Response of CFRP Laminates under High Strain Rate Compression until Failure

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Summary

The present study aims at characterizing the rate-dependent behavior until failure of one polymeric composite material system, the unidirectional Texipreg® HS160 REM high strength carbon fiber and epoxy resin. Two different stacking sequences were considered, $[0]_{16}$, designated as unidirectional (U) laminates, and $[0/90/+45/-45]_{2S}$, designated as quasi-isotropic (Q) laminates. The laminates were produced on a 40-ton hot plate press. The main testing equipment was a conventional mechanical testing machine (INSTRON) and a Split Hopkinson Pressure Bar (SHPB) adapted to test CFRP laminates. In-plane compression tests using four different strain rates took place in the range of 0.0001 to 400/s. The unidirectional laminates were subjected to loading along the 0º and 90º directions.

A failure analysis was performed. According to the three specimen families, three different occurrences were observed: crushing for U 0º laminates; shear failure for U 90º laminates and delamination for Q laminates (in which many layers split). In addition, a detailed analysis was performed about the mechanical behavior in the transverse direction of unidirectional laminates. A clear viscoplastic behavior was detected which demonstrated to be well represented by the constitutive model proposed by Sun et al.[1-2]. The strength clearly exhibit a strain rate dependency which was represented by a power law as it was also proposed by Sun et al.[1-2]. Nevertheless this power law does not predict correctly the strength when used to extrapolate data from low strain rate 0.0001-0.07/s to high strain rate 400/s. On the other hand the Monkman Grant equation appeared more appropriate to extrapolate failure data from low strain rate to high strain rate.

Introduction

Some applications of composite materials are in structures subject to dynamic loads. For example, bird strikes or tool drops on aircraft structure, underwater mine explosions on ship hulls and automobile crash accidents. Therefore, it is essential to characterize the composite materials under high strain rate loading. Studies related to composites testing at high strain rates are recent. Hamouda and Hashmi [3] discussed the development and the present state of the experimental techniques employed for determining the behavior of

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composites at high strain rate. This discussion included their advantages and limitations. Hosur et al. [4] studied the response of CFRP laminates under high strain rate compression loading using the Split Hopkinson Pressure Bar (SHPB) and compared it with static results. They concluded that the dynamic strength and stiffness exhibit considerable increase when compared to the static values. The SHPB is widely used to generate high strain rate response data. Ninan, Tsai and Sun [5] pointed some relevant aspects of this testing practice, such as lapping and lubricating the specimens loading faces. These recommended procedures were found to produce near homogeneous deformation. In the present research work, such considerations on the specimen preparation were also taken in account.

It is reasonably accepted that in the fiber direction, unidirectional fiber reinforced polymer matrix composites are insensitive to load level and time of load application, i.e. exhibit a linear behavior. Then again in other directions polymer composites exhibit non-linear and time-dependent behavior, which also means a rate-dependent behavior. A quit simple methodology associated to a simple constitutive elastic-viscoplastic model was developed by Sun et al.[1-2]. This methodology was applied in the present work to study mechanical behavior of a composite laminate in the transverse direction with good success.

Materials and Specimen Preparation

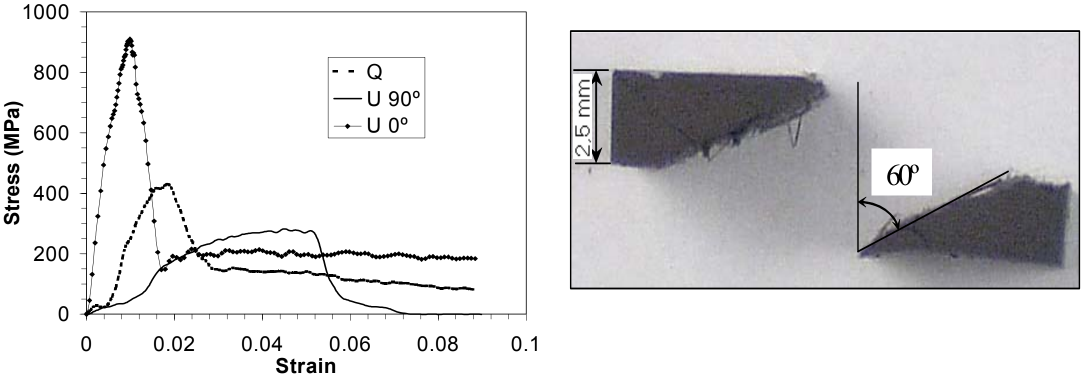
The epoxy pre-preg system, manufactured by SEAL, was used in this work, the Texipreg® HS160 REM, a modified epoxy REM reinforced with high strength carbon fiber in the form of unidirectional tape (0.125 mm thick). The laminates studied in this work were based on two different stacking sequences, $[0]_{16}$ and $[0/90/+45/-45]_{4S}$. The laminates based on the former sequence are designated as U (unidirectional) and the others as Q (quasi-isotropic) laminates. The laminates were produced on a 40-ton capacity SATIM hot plate press at 130 °C under 1 bar pressure during 50 minutes and 3 bar pressure during more 60 min, which gives 110 min of dwell time. The average thickness of cured laminates was 2.5 mm and fiber content by volume, based on the fiber contents supplied by the pre-preg manufacturer, was $V_f \cong 0.6$. From the original manufactured laminates, square samples with 8.5 mm side were cut using water jet. Since the specimens would be tested in the Split Hopkinson Pressure Bar (SHPB), it was essential to obtain an accurate parallelism between the faces that would be in contact with the bars. A specific tool was designed to perform this task. The square specimens were then lapped using fine sandpaper (grit #600).

