International Journal of ChemTech Research
CODEN(USA): IJCRGG ISSN : 0974-4290
Vol.1, No.3 , pp 470-475, July-Sept 2009

Comparison of Mechanical Properties of Glass-Polyester Composites Formed by Resin Transfer Moulding and Hand Lay-Up Technique

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Abstract: Flexural properties of continuous random glass-polyester composites formed by resin transfer moulding (RTM) and hand-lay up (HLU) moulding have been studied to determine the effects of glass content, composite thickness, reinforcement geometry and type of fabrication on damage developed during flexure tests. Flexural parameters derived from the force-deflection data of composites containing 20 % and 30 % continuous random fibre showed mean values of flexural strength and modulus of 84 MPa and 7 GPa and 110 MPa and 10 GPa for the HLU composites (Cx20 and Cx30 test groups), respectively and similarly, the mean values of flexural strength and modulus of 96 MPa and 7.6 GPa and 120 MPa and 11 GPa for the RTM composites (Cx20 and Cx30 test groups), respectively. Strain values both at maximum-load and failure were also determined. The failure strains of the two sets of composite series were relatively constant. Thus, both types of composite series appeared to fail at a critical strain (ε_c) value. The damage developed during the test was monitored on the side of each polished beam using an optical microscope. The damage generated in the composites exhibited matrix cracking on the lower face of the specimens followed by fibre fracture resulting from the bending stresses rather than delamination.

Keywords: Continuous Random Composites, Flexural Test, Resin Transfer Moulding, Onset of Damage, Hand Lay-Up Moulding.

Introduction

Bending stresses are developed in structures such as plates or shells due to a variety of loading situations in service. It is desirable to determine their behaviour and properties, usually using beam flexure tests. However, the results of flexure tests can provide a first check when attempting to usefully apply tension and compression test data to structural designs. Moreover, the scale effect must be understood if different thicknesses of laminates are involved and if test data obtained using small-scale specimens are used to predict the response of full-scale structures [1-10]. This paper reports on the flexural behaviour of continuous random glass-polyester laminates, and the effects of moulding method, glass content, specimen thickness, and their mode of failure, on damage developed during flexure test.

Experimental

Materials. The polymer matrix used was a low-viscosity unsaturated polyester resin of the orthophthalic type (Boytek Ltd, Turkey), cured using a cobalt/MEKP curing system (Merck, Germany). The glass reinforcements used were a continuous random fibre mat (CNBM Ltd, China) treated with a high solubility binder. It had a nominal areal weight of ≈ 600 g m^{-2} and thickness of ≈ 1.60 mm.

Laminate Moulding. To mould laminates by hand lay-up (HLU) technique, frame moulds of 40 cm x 30 cm were used to produce laminates of nominal thicknesses of 4 and 6 mm (Table 1). The weight of glass in the mould was calculated to give the nominal fibre volume fractions (V_f) of 0.20 and 0.30 for the laminates moulded. To mould laminates by resin transfer moulding (RTM), a Plastech Thermoset Tectonics Hypaject-3 machine was used to mould laminates of nominal thicknesses of 4 and 6 mm (Table 1). Similarly, the weight of glass in the mould was calculated to give the nominal fibre volume fractions (V_f) of 0.20 and 0.30 for the laminates moulded. In RTM, all laminates were moulded using an injection pressure of 0.30 MPa and a mould temperature of 40 ^{0}C. After fabrication all laminates with required thickness were then left to cure for several hours at room temperature. Experimental values of V_f and void content V_v in the composites were determined by volatizing the matrix from specimens of known volume in a furnance (700 ^{o}C for 3 h) and calculated V_f and V_v from the remaining weight fraction of the glass using the densities of the glass and the matrix. Typically, V_f values were within the range ±3 and ±2 of the nominal value, as shown in Table 2 for the HLU and RTM, respectively and values of V_v were <3.5% and <2.2% for laminates prepared by HLU and RTM, respectively. Experimental values of V_f and V_v were determined, using;

$V_f = (M_f / \rho_f) / V_c$
where M_f is the mass of fibre, V_c is the volume of the composite specimen and ρ_f is the density of the glass fibre (2.56 g cm^{-3})

$V_v = 1 - [(M_f / \rho_f + M_m / \rho_m) / V_c]$
where M_m is the mass of matrix lost during burn-off test and ρ_m is the density of the matrix (1.20 g cm^{-3}).

