EFFECTS OF STRAIN RATE AND FIBER WAVINESS ON THE COMPRESSIVE BEHAVIOR OF COMPOSITE LAMINATES

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SUMMARY: Experimental methods, including falling weight and split Hopkinson bar, were developed and applied for characterization of mechanical behavior of unidirectional and crossply carbon/epoxy laminates at strain rates up to 1,800 ms^{-1}. Dynamic stress-strain curves to failure were obtained at various strain rates under longitudinal and transverse compression and shear for the unidirectional material, and under axial compression for crossply laminates. The behavior of the crossply laminate is governed primarily by that of its 0-deg. plies, with a constant initial modulus and ultimate strain and strength increasing significantly with strain rate. One characteristic difference is that the ultimate strains of the crossply specimens are higher than those of the 0-deg. material at the same strain rates. This can be attributed to the fact that the 0-deg layers in the crossply specimen are supported by the adjacent 90-deg. layers and thus can sustain higher stresses and strains before failure.

KEYWORDS: Strain rate effects, fiber waviness, dynamic response, compressive testing of composites, impact testing, Hopkinson bar technique, carbon/epoxy laminates, dynamic stress-strain behavior.

INTRODUCTION

Some applications of composite materials involve dynamically loaded components and structures. The analysis and design of such structures subjected to dynamic loadings, ranging from low-velocity impact to high-energy shock loadings, requires the input of high strain rate properties. Numerical simulations, such as finite element analysis, need an accurate description of effects such as strain rate, loading history, deformation, internal damage, and wave propagation.

Experimental methods have been developed for characterization of mechanical behavior of unidirectional composites under longitudinal and transverse compression and under shear, at strain rates up to 1,800 ms^{-1} [1-3]. Falling weight impact and Split Hopkinson Pressure Bar Systems were developed and used. Dynamic stress-strain curves to failure were obtained at various strain rates. Moduli, strengths and ultimate strains were obtained as a function of strain rate.

Fiber waviness is a type of manufacturing defect that occurs particularly during the filament-winding process. Inspection of composite cylinder cross sections often reveals localized regions of layer waviness in the hoop direction resulting from post consolidation and cure shrinkage. Fiber/layer waviness represents one major factor that may partially explain why failure analysis of hydrostatically loaded composite cylinders based on properties obtained from flat and autoclave-cured specimens do not correlate well with cylinder test results. The degrading effect of fiber waviness on the stiffness and strength of composites has been studied by various investigators [4-6]. Analytical models were developed by the authors to predict the elastic properties, stress-strain behavior, and compressive strength degradation as a function of fiber waviness. Predictions were in good agreement with experimental results [7-9].

The combined effects of strain rate and fiber waviness have been investigated for unidirectional composites [10]. The results of the high strain rate characterization of the unidirectional material were used in an incremental analysis to predict high strain rate behavior of composites with fiber waviness. Longitudinal stress-strain curves for a material with a specified degree of uniform fiber waviness were obtained at various strain rates. The nonlinear stress-strain curve stiffens significantly with increasing strain rate because of the strain-rate sensitive shear component involved.

The subject of this paper is the dynamic compressive behavior of unidirectional laminates with fiber waviness and crossply laminates containing a wavy layer at the center. Layer waviness under quasi-static loading reduces the strength of the crossply laminate significantly but it reduces the stiffness only slightly. The observed increase in stiffness and strength of the crossply laminate with a central wavy layer is related to the dynamic behavior of the aligned as well as the wavy unidirectional material.

HIGH STRAIN RATE CHARACTERIZATION OF UNIDIRECTIONAL COMPOSITE

The material investigated was carbon/epoxy composite (IM6G/3501-6). Seventy-two and forty-eight-ply unidirectional laminates were selected for the basic high-strain-rate characterization. Experimental methods developed for the purpose have been described before [1-3]. They include fast loading with a servohydraulic machine, falling weight impact and Split Hopkinson Pressure Bar (SHPB) systems. Strains rates below 10 s^{-1} were generated using a servohydraulic testing machine. Strain rates between 10 s^{-1} and 300 s^{-1} were generated using the drop tower apparatus. Strain rates above 300 s^{-1} were generated using the Split Hopkinson Pressure Bar.

