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Compressive Properties of Carbon Fibre Reinforced Plastic (CFRP) at Low Strain Rate

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ABSTRACT

An experimental programme was carried out for testing and characterising the mechanical properties of carbon fibre reinforced plastic (CFRP) at low strain rates ranging from 10^{-4} to 10 /s. Transverse compressive properties were obtained by carrying a series of quasi-static and dynamic tests on filament wound CFRP tubes with winding angle of ± 90° (the angle is relative to the tube axis).

The quasi-static test were carried out using an Instron and RDP machines whereas dynamic tests on drop hammer rig. Axial and hoop strains were measured by foil strain gauges bonded to the specimen inside and outside surfaces. Load-displacement, load-time and strain-time signals recorded during relevant tests are used to produce stress-strain curves.

The transverse compressive strength and ultimate failure strain increases with increasing strain rate. The modulus and Poisson's ratio are independent of strain rate. The stress-strain curves at different strain rates exhibit a degree of non-linearity. No rate effect is observed on the mode of failure.

Keywords: Mechanical properties, testing and characterisation, low strain rates, carbon/ epoxy

INTRODUCTION

The effect of strain rate on mechanical properties has been studied fairly extensively in recent years, the initial work having commenced during the Second World War. In general past work has mainly concentrated on conventional metals such as steel and aluminium. For these metallic materials a considerable body of data is available on their mechanical performance at low and high rates of loading and some well-defined principles governing their general behaviour are quite establish, while the situation still remains unsettled for composite materials.

It is relatively recent that the composite materials have begun attracting the engineers in the fields of defence, aerospace, offshore, marine technology and others. The demand of using these materials are increasing rapidly and recognised since they offer better capabilities beyond the limits of the physical properties of conventional materials. The unique advantages of composite materials are such as high specific mechanical properties, fairly low costs, weight saving, anti-corrosion and electrical insulation. However, the engineering applications of composite materials require adequate assessment of their response under severe conditions like impact loading and high strain rates.

Compression failure in fibre reinforced composites is of much interest and is often a limiting factor in load application because of the lower compressive strength relative to tensile strength. Compression failure in laminates is inherently complex. There is at present a large uncertainty and lack of understanding of the mechanism triggering compressive failure. This paper describes mainly on an experimental work, deals with the effect of strain rate on the compressive properties; namely, the stress-strain characteristics up to failure, moduli, Poisson's ratio as well as the transverse strength and strain. Further, this paper deals almost exclusively with the axial impact behaviour of carbon fibre reinforced plastic (CFRP). Axial compression through end loading by means of a drop hammer was chosen for the dynamic tests. Prior to the drop hammer tests, static tests by end loading were also carried out on an Instron/RDP test machine to compare the static values which are important reference value in assessing rate effects on various properties.

EXPERIMENTAL PROCEDURE

The specimen tested was 50 mm inside diameter carbon fibre reinforced plastic (CFRP) hoop wound tubes (±90° - with and without end reinforcement). The angle represent the fibre orientation relative to tube axis. The reinforcement fibre used was XAS High Strain 2 carbon fibre and the matrix was CIBA-GEIGY MY750/HY917/ DY063 epoxy resin. The tubes made by wet filament winding, cured at 90° C for 2 hrs and then at 130° C for 1.5 hrs, followed by 2 hrs at 150° C with a maximum rate of change of 1° C/min. The fibre volume fractions of the finished tubes ranged between 50% to 60%.

The tubes were end reinforced and the tests included specimens of gauge lengths of 50 mm and 80 mm long. End reinforcement tube had a circumferentially wound reinforcement of carbon/epoxy on each end. For example, for a specimen wall thickness of 5.6 mm and gauge length of 50 mm, the reinforcement had a wall thickness of 8.2 mm at the end of the specimen, was parallel for 35 mm from the end, then tapered gradually for the remaining part of the length. The profile of the tapered part is designed to eliminate the charp discontinuity between the reinforcement region and the gauge length, thus avoiding end effects and induced failure at gauge length.

Three type of axial compression tests were carried out, ie. quasi-static, low strain rate and drop hammer tests. Quasi-static axial compression tests were performed using an Instron Universal Testing Machine at crosshead speed of 0.5 mm/min whereas low strain rate tests were carried out using servo hydraulic or Research, Development and Production (RDP) machine at different crosshead speed. An external device interfaced to the machine provides a supervisory control and the recording of the test data especially the load and the crosshead displacement. Data acquisition was achieved using a Solatron interfaced with the Instron machine. The Instron and the Solatron were set to the correct conversion factor to provide suitable maching and compatibility between the two so that quick and direct results may be obtained. As the Instron crosshead speed was constant, the load-time trace during any particular test can also be interpreted as the load-displacement trace for that test.