Flexural Testing of Composites. The flexural properties of the composites were determined in three-point bending. At least five rectangular beam specimens were tested for each composite at a support span-to-depth ratio of 16:1 according to ASTM, D790M [11]. Tests were conducted at 22±2 ^{0}C, using a Instron 6025 testing machine. Specimens were centre loaded in three-point bending as a simply supported beam, using 3 mm diameter supports and loading bar. The damage developed was monitored on the side of each polished beam using an optical microscope. The maximum tensile stress in the outer fibres was calculated according to [11];

$\sigma_m = 3FL / 2bd^2$

where F is the force at a given point on the Force-deflection curve, L is the support span and b and d are the width and depth of the beam, respectively. The modulus of elasticity was calculated according to;
$E = L^3 m / 4 bd^3$
where m is the slope of the tangent to the initial straight-line portion of the force-deflection curve. The maximum tensile strain in the outer fibres was calculated according to;
$\varepsilon = 6Dd / L^2$
where D is the deflection of the beam at a given point on the load-deflection curve.

Results and Discussion

Force-deflection data and damage development for HLU and RTM composites. Typical force-deflection data obtained for the continuous random composites with volume fractions of 0.20 (Cx20 test groups) and 0.30 (Cx30 test groups) are shown in Figure 1 and Figure 2 for the HLU and RTM composites, respectively. The flexural parameters [11] calculated from these curves are shown in Table 3 and Table 4 for the HLU and RTM composites, respectively.

The force-deflection curves for the continuous random composites (Cx20 and Cx30 test groups) exhibit two deformation regions; an initial linear-elastic region followed by a non-linear deformation region, the latter being initiated by the formation of a large transverse crack under the point of loading on the lower face of the specimen due to tensile stresses (see Figure 3A). In fibre-reinforced composite materials, the matrix material is much weaker than the fibre and is probably weaker than the interfacial bond as well, in terms of strength. Thus, failure usually may occur in the form of matrix cracking prior to delamination or fibre fracture, as it was observed in the case of both HLU and RTM laminate composites. However, as level of loading increased crack growth soon resulted in the development of a large damage zone (see Figure 3B) through the composite thickness, via translaminar fibre fracture, rather than delamination, generating a significant drop in load at relatively low strains [4,10,12]. The load drop associated with critical failure of a specimen depends on the method of moulding, specimen thickness and the fibre volume fraction (see Table 3 and Table 4 for the HLU and RTM composites, respectively). From Table 3 it can be seen that mean values of flexural strength and modulus were of 84 MPa and 7 GPa and 110 MPa and 10 GPa for the HLU composites (Cx20 and Cx30 test groups), respectively and similarly, from Table 4 it can be seen that mean values of flexural strength and modulus were of 96 MPa and 7.6 GPa and 120 MPa and 11 GPa for the RTM composites (Cx20 and Cx30 test groups), respectively. From Table 3 and Table 4 it can be noted that laminate composites prepared by HLU have lower values of flexural strength and modulus than equivalent RTM laminate composites, and also lower strain values both at maximum load and failure. A comparison of mean flexural parameters obtained for both the HLU and RTM laminate composites is shown in Table 5. The lower values of flexural strength and modulus and strain of HLU laminate composites appears to be due mainly to the method of moulding which resulted in higher void contents V_v <3.5% than RTM laminate composites with void contents V_v <2.2%. In composite materials, flaws at microscopic level appear in the form of voids in the matrix, at the fibre-matrix interface and in particular at fibre cross-overs, and at masroscopic level in the form of possible non-uniform ply spacings [4]. Therefore, the differences in the measured values for both HLU and RTM specimens is a reflection of microstructural inhomogeneity, which is often described by the volumetric distribution of inherent flaws introduced during fabrication. Within each test groups of laminate composites the modulus is similar, because the composite flexural modulus is dominated by the fibre volume fraction. The values of flexural strength generally increased with the thickness of the composite, but the failure strains of both HLU and RTM composite were relatively constant at ≈ 0.016 (SD 0.0028) and ≈ 0.019 (SD 0.0028), respectively. Thus, although the specimens of varying thickness failed at different deflections (Figures 1 and 2) and stresses (Tables 3 and 4) the onset of failure would appear to be conditional on attaining a critical strain (ε_c) on the lower face of the specimen with ε_c varying with type of fabrication.