Transverse Compressive Behavior

Stress-strain curves to failure in the transverse to the fiber direction, under quasi-static and high strain rate loading, are shown in Fig. 1. They show a significant strain rate effect. The transverse strength, which is a matrix dominated property, shows a nearly twofold increase from the quasi-static value. The initial modulus follows a similar trend, although not as pronounced, with an increase of up to 37%. The ultimate strain shows no strain rate effect at all, which implies that it can be used as a failure criterion in analysis under dynamic loading. Figure 1 also shows that the stress-strain behavior changes with strain rate. The material stiffens as the strain rate increases. This stiffening behavior is very significant in the nonlinear region between quasi-static and 1 s^{-1} strain rates. Above the 1 s^{-1} strain rate, the material continues stiffening until it behaves almost linearly at a strain rate of 1800 s^{-1}. Two

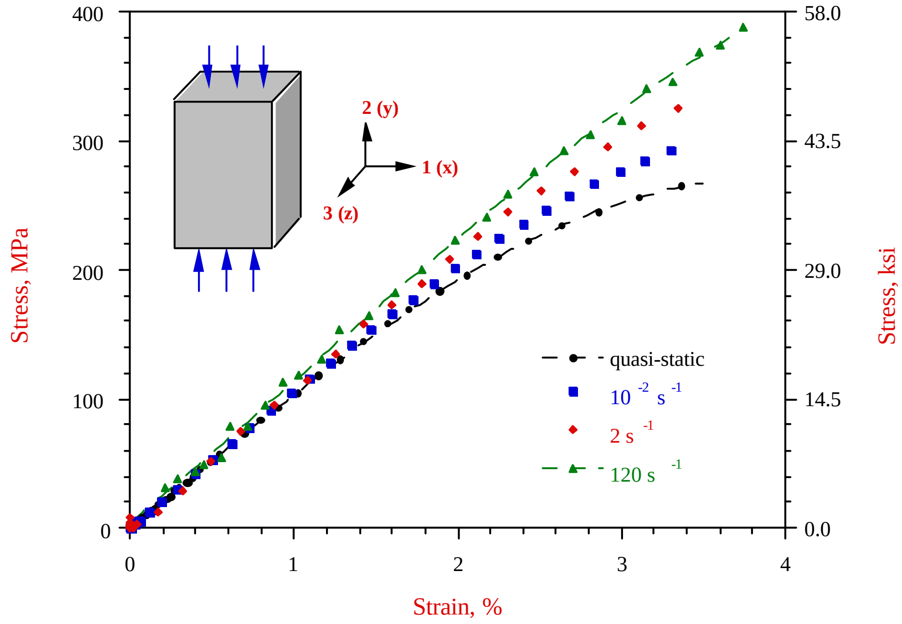

Fig. 1: Transverse compressive stress-strain curves for unidirectional IM6G/3501-6 carbon/epoxy under quasi-static and high strain rate loading

possible reasons for this phenomenon are proposed. The first is the viscoelastic nature of the polymeric matrix itself, and the second is the time-dependent nature of damage development. At lower rates, damage grows more gradually causing a well defined nonlinear region near the end of the stress-strain curve. At higher rates, however, damage does not have enough time to develop and thus it has a diminishing effect on the stress-strain curve.

In-Plane Shear Behavior

A 45° off-axis compression test was used to determine the in-plane shear behavior of the unidirectional composite. Figure 2 shows the shear stress-strain curves obtained under quasi-static and high strain rates of loading. This comparison reveals a strong strain rate effect. The shear stress-strain behavior, which is also matrix-dominated, shows high nonlinearity with a plateau region at a stress level that increases significantly as the strain rate increases. The "yield point" of the curve also increases with increasing strain rate. The strength increases sharply with strain rate from the quasi-static value by up to 80%. The initial modulus follows a similar trend, although not as pronounced, with an increase of up to 18%.

Longitudinal Compressive Behavior

Figure 3 shows longitudinal stress-strain curves to failure under quasi-static and high strain rates of loading by the pure end loading method. The stress-strain curve stiffens as the strain rate increases, although the magnitude of the change is much smaller compared to the transverse and shear behavior. The initial modulus shows only a slight increase with strain rate. The strength and ultimate strain are significantly higher than the static values by up to 79% and 74%, respectively. The increase in strength and ultimate strain observed may be related to the shear behavior of the composite and the change in failure modes. It is known that longitudinal compressive failure is intimately related to and governed by the in-plane shear response of the composite and the initial fiber misalignment [11,12]. According to the model described by the authors in ref. [12] the predicted longitudinal compressive strength increases as the in-plane shear stress-strain curve gets stiffer. The observed results of Fig. 3 are very compatible with those of Fig. 2 for in-plane shear behavior.

