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Effects of Laminate Thickness and Ply-Stacking Sequence on the Mechanical Properties and Failure Mechanism of Unidirectional Glass-Polyester Composites

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Abstract: Mechanical behaviour of unidirectional glass-polyester composites formed by hand lay-up moulding (HLU) have been studied to identify performance differences of composites with different glass lay-ups and laminate thicknesses during flexure and tensile testing. Simple energy model was used to provide a relationship between tensile parameters and relative impact energy performance of these composites. The damage generated in the composites exhibited matrix cracking on the lower face followed by the coalescence of delaminations formed within the reinforcing plies.
Keywords: Unidirectional Composites, Flexural Test, Hand Lay-up Moulding, Delamination Damage.

Introduction

Fiber-reinforced composite laminates are commonly used in the construction of aerospace, civil, marine, automotive and other high performance structures due to their high specific stiffness and strength, excellent fatigue resistance, longer durability as compared to metallic structures, and ability to be tailored for specific applications. Composite materials can be tailored to meet the particular requirements of stiffness and strength by altering lay-up and fiber orientations. The ability to tailor a composite material to its job is one of the most significant advantages of a composite material over an ordinary material. So the research and development of composite materials in the design of mechanical, aerospace, and civil structures has grown tremendously in the past few decades. Composites based on thermoplastics and thermosetting plastics, the most widely used reinforcements in load bearing structures are glass fibres, although carbon fibres and aramid fibres are used for high performance applications. In polymer composites the fibres are stiffer and stronger than the polymer matrix. Thus, the fibres act as load bearing reinforcement and the matrix acts to protect the fibres, maintain the required fibre orientation, and to transfer external loads to the fibres [1-8]. This paper studies the mechanical properties of unidirectional glass-polyester composites formed by HLU, and their mode of failure, especially on the effects of fibre lay-ups, and composites thicknesses on damage developed during flexural test.

Experimental

Materials

Polymer matrix. The resin used for moulding sheets of laminate compositess was based on a low-viscosity unsaturated polyester resin of the orthophthalic type (UP-973 ST V, Reefiran Polimer Khodrang, Iran). It is especially suitable for hand lay-up (HLU) moulding due to its low viscosity and non-thixotropic nature.

Glass Fibre Reinforcements. The type of E-glass fibre reinforcements used to produce laminate composites was unidirectional (0^0) fibre reinforcement (L400E10A, Metyx composites of Turkey) with roving tex of 900 warp/200 weft with a nominal areal weight of 409 g m^{-2}.

Curing System. The curing agent used was a cobalt octoate accelerator (Unidry Co 12, Pamukkale Company of Turkey)/methyl-ethyl-ketone peroxide (MEKP) (EPerox-P, Pamukkale Company of Turkey) initiator system of 0.03/2.0 weight ratio, respectively. The cobalt accelerator was a solution of cobalt salts diluted in styrene and white spirit of 12% (w/w) cobalt content, which was mixed into the resin first, before the MEKP initiator. The initiator was a solution of MEKP diluted in dibutyl phthalate of 50% (w/w) MEKP content. This cure system was chosen to allow cure to occur in a reasonable time, in order to allow sheets of resin to be moulded before gelation occurs. To determine reactivity a pre-mixed resin (0.03 g accelerator/2 g MEKP and 100 g resin) was poured into a thermoset cup and allowed to react from an initial mould temperature of 25 ^{0}C. Chemical activity of the resin system during its transition from liquid to a solid was monitored to determine the gelation time ≈ 27 minutes. Experimental values of fibre mass fraction, M_f and void content, V_v in the composites were determined by burning the matrix from specimens of known volume in a furnance (750^o C for 2.5 h) and calculated M_f and V_v from the remaining weight fraction of the glass using the densities of the glass fibre and the matrix. Typically, M_f values were within the range ±3 of the nominal value (Table 1) and values of V_v were <3%. Experimental values of M_f and V_v were determined, using;

Mf = (Mc-Mm) / Mc (1)

where Mc is the mass of the composite, and Mm is the mass of the matrix after burn-off test.