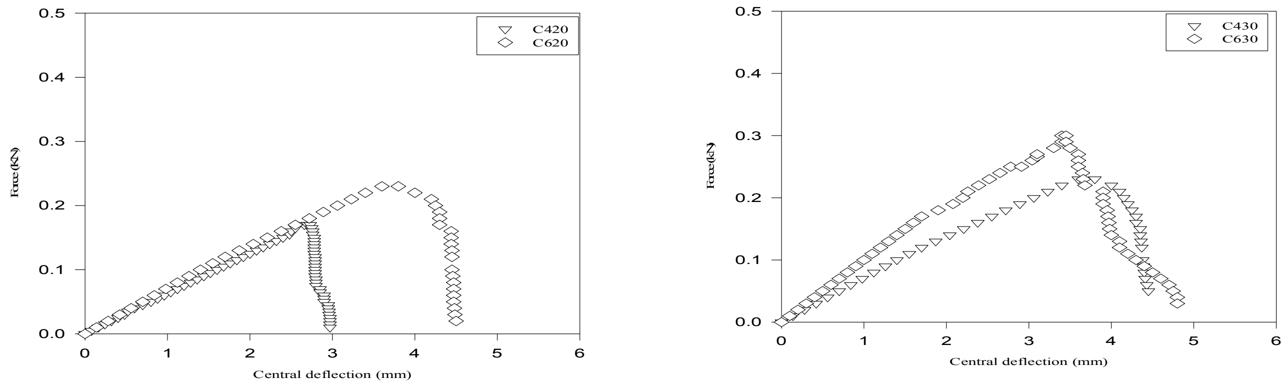


Figure 1. Typical force versus deflection curves for continuous random composites (formed by HLU) with V_f = 0.20 (Cx20) and V_f = 0.30 (Cx30). The first number in the sample code denotes the nominal thickness of the specimens (in mm), and the second number denotes the nominal fibre volume fraction.

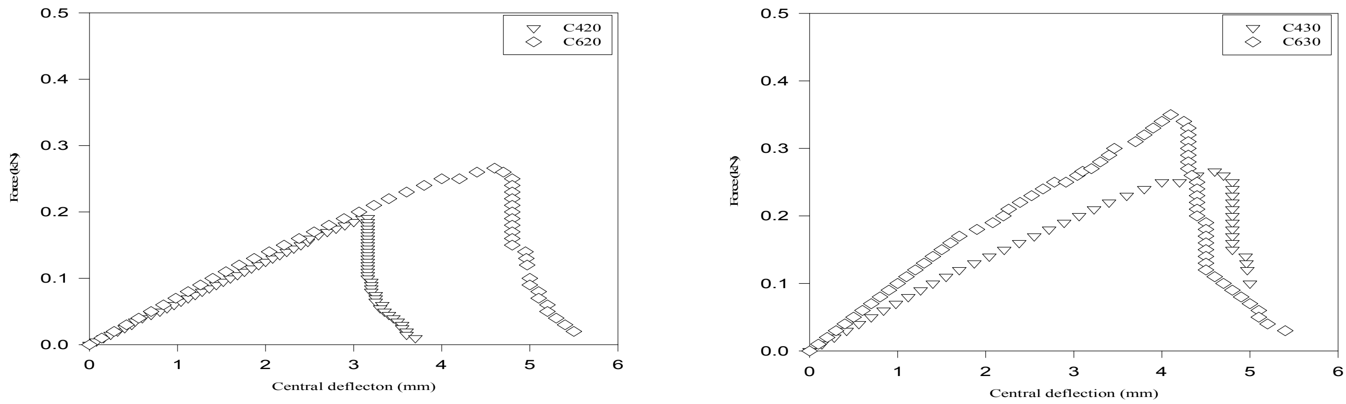
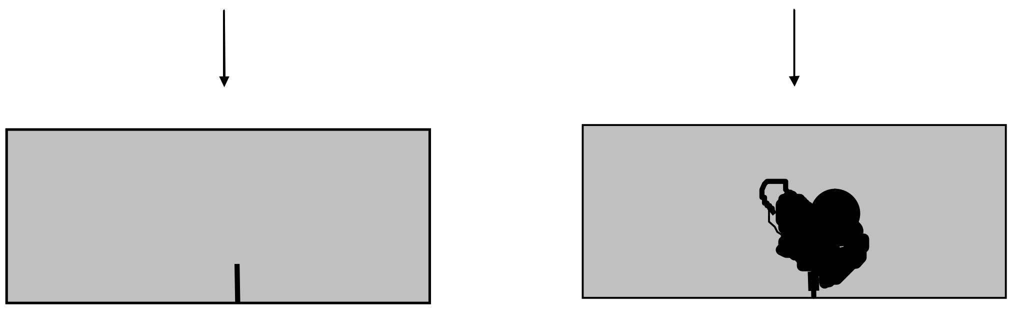


Figure 2. Typical force versus deflection curves for continuous random composites (formed by RTM) with V_f = 0.20 (Cx20) and V_f = 0.30 (Cx30). The first number in the sample code denotes the nominal thickness of the specimens (in mm), and the second number denotes the nominal fibre volume fraction.



