THE INFLUENCE OF STRAIN RATE AND STACKING SEQUENCE ON COMPRESSIVE BEHAVIORS OF WOVEN FABRIC REINFORCED COMPOSITE LAMINATE

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1 Introduction

Fiber reinforced composite laminates are finding increasing applications in various engineering fields, such as aerospace, automotive and military, because of their low density, high strength-to-weight and stiffness-to-weight ratios. The mechanical response and failure modes of fiber reinforced composite laminates under dynamic loads are inherently more complex due to a multitude of factors such as: impact velocity, loading direction, fiber orientation, woven architecture, stacking sequence etc. Therefore, it is needed to investigate the effect of these factors on their mechanical behavior.

Many researchers have experimentally studied the high strain rate response in fiber reinforced composite laminates under different impact velocity [1-4]. Sierakowsi [1] has reviewed over 120 articles dealing with high strain rate behavior of filamentary composite materials. In that article, various experimental techniques used for evaluating the dynamic performance of composites, as well as the results obtained by researchers for various types of filamentary composites were discussed. When composite subjected to high strain rates of loading, Hopkinson Bar apparatus was used by the researchers as the best choice. The history of the development and theory of the Hopkinson Bar for high strain rate testing of materials was presented by Gama et al. [5] in the critical review.

Fiber orientation effects on high strain rate properties of unidirectional [6], balanced angle-ply [7], plane weave [8] and satin weave [9] composite laminates along out-of-plane and in-plane direction were investigated over past one decade. Some conclusions were received: the dynamic mechanical properties of composite laminates were strongly dependent on the fiber orientation; balanced angle-ply laminates were found to be highly strain rate sensitive in a manner similar to unidirectional laminates of the same material; meanwhile, through the thickness loading exhibited the higher compressive strength than other directions, which response was completely dominated by the matrix and the fibers did not get loaded.

The objective of this study is to investigate the dynamic mechanical properties and failure modes of woven composite laminate under different strain rate and identify the effect of stacking sequence. Satin weave E-glass/epoxy composite laminate with lay-ups of $[45/-45/0/90]_{ns}$ is investigated experimentally along in-plane direction. Compressive strength, modulus and strain at peak stress are evaluated under different strain rate. Optical and microscopic graphs are further practiced on the specimens to determine operative failure modes.

2 Materials and Experiment

2.1 Material

The composite laminate used was fabricated from satin weave E-220 glass/epoxy pre-impregnated tape. The pre-impregnated tape was manually laid up to fabricate laminates with stacking sequence of $[45/-45/0/90]_{ns}$. The 104-layers laminate was cured in the Autoclave in 0.2827 MPa pressure at 121℃ for 2 hours in accordance to standard curing cycle recommended by manufacturer.

Cubic specimens were cut from 300×300mm square panels by using a water-jet machine. The specimen geometry, dimensions, and loading direction are presented in Fig.1. The faces of the specimens were polished with 600-grit sandpaper to ensure parallel loading edges. To avoid uncertainties related to size effects, the specimens in all the tests are of the same geometry.

In this paper, the compressive loading was applied in a direction parallel to the composite sheet so that the response of the composite in the in-plane direction could be obtained. Because of the stacking sequence, the specimen was plane symmetry. Hence, it only needed to do the experiment along one direction.

2.2 Experimental Procedure

To determine the static properties, quasi-static test was performed on Instron 5569 electromechanical test machine (Figure 2), which was used for testing a wide range of materials in compression by moving the crosshead in a downward direction via drive system. The test specimen was secured between the rigid frame base and the moving crosshead. Quasi-static mechanical properties of the composites along in-plane direction were measured in displacement control mode with constant crosshead speed of 1.00 mm/min and 10.0 mm/min. Three samples to each speed were tested.

For high strain rate testing, a pulse shaper modified Split Hopkinson Pressure Bar (SHPB) apparatus, firstly introduced by Kolsky [10] in 1949, was performed. The SHPB apparatus is a commonly used experiment technique for direct determination of high strain rate mechanical properties in the range of 2.0×10^{2}~$1.0\times10^{4}s^{-1}$. Photograph of the pulse shaper modified SHPB apparatus is shown in Fig. 3. In this study, the SHPB apparatus consists of 16mm diameter Inconel 718 striker, incident and transmitter bars which are 300, 1600 and 1600 mm in length, respectively.

