MEASUREMENT OF RESIDUAL STRESS IN UNIDIRECTIONAL GFRP

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1 Introduction

The process plant environment makes extensive use of glass fibre reinforced plastic (GFRP) due to its excellent corrosion resistance. GFRP is, however, susceptible to environmentally assisted cracking. In this situation, the rate of crack growth is significantly affected by the stress state, comprising both stress due to mechanical loading and as well as residual stress. Design codes limit the former stress to fairly low values, and consequently residual stresses can often be of a similar magnitude[1]. Neglecting residual stresses, therefore, completely misrepresents the state of stress and consequently the rate of crack growth. It is thus necessary to be able to assess the state of residual stresses within a GFRP component.

A wide variety of methods have been employed to measure these stresses in typical structures, but very few techniques are available to measure the state of stress that occurs in the simplest of composite configurations – the unconstrained unidirectional laminate. The structure is in an overall state of equilibrium and is macroscopically homogeneous. Consequently, techniques that locally relieve the residual stresses while measuring the response on a macroscopic scale (such as hole drilling and slitting) do not respond to the presence of residual stresses. Techniques that directly measure intermolecular stresses (such as Raman spectroscopy and neutron diffraction) also cannot be successfully employed on GFRP since neither the fibre nor the polymer matrix has a crystal structure.

Relieving the residual stresses in the entire laminate simultaneously, however, allows a significant response to develop which can be readily measured using fairly simple equipment. This work presents the method for performing such measurements and provides typical results.

2 Theoretical Background

The new technique relies on the exploitation of the low stiffness of a polymer matrix at high temperatures. As the temperature of a polymer system increases past the glass transistion temperature (T_g), the modulus decreases until it becomes essentially negligible and is unable to apply significant restraint to the fibres. The effective coefficient of thermal expansion (CTE) of the system therefore tends towards the value of unloaded fibres irrespective of the initial state of stress in the system. It is this phenomenon that provides a basis for determining the absolute state of residual stress in a GFRP laminate.

When the resin system is no longer able to restrain the glass fibre, the strain-temperature curve defines the locus of zero stress in glass fibre. Since the expansion of unloaded glass fibres is essentially linear with temperature this locus can be easily extended back to lower temperatures. Measurement of the strain variation relative to this locus provides an absolute value of strain, and hence stress, within the glass fibres. Since the overall laminate is in a state of self-equilibrium, the stress within the polymer system can be readily determined if the volume fractions of the two constituents are taken into account.

The process of heating the composite material can cause the strain measurements to be affected by a range of additional effects including inelastic flow. None of them, however, affect either the path taken at low temperatures or that taken at high temperatures. Consequently, measurement of the state of residual stress at low temperatures is unaffected by these effects.

3 Experimental Approach

Two sets of symmetrical GFRP specimens with 40% nominal fibre volume fraction were manufactured using Derakane Momentum 411-350 vinyl-ester resin and 400 tex unidirectional E-glass rovings. The rovings of one set of specimens,

designated as "Unloaded", were tensioned just sufficient to prevent fibre movement during resin infusion. The rovings of the other set of specimens, designated as "Prestressed", were loaded in tension prior to resin infusion. Fibre tension was removed from both sets of specimens after post-cure at 92°C.

The thermal response of the specimens was measured while they were heated in an oven at a rate of 6°C per hour. Measurement of thermal strain was accomplished using a dilatometer built around a Kaman Measuring Systems 1UEP non-contact displacement sensor coupled with a KD2300 oscillator/demodulator.

4 Results and Discussion

Fig. 1. shows that both sets of specimens exhibit regions of linearity at low temperatures and again at temperatures greater than about 100°C. The measured coefficients of thermal expansion at high temperatures all lie between 4.1με/°C and 6.1με/°C and are thus in reasonable agreement with the range of 4.7 με/°C - 5.4 με/°C quoted for E-glass fibre[2,3]. The underlying basis for the technique is thus validated.

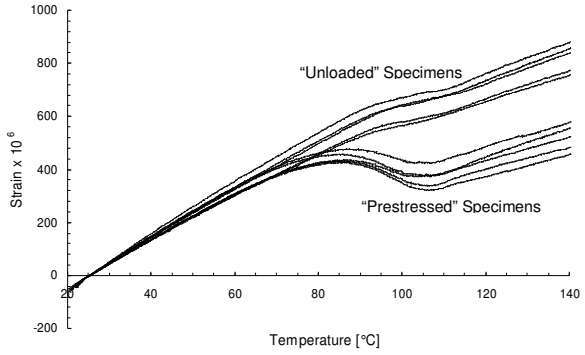

Fig. 1. Thermal strain vs. temperature

Between the regions of linearity the response of the two sets of specimens is quite different. The "Unloaded" specimens have a linear response up to a temperature around that of post-cure whereas significant non-linearity is observed in the "Prestressed" specimens. This can be attributed to the release of internal stresses as the modulus of the resin system drops.

This effect is seen more clearly in Fig. 2. where the residual strain in the glass fibres is plotted as a function of temperature. It is seen that the "Prestressed" specimens are essentially unloaded at room temperature and that the fibre strain, and stress, becomes increasingly tensile as the temperature increases. The CTE of the resin system is greater than that of the fibres and thus the resin applies a tensile load to the fibres as the temperature increases.

Eventually the residual stresses in the resin become high enough and the resin modulus low enough that the resin is unable to support the compressive load applied to it by the fibres. The strain in the fibres therefore decays to zero at high temperatures.

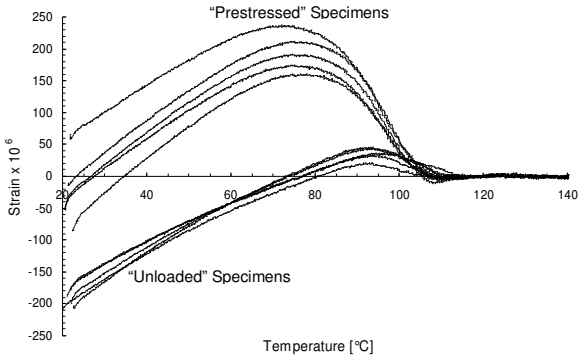

Fig. 2. Residual strain in glass fibres vs. temperature

The response of the "Unloaded" fibres is far more linear because the load in the resin system is significantly lower at high temperatures when the resin modulus is reduced. In this case the residual strain in the fibres is approximately -200 με, or 14MPa, at room temperatures.

5 Conclusions

A novel method for measuring the residual stresses in unidirectional GFRP has been presented. The technique relies on the modulus of the resin system becoming negligible at high temperatures. The method is based on measurement of elastic strains in the fibres, and consequently is unaffected by inelastic processes in the resin system.

References

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