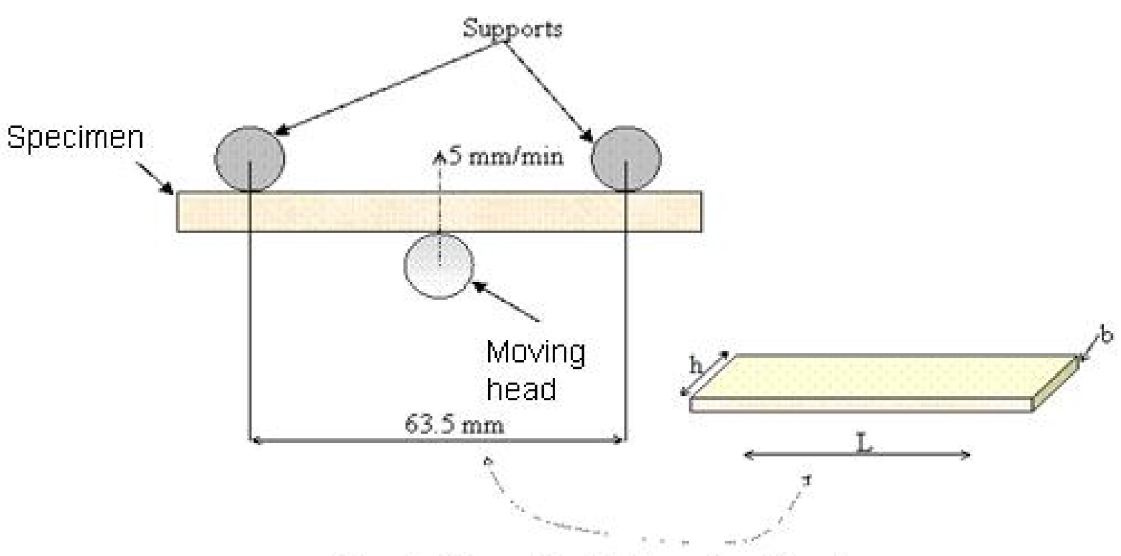

Fig. 4. Three Point Bending Test

RESULTS AND DISCUSSION:

Experimental results along with respective predictions based on the Residual Property Model (RPM) which will be presented and discussed in the next paragraph are shown in Figs. 5, 6, 7, 8, 9 and 10.
All points seem to follow the same degradation path. The material reaches it equilibrium state from the first cycles. It is significant that the value of flexural modulus drops about 60%. The value of σmax drops to 55% of its initial value. However, it is not reduced as fast as the flexural modulus. This "delay" is probably caused by the post-curing phenomena.
In figs 7 and 8 it is clear that when material 2 is tested in a wider temperature range, in contrast with material 1, its degradation is greater. Obviously, in the case of high temperature loading (T max = 124oC > Tg), the energy threshold is overridden even from the first loading cycle, where a significant reduction is observed, mainly in the value of the material strength (Fig. 8).
Finally, material 3 shows a behavior quite different from the other materials (Figs 9 and 10). Flexural modulus degradation (about 60%) is relatively slow and independent from the temperature range, like material 1. This leads to the conclusion that the matrix plays an important role for this degradation especially through the fiber-matrix adhesion bond quality. On the other hand, material strength rather increases than decreases. This should be happening due to post-curing effects; the high temperature should affect only the structure of the resin matrix, the fibers should be intact; otherwise, great changes would be noticed at both flexural modulus and material strength.