To increase the rise time, smoothen the pulse and to modify the shape of the pulse, a thin copper disk was used as pulse shaper [11, 12]. The conventional SHPB apparatus was modified by shaping the incident pulse such that the specimens were in dynamic stress equilibrium and had early constant strain rate over most of the test duration. The diameter of pulse shaper was 10.0 mm whereas the thickness was varied in the range of 0.1~0.5 mm. In addition, a thin film of EP Grease was used as lubricant to decrease the friction constraint exists at the pressure bar-specimen interfaces due to the radial expansion of the specimen during loading.

Using strain gage signals obtained on Pro 940 oscilloscope during testing, the stress, the strain and the strain rate of the tested specimen were calculated using the following equations:

$$\sigma = E(\frac{D}{D_S})^2 \varepsilon_t(t) \qquad (1)$$

$$\varepsilon = \frac{2C_0}{l_s}\int_0^t \varepsilon_r(t)dt \qquad (2)$$

$$\dot{\varepsilon} = \frac{2C_0}{l_s}\varepsilon_r(t) \qquad (3)$$

where E is the Young's modulus of the bars, D and D_s is the diameter area of the bars and the specimen, C_0 is the elastic wave velocity in the bars, l_S is the specimens gage length, ε_r is the reflected strain pulse, ε_t is the transmitted strain pulse and t is the time duration.

The experiments were performed at different test pressures with the aim of describing the strain-rate depend behavior of the materials. The strain rate in the experiments defined as the strain at peak stress divided by the time to failure.

3 Results and Discussions

The compressive stress-strain curves at strain rates from 2.9×10^{-3} to 1.2×10^{3} s^{-1} for the above composite are presented in Fig.4. Here, each curve is a representative specimen for quasi-static and high strain rate loading and is not the average of three specimens tested for each case.

The compressive stress-strain curves exhibit strong sensitivity to strain rate at high strain rates, but don't show a clear rate sensitivity to quasi-static strain rates. The quasi-static curves indicated a linear elastic response up to the peak stress level and followed by a sudden drop in the stress at the onset of inelastic deformation. During quasi-static experiment, the broken voice could be hearted clearly at that drop point. At high strain rates, the response indicated initial linear elastic at small strains and then become nonlinear as the strain increased. Some possible reasons for this nonlinear phenomenon are proposed. One is because of the softening of the epoxy matrix which happened in the process of damage accumulating. It is also due to the coupling of axial and sheared deformation. Through in-plane loading, the matrix and the fabric get loaded together. It is well known that polymeric materials are very sensitive to strain rate and temperature [13]. The compressive stress-strain curves for the neat resin showed a linear elastic region followed by a strain softening region that was characterized by a slight drop in stress [14]. During high strain rate impact, the temperature of the specimen rose gradually, which caused the soft of epoxy resin and indicated a speed damage accumulation process [12]. The detail values and the average values of the compressive properties for both quasi-static and dynamic tests are listed in Table 1. Compressive strength of composites is defined as the first peak in the stress-strain curves.This comparison in the table shows a significant strain rate effect. The compressive strength and modulus almost increases with increasing strain rate. The dynamic strength is about 1.35~2.03 times higher than the quasi-static strength. There is an increase in the modulus by about 2.97~3.72 times as compared to the quasi-static values. The strain at peak stress under dynamic loading is about 49.95~70.55% as compare to the corresponding value under quasi-static loading. Under dynamic loading, variation in the strength, modulus and strain at peak stress is 28.2%, 23.96% and 20.51%, respectively. Hosur et al. [9, 16] studied the response of the typical satin weave composite laminates subjected to high strain rate compressive loading under off-axis loading. Along fill direction, when compared to the quasi-static properties, dynamic properties were higher by about 25%~200%, 3~6 and 33% times for peak stress, modulus and strain at ultimate stress respectively. Along warp direction, when compared to the quasi-static properties, dynamic properties were higher by about 1.5~1.9, 5.5~6.7 and 25~32% times for peak stress, modulus and strain at ultimate stress respectively. The stress-strain response was linear up to about 70% of the loading. Along 45° direction, when compared to the quasi-static properties, dynamic properties were higher by about 20~33%, 5.5 and 33% times for peak stress, modulus and strain at ultimate stress respectively. The ratio of linear to nonlinear response was about 4~5 [8]. Comparing the above results in the literatures with this paper, it could be found that variation range of the dynamic compressive properties were between 45° and in-plane principal directions and the linear region was decreased greatly, which were obviously caused by the stacking sequence.