High Strain Rate Set-up

The compression tests were performed with the Split Hopkinson Pressure Bar (SHPB). The particular setup used in the current study consists of striker, incident and transmission bars made of steel. The bars diameter is 12 mm. The striker bar is 1 m long, while the incident bar length is 2.5 m and the transmission bar 1.5 m. The specimen was sandwiched between the incident bar and the transmission bar. Lubricant grease was applied at the specimen surfaces in contact with the bars to reduce the effect of friction and to provide better contact. Equally, a small amount of lubricant grease was applied at the end of the striker bar to avoid high frequency phenomena in the signal acquired by the oscilloscope, consequence of heterogeneous contact. The full bridge with strain gage transducers A and B, used as signal monitors, were mounted at 1250 and 215 mm from the specimen, respectively. The striker bar was released at a pressure of 1 bar by a gas gun specially made for that proposes. The transient strain history is recorded from the strain gages A and B set up on the incident and transmission bars. A PICO CM001 signal conditioner adapter amplifies the gages output signal 10 times. The data is acquired using a LeCroy 9450A digital oscilloscope at a sampling rate of 1 MHz. A program named ADAVID® [6] imports the data from the oscilloscope data storage to the PC for posterior analysis.

Analysis of Failure Modes under In-Plane Compression Tests

High strain rate tests were performed on 25 unidirectional and quasi-isotropic laminates. Figure 1 depicts the obtained stress strain plots and the shear fracture of the U 90º laminates. It is possible to note that the U 90º laminates present the lowest value of maximum stress and the highest strain before failure. The strain at failure in transverse direction (U 90º) is 3 times greater than in fiber direction (U 0º) and the ultimate stress is approximately 30%. The Q laminates represent an intermediate case, namely, its strength and stiffness is half-a-way between the U 0º and U 90º laminates.



(a) (b)

Figure 1: (a)-Stress-Strain plots for the three families of laminates; (b)-Shear fracture of the U 90º laminates.

Three different failure modes, corresponding to the three families of laminates, were observed: Splitting in the case of Q laminates; Shearing, in the case of U 90º laminates; and Crushing, in the case of U 0º laminates. Figure 1b illustrates the shear rupture verified in the U 90º laminates. It is possible to see that the two halves have slithered by a defined angle. The measurement of that angle was carried out. The total average yields an angle of 60º±3.8º. For similar materials Puck and Schürmann [7] measured this fracture angle as being between ±50º and ±55º.

In-Plane Transverse Compression Tests and Discussion

A deeper analysis of mechanical behavior in the transverse direction of unidirectional laminates (U 90º) was performed. In Figure 2 the stress-strain plots are represented for three different strain rates and effective stress-effective plastic strain rate for the same strain rates. In this study, it was used the viscoplastic model proposed by Sun et al.[1-2]. This model is very simple to use and in this case the plastic strain was represented as follows,

$$\bar{\varepsilon}^{p} = A\left(\bar{\sigma}\right)^{5.30}, \tag{1}$$

where $\bar{\varepsilon}^{p}$ is the effective plastic strain and $\bar{\sigma}$ the effective stress and A the strain rate-dependent coefficient as defined by Sun et al.[1-2], which in this case is given by,

$$A = 4.156 \cdot 10^{-15}\left(\dot{\bar{\varepsilon}}^{p}\right)^{-0.2759}, \tag{2}$$

where $\dot{\bar{\varepsilon}}^{p}$ represents the effective plastic strain rate. The model represents quit well the viscoplastic behavior as shown in Figure 1b.

Finally a tentative was made to represent the strength dependency on the strain rate using a power model as suggested by Sun et al.[2].