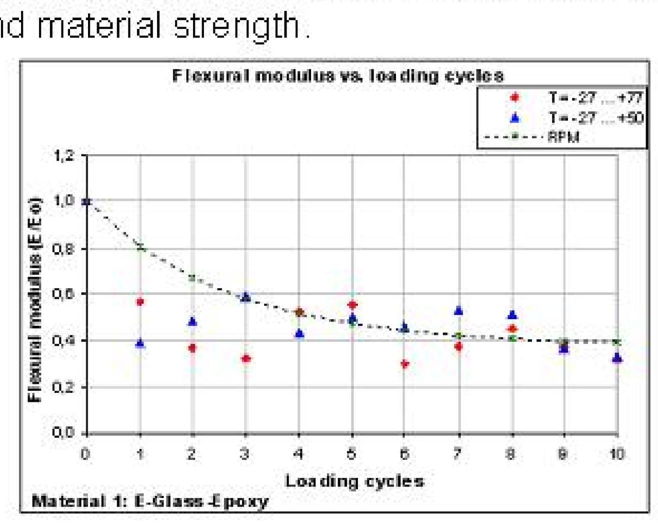

Figure 5. Flexural modulus vs. loading cycles for material 1

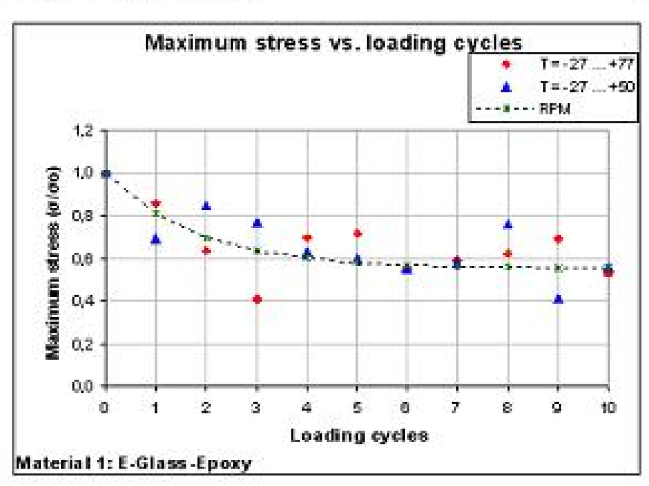

Figure 6. Maximum stress vs. loading cycles for material 1

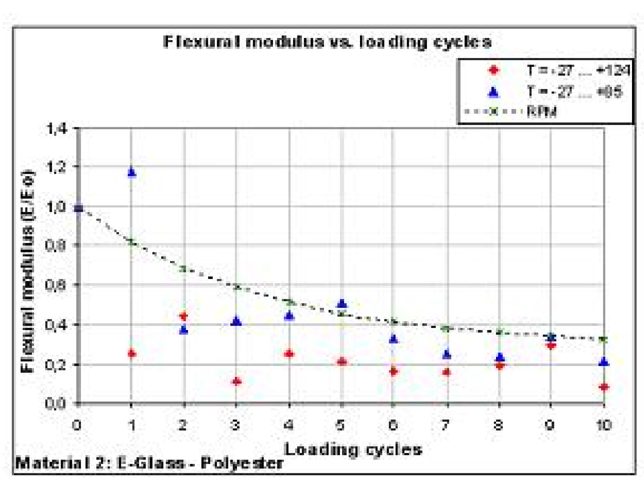

Figure 7. Flexural modulus vs. loading cycles for material 2

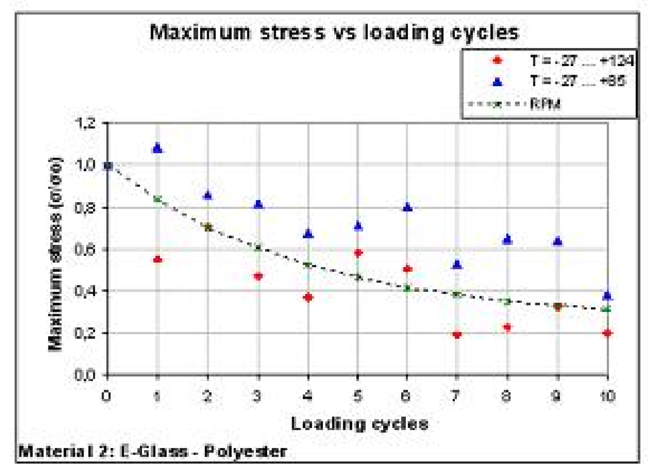

Figure 8. Maximum stress vs. loading cycles for material 2

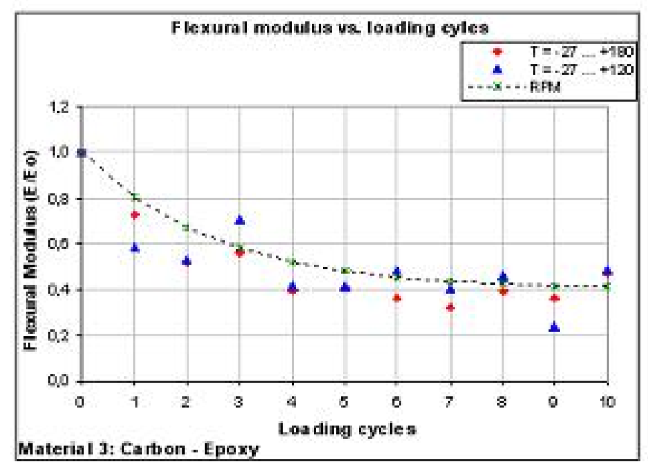

Figure 9. Flexural modulus vs. loading cycles for material 3

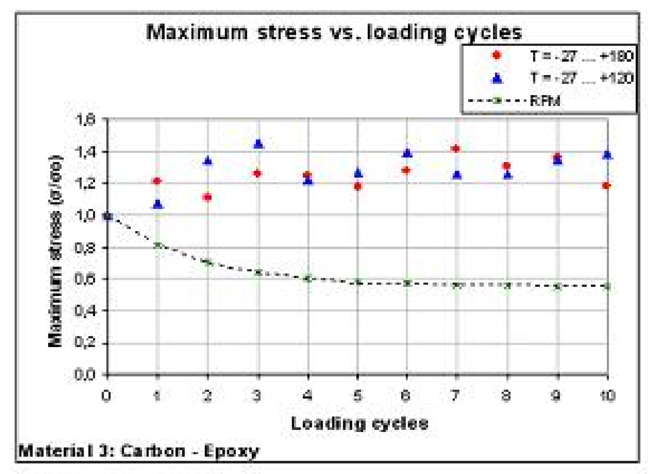

Figure 10. Maximum stress vs. loading cycles for material 3

RESIDUAL PROPERTY MODEL (RPM)

In each diagram, apart from the material properties, a curve called 'RPM' is plotted, too. RPM is a model developed by the authors, which actually predicts the degradation of material properties due to damage. The basic equation for the prediction is:

$$\frac{P_r}{P_o} = s + (1-s)\cdot e^{-SM} \quad , \; s = \frac{P_\infty}{P_o} \qquad \{2\}$$

Where:
Pr: The residual property. Pr should be replaced by the flexural modulus (E) or the maximum strength (σmax) respectively. Practically, this is the prediction of the measured property after every loading cycle.
Po: The property of a "virgin" specimen, in order to be accurate, Po was measured from the so called "reference specimens". It is actually the E and/or the σ_{max} for 0 loading cycles.
P_∞: The residual property of the material after – theoretically – infinite number of loading cycles.
M: The degradation parameter. For the experiments described in this paper, M is the number of the loading cycles.