All the specimens failed during loading in both quasi-static and dynamic experiments. The deformed specimens were viewed under optical and electron microscope for identification of failure modes caused due to static and dynamic compressive loading. For Scanning Electron Micrograph (SEM) observations, specimens were coated with platinum. The optical micrographs for the specimens loaded in in-plane direction for different ranges of strain rates are illustrated through side face in Fig. 5 SEMs of specimens loaded at strain rates of 0.0287, 839.03 and 1217.78s^{-1} are shown in Figs 6-8, respectively.

The crushing of loading face is shown in Fig. 6 (a) and the splitting of the laminate is shown in Figs. 6 (b) and (c). Since the axially split regions were bent by the microbuckling, the failure sequence of fiber microbuckling was followed by axial splitting. Similar quasi-static strain rate failure mechanism was also found for unidirectional E-glass fiber reinforced vinyl ester composite [15] and S2-glass woven fabric/vinyl ester composite [16]. Li and Lambros [15] showed that heat was generated from damage mechanisms. As the temperature rising, due to matrix softening caused the relaxation of the surrounding matrix which leads to microbuckling formation. Under quasi-static loading, the laminate has lot of time to distribute the load and undergo steady deformation. Hence, the strain for the quasi-static loading is higher as compare to the high strain rate loading.

Compare the Figs. 5 (c)-(e) with (a) and (b), it is observed that the failure modes under high strain rate loading are distinctly different with the quasi-static case. At high strain rates, the specimens failed by delamination, shear fracture and splitting into two or more pieces along the loading axis (Figs 7, 8). The change in failure modes results in an increase in the compress strength form quasi-static to dynamic strain rates. A possible explanation for the observed change in failure modes could be due to the lack of sufficient time for buckling and growth at increasing strain rates. During experiment, the stress loading on the specimens exceeds the matrix/fiber interfacial strength, which results in the observed extensive debonding and delamination. This is consistent with the finding of Song et al. [10] that the interface strength between the fiber and the resin was very low.Figs. 7(b), 7(c), 8(b) and 8(c) show that when debonding of fiber and matrix happens between 0° and 90° layers, the failure mode is delamination and the fibers are almost not failed, if the debongding interface connected with 45 layer, shear fracture happened. Hosur et al. [9] showed that the satin weave samples tested under high strain rate along 45 were not failed. The failure mode of samples loaded under high strain rates along warp/fill was predominantly by splitting of the sample into two or three sublaminates [8, 14]. There was no indication of any shear fracture [8, 14]. In this study, the specimens was fabricated with stacking sequence of $[45/-45/0/90]_{ns}$ then the shear fracture under high strain rates was not avoided.

4 Conclusions

Quai-static and high strain rate compressive behavior of woven E-glass fabric/epoxy composites along in-plane direction was determined for strain rates between 0.2×10^{-3} and 1.2×10^{3} s^{-1}. The compressive stress-strain curves exhibit strong sensitivity to strain rate at high strain rates, but don’t show a clear rate sensitivity to quasi-static strain rates. Compressive strength, ultimate strain and modulus were found to be rate sensitive. The modulus of the composites increases with increasing strain rate from quasi-static to high strain rates. Within the studied high strain rate regimes, the compressive strength and modulus almost increases as the strain rate increasing.

All the specimens failed during loading in both the quasi-static and dynamic experiments. In the case of quasi-static loading, the dominant damage mode for the specimen is shear fracture caused by the crushing on the load in face and splitting of the laminate with the microbuckling of fibers along the shear plane. The failure modes changed to delamination and shear fracture as the strain rate changed from quasi-static to high strain rates.

Compressive properties and failure modes of E-220 satin weave composite laminate are not only depend on the loading strain rate but also sensitive to stacking sequence.

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Table 1 Compressive properties of E-220 glass fabric reinforced composite under different strain rate.