(A) **(B)**

Figure 3. Typical damage development in a continuous random composite observed using optical microscopy; (A) Initial transverse matrix cracking and (B) final damage zone formed for both HLU and RTM specimens.

Table 1. Mean values of thicknesses for glass-polyester composites prepared by HLU and RTM (± 95% confidence limits)

Code[1]	Actual laminate thickness[2] (mm) for HLU	Actual laminate thickness[2] (mm) for RTM
C420	4.30±0.04	4.10±0.02
C430	4.40±0.05	4.20±0.03
C620	6.40±0.06	6.20±0.02
C630	6.45±0.04	6.15±0.03

[1] Coding: C = continuous random fibre, 1st digit indicates the nominal thickness (mm) and the next two the nominal V_f. [2] Mean values with standard deviations.

Table 2. Mean values of glass volume fractions for glass-polyester composites prepared by HLU and RTM (± 95% confidence limits)

Code	Fibre volume fraction (V_f) for HLU	Fibre volume fraction (V_f) for RTM
C420	21±1.6	19.7±1
C430	31.5±0.7	30.2±0.9
C620	21±0.9	20.0±0.8
C630	31.2±3	30.3±2

Table 3. Mean flexural parameters derived from the force-deflection data (± 95% confidence limits) for the HLU composites

Code	Maximum Stress σ_m (MPa)	Flexural Modulus E (GPa)	Strain at Max. Load ε_{Fm} (%)	Strain at Failure ε_c (%)
C420	80±5.0	6.50±0.2	1.8±0.2	2.0±0.3
C620	84±3.0	7.0 ±0.4	1.6±0.3	1.7±0.2
C430	98±4.0	9.40±0.6	1.3±0.1	1.6±0.3
C630	106±3.0	10.0±1	1.1±0.2	1.3±0.2

Table 4. Mean flexural parameters derived from the force-deflection data (± 95% confidence limits) for the RTM composites

Code	Maximum Stress σ_m (MPa)	Flexural Modulus E (GPa)	Strain at Max. Load ε_{Fm} (%)	Strain at Failure ε_c (%)
C420	90±3.0	7.0±0.5	2.0±0.5	2.3±0.1
C620	96±5.0	7.60±1	1.8±0.4	2.0±0.3
C430	110±6.0	10.0±0.5	1.6±0.3	1.9±0.4
C630	120±5.0	10.70±0.3	1.4±0.3	1.7±0.3

Table 5. Comparison of mean flexural parameters for the RTM and HLU composites

Code	Maximum Stress σ_m (MPa)	Flexural Modulus E (GPa)	Strain at Max. Load ε_{Fm} (%)	Strain at Failure ε_c (%)
C420 (RTM)	90	7.0	2.0	2.3
C420 (HLU)	80	6.50	1.80	2.0
% increased	12.5	7.69	11.11	15
C430 (RTM)	110	10.0	1.60	1.9
C430 (HLU)	98	9.40	1.30	1.6
% increased	12.24	6.38	23.07	18.75
C620 (RTM)	96	7.60	1.80	2.0
C620 (HLU)	84	7.0	1.60	1.7
% increased	14.28	8.57	12.50	17.64
C630 (RTM)	120	10.70	1.40	1.70
C630 (HLU)	106	10.0	1.10	1.30
% increased	13.20	8.0	27.27	30.76

Conclusions

1. Glass-polyester composites were formed by HLU and RTM, containing continuous random reinforcement, all exhibited significant damage as a result of flexural test.
2. Both HLU and RTM laminate composites suffered matrix cracking and exhibited mainly fibre fracture.
3. HLU method was found to exhibit lower values of flexural properties than RTM method. The mean values of flexural parameters obtained for the HLU laminate composites (Cx20 and Cx30 test groups), were slightly lower than RTM laminate composites (Cx20 and Cx30 test groups), due to higher void contents obtained in the HLU specimens.
4. The laminate composites of varying thickness failed at different deflections and stresses and the onset of failure would appear to be conditional on attaining a critical strain (ε_c) on the lower face of the specimen with ε_c varying with type of fabrication.

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