It is obvious from the Diagrams in Figs 5-9 that the RPM fits well the experimentally derived degradation variation. The divergence that appears in Diagram in Fig. 10 must be due the post-curing and stress relief effects described previously. From the definition of RPM it is obvious that the only input required for its application is the reference material properties, the degradation parameter and the P_∞ value which corresponds to the P-value of an already used under the given conditions material after an infinite number of cycles. When using RPM, the selection of the degradation parameter M should be done very carefully. M has to be a parameter that includes all – or at least most of the – damage mechanisms. The better the selection of M, the more accurate results will derive from RPM.
RPM has also been successfully used to predict the residual properties variation of different materials subjected to a series of different types of applied loads with very good results; among others: mechanical fatigue, erosion, single impact, repeated impact, water absorption, hygrothermal fatigue, etc.[4].

CONCLUSIONS

The general conclusion that could be extracted from the present work is that thermal fatigue should be taken into account during the design of a composite structure, especially when thermal shock conditions should occur. The degradation caused to a material is significant even for low-cycle fatigue. Most affected seems to be the matrix; thermoplastic matrices should be avoided if possible, since their degradation is not only faster, but also greater. Considering the RPM, although it is in a development and testing phase yet, it may be used to provide an initial approach of a material degradation due to damage. Extreme attention must be paid to the selection of the degradation parameter M, as it is critical for its accuracy.

Acknowledgments
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