Specimen No	Strain rate (s^{-1})	Peak stress (MPa)	Strain at peak stress (%)	Modulus (GPa)
1	0.0029	211.09	9.69	2.59
2	0.0029	225.83	8.66	2.57
3	0.0029	223.94	9.51	2.58
Average	0.0029	220.29	9.29	2.58
4	0.0287	222.47	10.15	2.62
5	0.0287	246.95	9.87	2.57
6	0.0287	237.36	9.99	2.60
Average	0.0287	235.59	10.00	2.60
7	839.03	427.53	6.11	8.31
8	894.43	353.01	5.64	7.72
9	920.18	333.49	5.07	8.41
Average	884.55	371.34	5.61	8.15
10	972.48	377.74	5.49	8.37
11	1128.04	393.59	5.11	9.57
12	1217.78	400.78	5.56	9.33
Average	1106.10	390.70	5.39	9.09

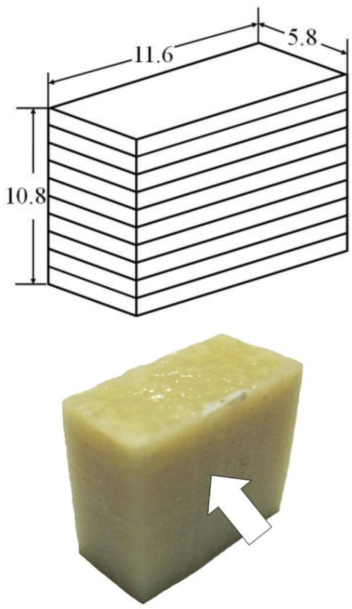

Fig.1 Specimen dimensions and loading direction.

Fig.2 Instron 5569 electromechanical test machine.

Fig.3 Photograph of Pulse shaper modified SHPB apparatus.

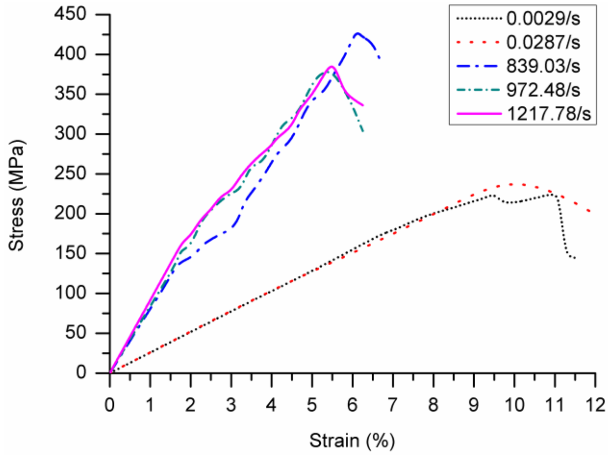

Fig. 4 Compressive stress-strain curves of E-220 composite under different strain rates.

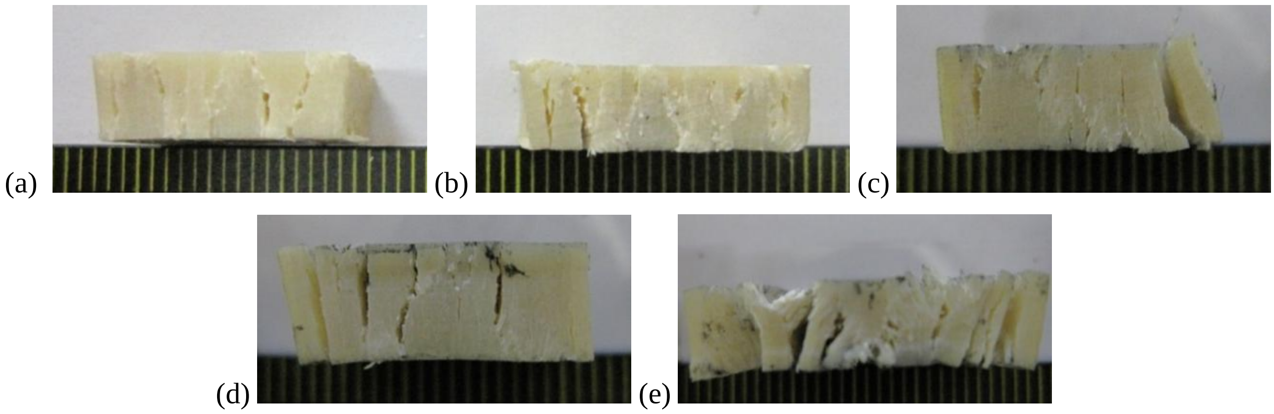

Fig.5 Side views of E-7781 glass fabric reinforced composite failed under different strain rate: (a) 0.0029/s, (b) 0.0287/s, (c) 839.03/s, (d) 972.48/s, and (e) 1217.78/s.