Strain measurements during the tests were made using foil strain gauges. The strain gauges were attached to the outer and/or the inner walls of the tubes at the mid tube section depending on the type of the test conducted. At least two sets of strain gauges were used, mounted diametrically opposite, one aligned in the circumferential and the other in the axial direction to measure hoop and axial strains respectively.

All dynamic axial compression tests were performed on drop hammer rig. The rig consists of four basic components ie. a drop tower that guides a falling mass towards the specimen, a force transducer, a velocimeter and sensor units, and hardware and software dedicated to data acquisition unit. The quantities which need to be measured include the force resisted by the specimen, deformation of the tube (ie. axial and hoop strains), impact velocity and the corresponding deceleration of the tup.

During each test, load-time, hoop and axial strain-time traces were recorded. The load is converted to stress by dividing it by the tube cross-sectional area. By eliminating the time element from the stress-time and strain-time traces, it was possible to plot stress-strain curves.

In order to gain an insight into the mode of deformation and the response time of tubes to impact loading under dynamic axial compression, high speed photography was made using HS Motion Analyzer. This equipment enables the event to be recorded in the memory, to review the recorded events and to transfer the recorded events into a video tape. The frame speed was set between 4500 to 27000 frame per seconds.

RESULTS AND DISCUSSION

Quasi Static Tests

In determining the specimen geometry in axial compression test, susceptibility to buckling was a major consideration. It is important to design the test specimen to ensure that it does not fail prematurely in a buckling mode. The specimens were therefore kept short enough to avoid Euler's buckling but yet long enough to allow any stress concentration at the edge to degenerate to a uniaxial state of stress in the centre of the tube. A number of tube thicknesses ranging from 1.2 mm to 5.6 mm were tested. The tube inside diameter was 50 mm thus giving a corresponding range of thickness to diameter ratios of 0.024 to 0.112.

Axial alignment is extremely important to avoid premature bending. Hence specimens were machined with square ends and strain gauged before testing. More than one set of strain gauges is attached to each specimen, served as a check on repeatability and consistency of the recorded results. The specimens were tested to failure by compressing them axially between two plates at a rate of 0.5 mm/min. During crushing, the load-displacement curved was obtained directly from the testing machine. Typically, the load-displacement trace exhibit an increase in load with increasing displacement until specimen failure took place. The failure was characterised by a sharp distinct sound with an instantaneous drop to zero in load. The corresponding stress-strain curve is shown in Figure 1. The failure of all specimens tested occured over the gauge length. The fracture mode (Figure 2) was in the form of "shear lips" indicating a resin shear initiated mode of failure. Each test was repeated several times to check for repeatability and consistency.

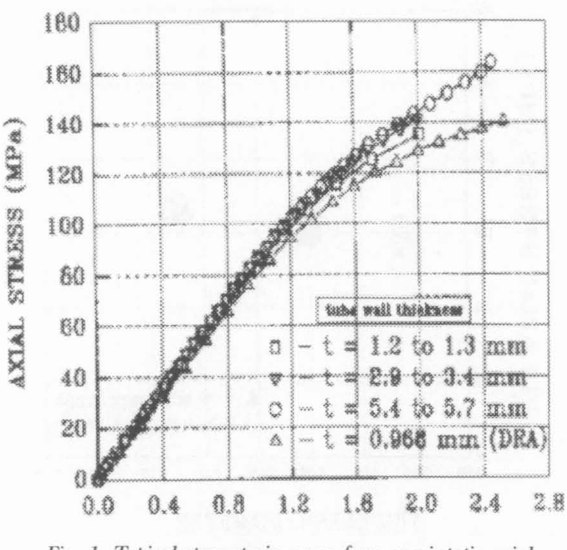

Fig. 1. Typical stress-strain curve from quasi-static axial compression test (different wall thickness)