Vv = 1- [(Mf / rf + Mm / rm) / Vc] (2)

where Mf is the mass of the fibre after burn-off test and rm is the density of matrix (1.2 g cm-3), rf is the density of glass fibre (2.55 g cm-3) and Vc is the volume of the composite sample.

Moulding. A hand lay-up (HLU) technique was used to mould sheets of various thicknesses in different lay-ups (Table 1).

Mechanical Testing. Tensile data for the laminate composites were obtained at 25±2 ^{0}C using a Santam, universal tensometer (15T). Tests were conducted on at least five specimens (dumb-bell specimens), according to ASTM D 3039 [9], at a cross-head rate of 2 mm min^{-1}.

Flexural Testing. The flexural properties for the laminate composites were determined in 3-point bending. At least five rectangular beam specimens were tested at a support span-to-depth ratio of 16:1. Tests were conducted at 25±2 ^{0}C, using a Santam, universal tensometer (15T). Specimens were centre loaded in 3-point bending as a simply supported beam, using 4 mm diameter supports and loading bar. The damage developed was monitored on the side of each polished beam using a camera (magnification 10x). The flexure parameters were calculated according to ASTM, D790M [10].

Table 1. Glass-polyester composites produced by HLU (± confidence limits).

Sample No	Fibre Lay-ups	Nominal Laminate Thickness (mm)	Actual Laminate Thickness (mm)	Nominal Fibre Mass Fraction (M_f)	Actual Fibre Mass Fraction (M_f)
1	$[(0/90/+45)_2]_s$	5	5.67±0.04	0.30	29.75±1.6
2	$[(90/0/+45)_2]_s$	5	5.62±0.01	0.30	29.30±2.7
3	$[(+45/-45/0)_2]_s$	5	5.66±0.20	0.30	29.85±1.8
4	$[(0/90/+45/-45)_2]_s$	7	6.81±0.05	0.30	29.85±1.3
5	$[(90/0/+45/-45)_2]_s$	7	6.92±0.03	0.30	29.93±2.5
6	$[(+45/-45/0/90)_2]_s$	7	6.50±0.05	0.30	31.50±2.2

Results and Discussion

Tensile Tests. Typical load-extension data obtained for the unidirectional composites with mass fractions of 0.30 with 5 mm and 7 mm nominal thicknesses are shown in Figure 1 and Figure 2, respectively. The tensile parameters derived from these curves (using ASTM D 3039) are shown in Table 2. Impact energy values derived from tensile testing for the composites with different thicknesses are shown in Table 3.

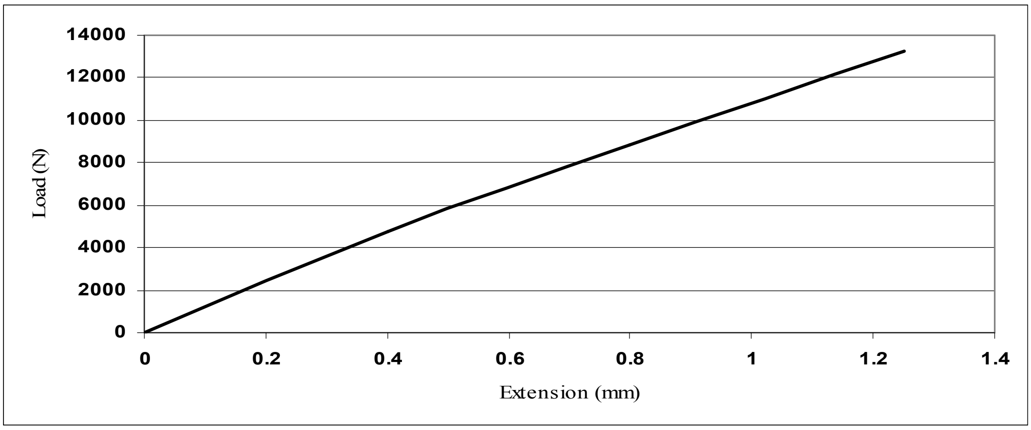


Figure 1. Typical load-extension curve for 5 mm composites with different lay-up.