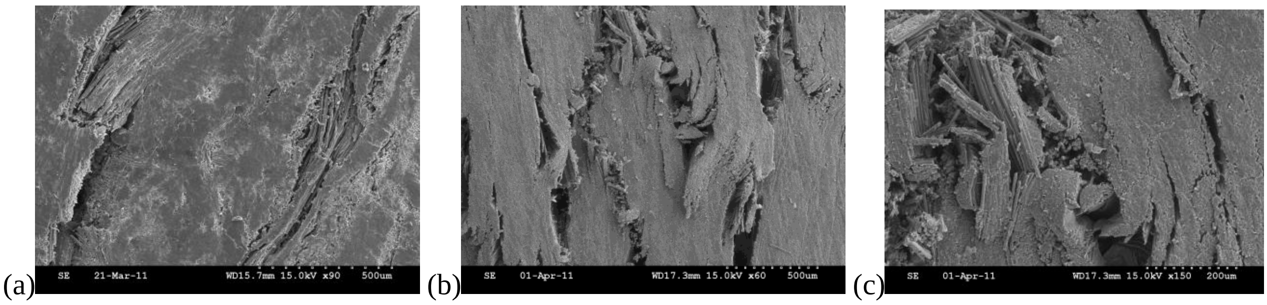

Fig. 6 SEMs of failed specimen under quasi-static loading from the (a) loading face, (b) and (c) side face.

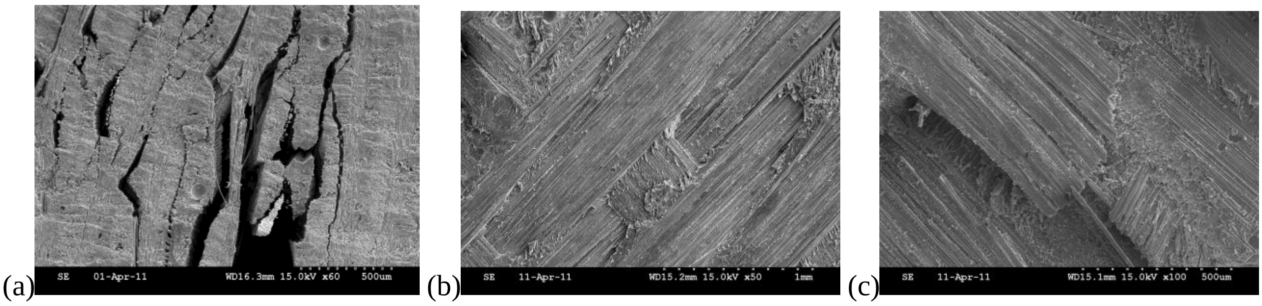

Fig. 7 SEMs of failed specimen under high strain rate (839 s^{-1}) loading (a) axial splitting, (b) delamination and (c) shear fracture.

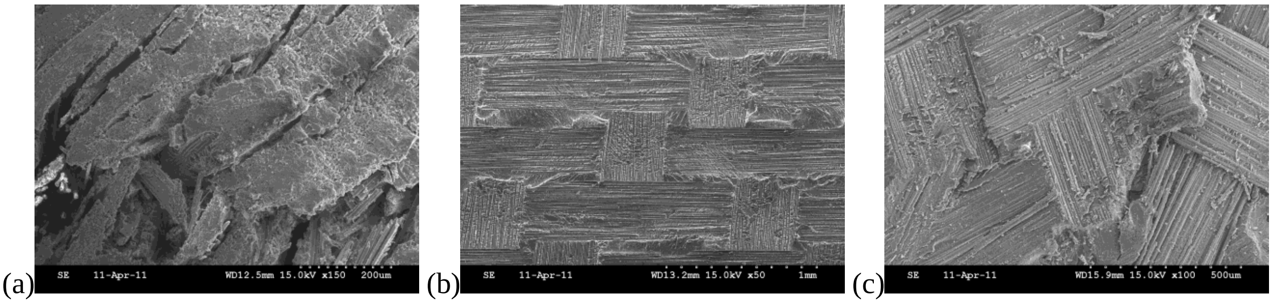
(a) (b) (c)

Fig. 8 SEMs of failed specimen under high strain rate (1217 s^{-1}) loading (a) splitting, (b) delamination, and (c) shear fracture.

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