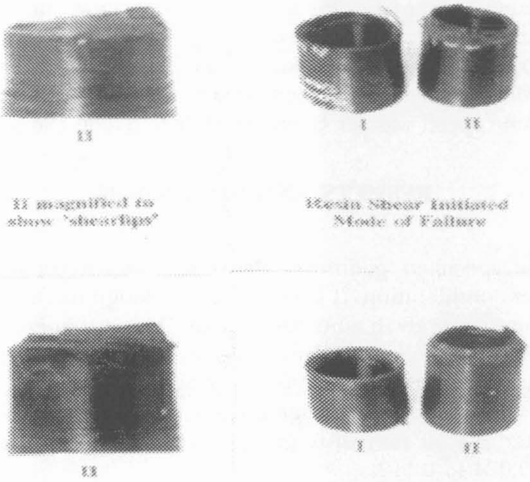

Fig. 2. Fractured specimens - shear mode of failure

Values of ultimate compressive strength were plotted against thickness/ diameter ratio (Figure 3). The results show a gentle increase in strength value with increasing thickness/ diameter ratio and at the same time a decrease in the scatter in the results with increasing thickness/ diameter ratio. In fact, the scatter was negligible at the maximum value of thickness/ diameter ratio tested (0.12) indicating that stability (no buckling) has been achieved. The transverse strength value at the maximum tested t/ D ratio was 166 MPa which compared favourably with corresponding results obtained by Defence Research Agency (DRA). The increase in recorded failure strength from the lowest to the largest t/D ratio was 12%.

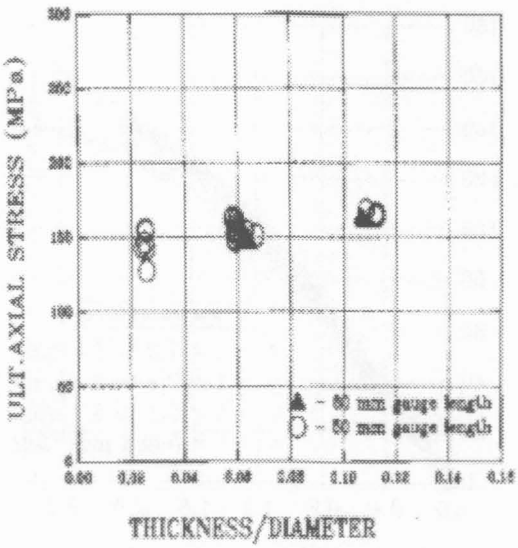

Fig. 3. Variation of ultimate axial stress with thickness/diameter ratio.

The average low strain modulus taken at 1.0% axial strain was 8.71 GPa and the average secant modulus at failure strain was 6.79 GPa. The later two values represent a 22% change between the moduli at low and ultimate strain values; a measure on non-linearity in the stress-strain response for this material and orientation. The average strain to failure was 2.4% and the average Poisson's ratio values measured at failure and at 1.0% of axial strain were 0.104 and 0.071 respectively (Figure 1). The above values are in good agreement with available published data.

Low Strain Rate Tests

All the quasi-static compression tests were conducted at crosshead speed of 0.5 mm/min. In an attempt to investigate the effect of strain rate on the compression response of CFRP tubes, a series of tests were carried out using the RDP (servo hydraulic) machine. These tests were conducted at speeds of 3 mm/min, 30 mm/min, 100 mm/min and 300 mm/min, i.e the strain rate was increased in steps by almost 3 orders of magnitude from the rate used in Instron machine. The test specimens, strain gauged as before, were of 50 mm gauge length, 5.4 mm nominal thickness and without end reinforcement.

A family of stress-strain curves at different crosshead speeds is plotted (Figure 4). Variation of axial stress, failure strain, secant modulus and secant Poisson s ratio with strain rate is presented in Figure 5. There is, in general, a small increase in ultimate stress value with increasing crosshead speed.

The mode of failure at different crosshead speeds are virtually identical, exhibiting similar features to those described earlier. The fractures were typically localised to mid gauge length consisting of a transverse fracture with circumferentially oriented delaminations extending from the transverse fracture. One half of the rings had 45° shear plane fractures. These were either a single 45° plane extending across the width of the ring from edge to edge or a 'V' shaped fracture consisting of two 45° fractures.

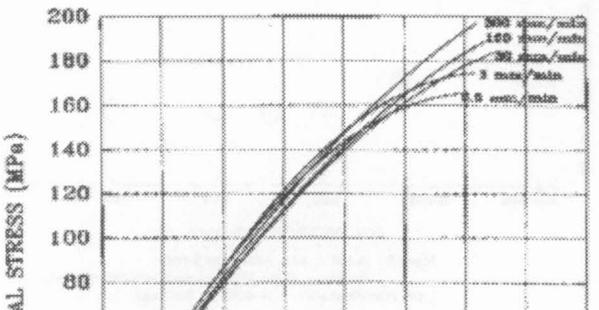

Fig. 4. Stress-strain curves of hoop wound CFRP tubes at different crosshead speed.