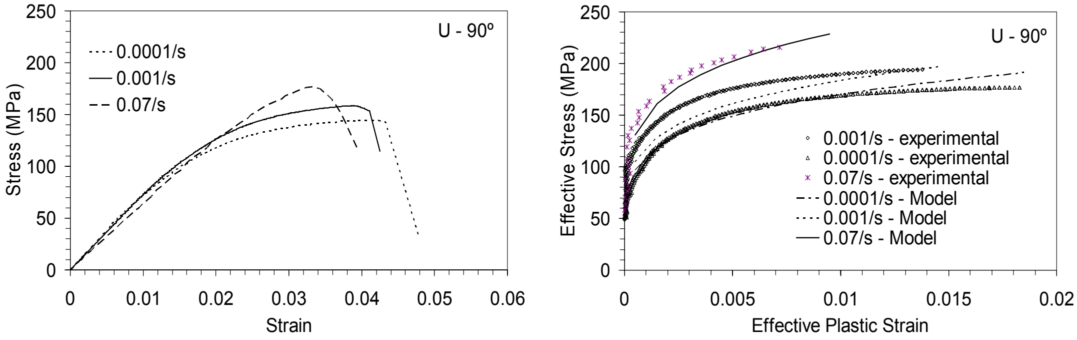
$$\sigma_{R} = 144.3\left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{0.03127}, \tag{3}$$

where σ_{R} represents the strength and $\dot{\varepsilon}$ the strain rate. The model extrapolation to larger strain ratios does not predict correctly the strength increase as shown in Figure 3a. This indicates that probably this is not a good model for extrapolation purposes.

Another approach to model the failure is to relate the time to failure with strain rate. Reifsnider et al.[8] verified that the Monkman Grant classical equation fits data for epoxy at strain rates from quasi-static to very high rate ranges, almost perfectly. For this case the Monkman Grant equation was determined as,

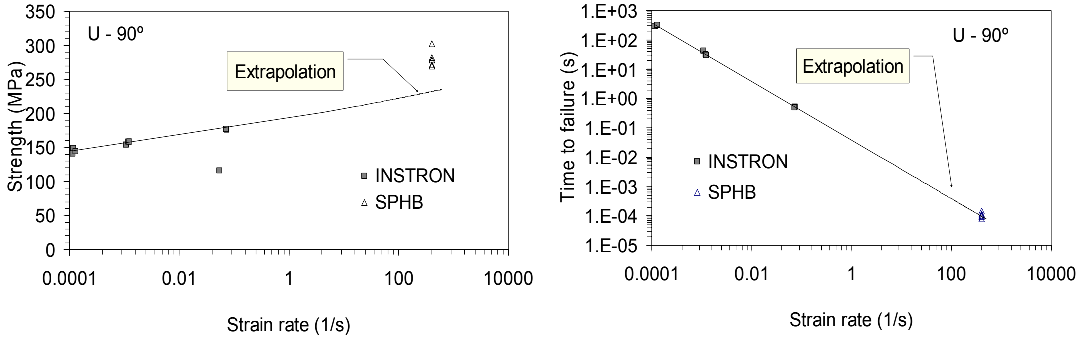
$$t_{R}\left(\dot{\varepsilon}\right)^{0.9983} = 0.03861, \tag{4}$$

where t_R represents time to failure and $\dot{\varepsilon}$ strain rate. The model extrapolation to larger strain ratios predicts quit well the time to failure for high strain rate as depicted in Figure 3b, confirming Reifsneider et al. observations.



(a) (b)

Figure 2: (a)-Stress-strain plots for three different strain rates; (b)-Effective stress/effective plastic strain curves and theoretical predictions for each strain rate



(a) (b)

Figure 3: (a)-Strength dependency on strain rate; (b)-Time to failure/strain rate fitted by Monkman Grant Equation.

Conclusions

Studies were carried out on 26 quasi-isotropic and unidirectional laminates under high strain rate compression loading. The setup used were one conventional mechanical testing machine (INSTRON) for strain rates between 0.0001 and 0.07/s and one Split Hopkinson Pressure Bar for strain rates of about 400/s. Three failure modes were detected: Splitting in the case of Q laminates; Shearing, in the case of U 90º laminates; and Crushing, in the case of U 0º laminates.

For the transverse direction it was measured the plastic behavior induced by the polymeric matrix. This phenomenon proved to be well represented by the viscoplastic model developed by Sun et al. [1-2]. Also, in the transverse direction, the strength exhibit a strain rate dependency which was represented by a power law, as proposed by Sun et al.[2]. Nevertheless, when this law was used to extrapolate data from low strain rate 0.0001-0.07/s to high strain rate 400/s, it predicted a failure stress quit lower than the experimental value. On the other hand the Monkman Grant equation appeared more appropriate to extrapolate failure data from low strain rate to high strain rate.

Acknowledgments

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