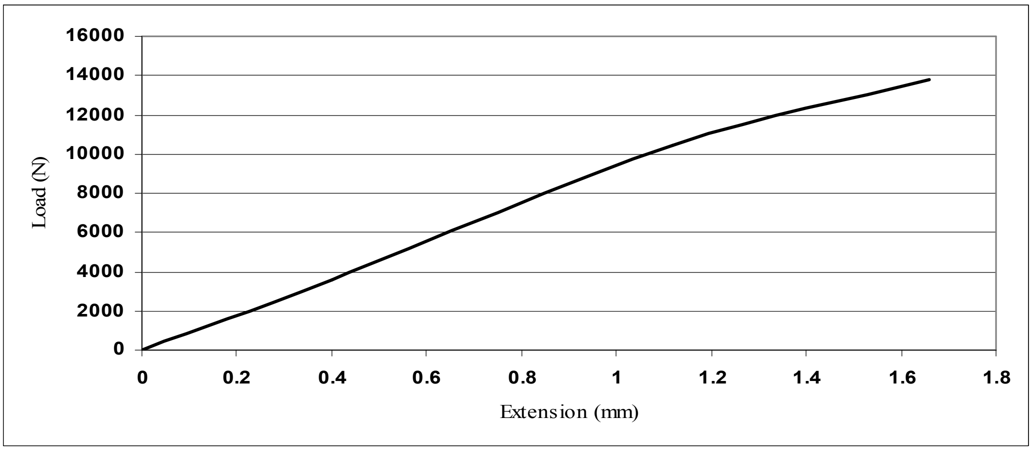


Figure 2. Typical load-extension curve for 7 mm composites with different lay-up.

Table 2. Mean tensile parameters derived from load-extension curves (± confidence limits).

Sample No	Fibre Lay-ups	Tensile Strength at Failure (MPa)	Tensile Modulus (GPa)	Tensile Strain at Failure (%)
1	$[(0/90/+45)_2]_s$	117±2	5.0±0.6	2.3±0.5
2	$[(90/0/+45)_2]_s$	82±4	4.6±0.3	1.7±0.2
3	$[(+45/-45/0)_2]_s$	114±5	4.5±0.1	2.8±0.3
4	$[(0/90/+45/-45)_2]_s$	170±3	4.3±0.4	1.7±0.3
5	$[(90/0/+45/-45)_2]_s$	115±6.6	5.0±0.2	2.4±0.5
6	$[(+45/-45/0/90)_2]_s$	142±5.5	4.7±0.2	2.7±0.1

Table 3. Mean impact energy parameters derived from tensile testing (± confidence limits).

Sample No	Actual Laminate Thickness (mm)	Tensile Strength at Failure (MPa)	Tensile Modulus (GPa)	Impact Energy (KPa.m)
1	5.67±0.04	117±8	5.0±0.6	16.37±0.5
2	5.62±0.01	82±6	4.6±0.3	8.21±0.4
3	5.66±0.20	114±5	4.5±0.1	15.50±0.2
4	6.81±0.05	170±4	4.3±0.4	45.76±0.7
5	6.92±0.03	115±5	5.0±0.2	18.30±0.8
6	6.50±0.05	142±9	4.7±0.2	27.88±0.3