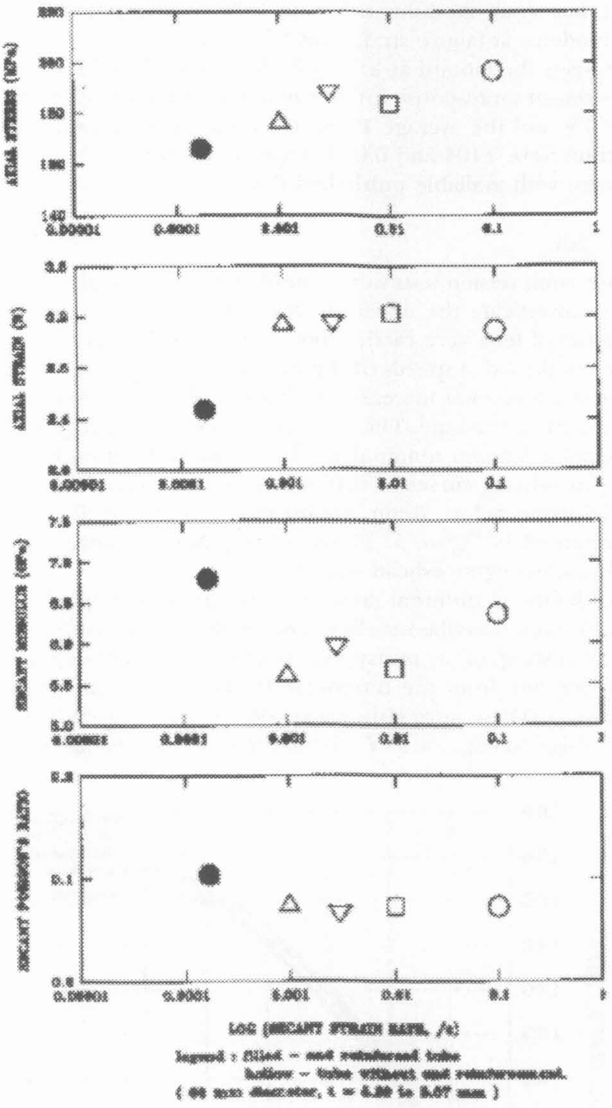

Fig. 5. Variation of axial stress, failure strain secant modulus and secant Poisson's ratio with secant strain rate

Drop Hammer Tests

Specimen of 50 mm gauge length and 5.6 mm thickness were tested; both with and without end reinforcement. By altering the drop height, a number of different strain rates were possible. The drop mass used was 94 kg and proved sufficient to fracture the test specimens. For end reinforced tubes, tests were carried out at two drop heights; 2.5 m and 3 m. For each case, three tests were performed. Typical raw data and stress-strain curve for each height, are presented in Figure 6 and 7 respectively.

Axial impact tests on hoop wound tubes without end reinforcement were carried out at five different strain rates corresponding to drop heights of 1.5 m, 1.75 m, 2.0 m, 2.5 m and 3.0 m. The force-time and strain-time response of the five specimens corresponding to the different drop heights show similar characteristics with an increase in load with time up to a maximum load of 250 kN, followed by a sudden drop in load at failure (Figure 8).

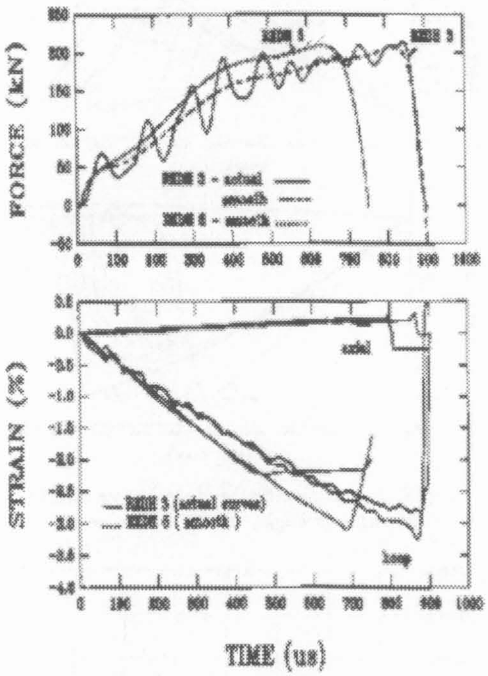

Fig. 6. Raw data: force-time and strain-time curves (end reinforced specimen)

Fig. 7. Stress-strain curve (end reinforced specimen) [drop height = 2.5 m (REDH3) and 3.0 m (REDH 5)]

The main difference between the response is the failure time; a higher drop height yields a shorter time to failure. Stress-strain curves at different strain rates is shown in Figure 9.