The curves for the unidirectional composites under tensile testing exhibit two deformation regions; i.e. an essentially linear elastic region followed by a non-linear stable deformation region. The onset of non-linear deformation behaviour was observed to coincide with the debonding of the fibre-matrix interface followed by fibre fracture. The mean tensile strength values obtained vary with composite thicknesses and fibre lay-ups for which the composite with $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups show highest values of tensile strength which are 117 MPa and 170 MPa for 5 mm and 7 mm composites, respectively (Table 2). Within each composite series, similar modulus are observed, given slight variations in the M_f and experimental scatter, because the composite tensile modulus is dominated by the fibre mass fraction. The failure strains of the composites with varying thicknesses failed relatively at similar values (Table 2). In the case of normal plate impacts, Coppa et al [11] suggested that, as a first approximation, plate impact energy is related to quasi-static flexural failure energy. For a beam type structure, this suggests that the impact energy should be proportional to the quantity $\sigma\varepsilon$ or σ^2/E, where σ and ε are the maximum stress and strain of the beam at failure and E is the modulus. Wardle and Tokarsky [12] have expanded this approach and suggested that the impact energy should be proportional to $t\sigma^2/E$, where t is the specimen thickness and σ and E are the tensile strength and stiffness rather than flexural. The calculated $t\sigma^2/E$ parameters are shown in Table 3 which are only qualitative values derived from tensile testing. As can be seen from Table 3, the calculated impact energy parameters show similar trends to that of tensile parameters for which $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups show highest values of impact energy for 5 mm and 7 mm composites, respectively.

Flexural Tests. Typical load-deflection data obtained for the unidirectional composites with mass fractions of 0.30 with 5 mm and 7 mm nominal thicknesses are shown in Figure 3 and Figure 4, respectively. The flexural parameters derived from these curves (using ASTM D 790) are shown in Table 4.

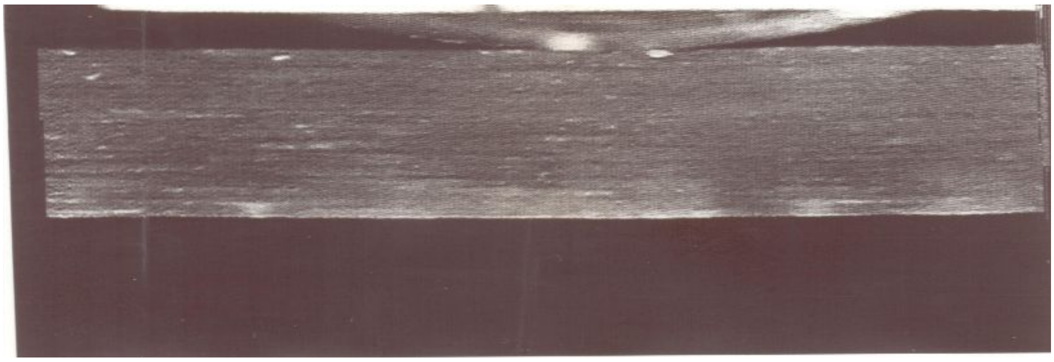
Figure 3. Typical load-deflection curve for 5 mm composites with different lay-up.

Figure 4. Typical load-deflection curve for 7 mm composites with different lay-up.

Table 4. Mean flexural parameters derived from load-deflection curves (± confidence limits).

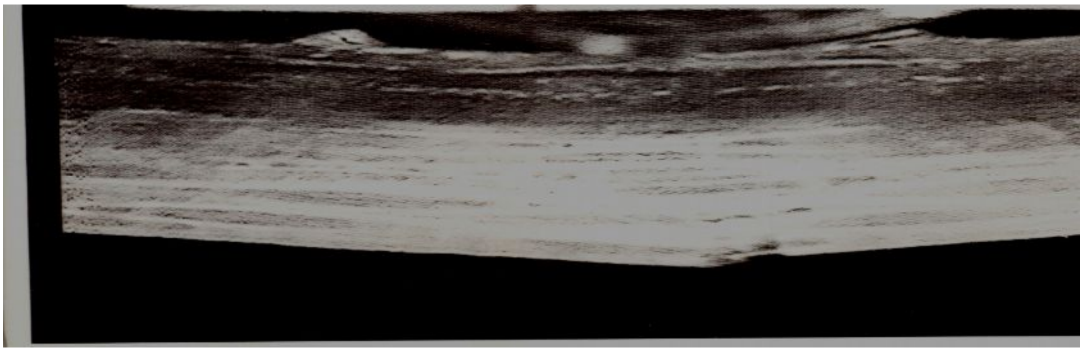
Sample No	Fibre Lay-ups	Flexural Strength at Failure (MPa)	Flexural Modulus (GPa)	Flexural Strain at Failure (%)
1	$[(0/90/+45)_2]_s$	277±5	5.67±0.8	3.2±0.6
2	$[(90/0/+45)_2]_s$	150±6	4.96±0.3	3.0±0.3
3	$[(+45/-45/0)_2]_s$	204±3	4.50±0.4	3.0±0.2
4	$[(0/90/+45/-45)_2]_s$	367±7	5.50±0.7	3.4±0.4
5	$[(90/0/+45/-45)_2]_s$	239±4	5.20±0.5	3.4±0.3
6	$[(+45/-45/0/90)_2]_s$	267±4	4.64±0.6	3.7±0.2