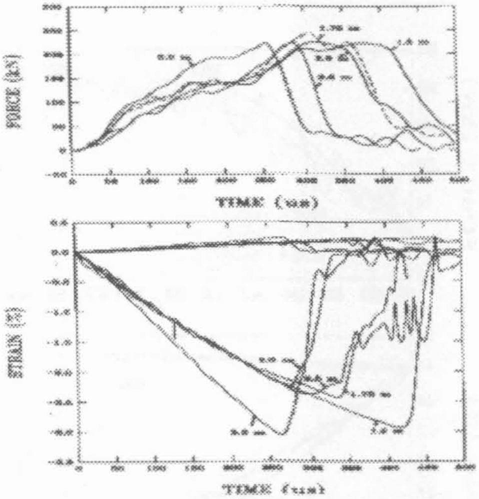

Fig. 8. Typical force-time and strain-time curves (different drop height, no end reinforcement)

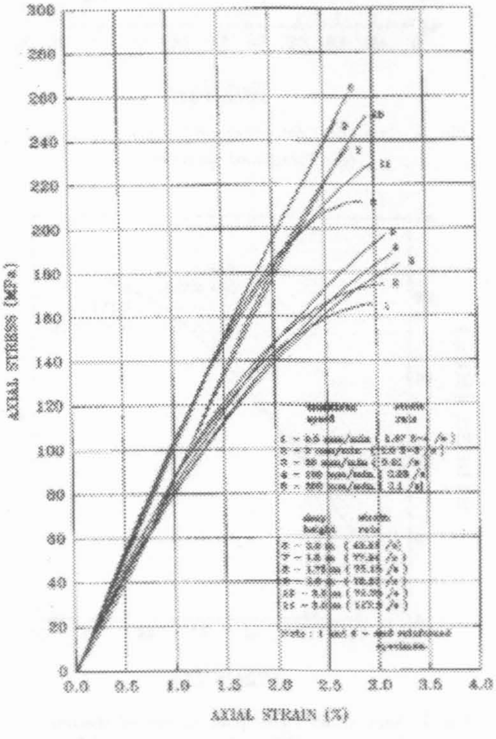

Fig. 9. Stress-strain curves at different strain rates.

A number of high speed photographs were taken during drop hammer tests to record the mode of failure. The setup used consists of a High Speed Motion Analyser and accessories and was run at 13000 frames/sec. Careful examination of these frames reveals that crack begins close to the middle of specimen gauge length. The high speed photography clearly enabled us to note the formation and development of the cracks. The mode of failure is fairly similar to the quasi-static tests in that the crack is seen to be forming within the specimen gauge length.

CONCLUSIONS

In compression testing using tubular specimen, it is necessary to use wall thickness values higher than that at which macro-buckling occurs. For this to be determined, a parametric study has to be carried out. Application of strain gauges at different stations around the tube circumference are essential for the compression tests in order to assess the validity of the test, particularly in order to identify macro-instability.

Quasi-static axial compression results show that tubular specimens having thickness ratio of about 0.1 and a gauge length of 50 mm are suitable for axial compression tests. The transverse strength of the ±90° CFRP tubes increases with increasing t/D ratio until a value of t/D>0.108 is reached. The increase becomes very gradual and the strength appears to be approaching a constant value of 166 MPa. The Poisson's ratio is shown to be 0.074.

The drop hammer results for CFRP show generally a higher strength and strain to failure values than the corresponding quasi-static values.

There is, in general, a small increase in transverse strength with increasing strain rate. No significant increases in secant modulus and Poisson's ratio with increasing strain rate was observed.

The failure modes for specimen tested under static conditions were similar to their dynamic counterparts but with greater damage being sustained by the specimens at high strain rates. This is due, in part, to the continued travel of the impactor after specimens failure. The mode of failure of hoop wound CFRP tubes in axial compression is resin induced shear failure and is independent of rate of loading.

Static and dynamic stress-strain curves show a slight non-linearity at high strain values near specimen fracture. The onset of non-linearity in the response of fibre composites is an indication of the onset of material degradation or degradation of stiffness, i.e. the initiation of matrix micro-cracking. The loading process is that when the stress level in fibre composites exceeds the limit of proportionality, cracks initiate in the matrix and with increasing load they propagate steadily until eventually total failure of fibres occurs.

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