The curves for the unidirectional composites under flexural testing exhibit two deformation regions; i.e. an essentially linear elastic region followed by a non-linear stable deformation region. The onset of non-linear deformation behaviour was observed to coincide with the development of transverse matrix cracking. Increased loading resulted in the formation of further transverse matrix cracking and in the initiation of short delaminations at the tips of these matrix cracks leading to the coalescence of delaminations formed within the reinforcing plies in the corresponding glass lay-ups, creating widespread unstable delamination propagation in the lower half of the samples. Figure 5 show a typical damage development in composites with different lay-ups observed using a camera. Similar behaviour to the damage development have been reported by Lammerant and Verpoest [13] during flexural testing of carbon/epoxy systems. Similar observations were also reported by Reed and Warnet [14] during flexural testing of carbon/polyether-imide cross-ply composites, and by Sankar [15] for the static indentation of carbon/epoxy systems with various quasi-isotropic (π/8, cross-ply and π/4) lay-ups. Microscopical analysis of specimens loaded in the non-linear deformation region showed evidence of delaminations in a zone under the loading point, and Sankar [15] concluded the cracking noise heard during initial loading is due to both matrix cracking and the initiation of small delaminations. Similar behaviour to the damage development was also observed here during flexural testing of composite materials.



(A)

(B)



(C)

Figure 5. Typical damage development in a unidirectional composite observed using a camera magnification (10x) showing (A) sample prior to flexural testing, (B) initial transverse matrix crack formed on the lower face, followed by initial delamination formed at the tip of the matrix crack, and coalescence of delaminations, (C) further delaminations with increased loading over the thickness of the beam.

The Mean flexural results obtained depends on the composite thickness, fibre masss fraction and fibre lay-ups (Table 4). From Table 4, it can be seen that the mean flexural strength depends on the composite thicknesses and fibre lay-ups for which the composite with $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups show highest values of flexural strength which are 277 MPa and 367 MPa for 5 mm and 7 mm composites, respectively. Each composites materials during flexural testing show similar modulus, given slight variations in the M_f and experimental scatter, because the composite flexural modulus is dominated by the fibre mass fraction. Thus, although the specimens of varying thicknesses failed at different deflections and stresses (Table 4) the onset of failure would appear to be conditional on attaining a critical strain values.

Conclusions

1. The mean tensile strength values varied with composite thicknesses and fibre lay-ups for which the composite with $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups gave highest values of tensile strength and the tensile strains of the composites with varying thicknesses failed relatively at constant strain values.
2. Within each composite series, similar modulus were observed, given slight variations in the M_f and experimental scatter, because the composite tensile modulus is dominated by the fibre mass fraction.
3. Calculated impact energy parameters showed similar trends to that of tensile parameters for which $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups gave highest values of impact energy.
4. Glass-polyester composites containing unidirectional reinforcement, all exhibited significant delamination damage as a result of flexural test.
5. The mean flexural strength also varied with composite thicknesses and fibre lay-ups for which the composite with $[(0/90/+45)_2]_s$ and $[(0/90/+45/-45)_2]_s$ lay-ups gave highest values of flexural strength. During flexural testing the unidirectional composites showed that failure strains of the two sets of composites were relatively constant.

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