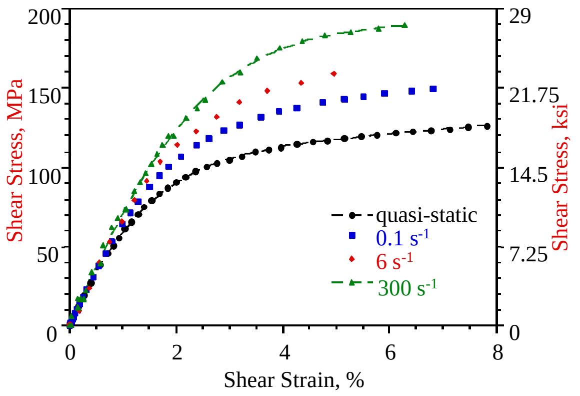

Fig. 2: Shear stress-strain curves for 45° off-axis unidirectional IM6G/3501-6 carbon/epoxy under quasi-static and high strain rate loading

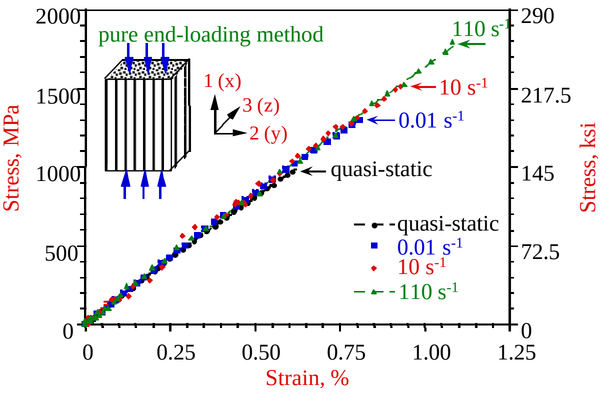

Fig. 3: Longitudinal compressive stress-strain curves for unidirectional IM6G/3501-6 carbon/epoxy under quasi-static and high strain rate loading

EFFECT OF FIBER WAVINESS

An incremental analysis was used to predict the dynamic behavior of wavy composites using the basic strain rate characterization data for the unidirectional material without fiber waviness [10]. A representative volume encompassing one period of waviness was divided into infinitesimally thin slices, which were analyzed as off-axis laminae (Fig. 4). Successive

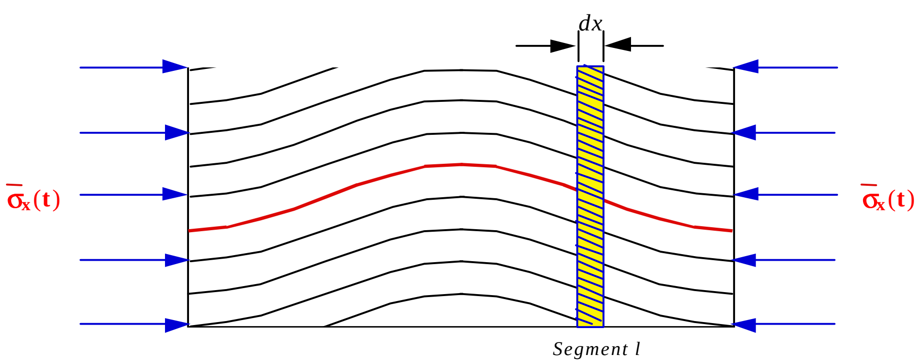

Fig. 4: Representative volume of a unidirectional composite with uniform waviness

load and time increments were applied with continuous monitoring of the resulting stress-strain behavior. The load increment can be controlled in such a way that either constant strain rate or constant stress rate can be achieved. The incremental analysis algorithm used consists of the following steps:

(1) Increase the applied stress and time by small increments.

(2) Calculate stress increments and corresponding loading rates along the principal material directions of segment dx.

(3) Calculate strain increments for each segment dx.

(4) Update effective (average) strain increments for entire representative volume.

(5) Update the effective stress and strain at every step to obtain the cumulative stress-strain behavior of the wavy composite.

(6) For each segment use the cumulative stresses along the local principal material directions and stress rates obtained in step 2 to find the corresponding instantaneous tangential stiffnesses from the basic strain rate characterization curves by interpolation/extrapolation on the $\log S_{ij}(\sigma_{ij}) - \log \dot{\sigma}_{ij}(\sigma_{ij})$ scale to update the material properties for the next increment.

(7) Obtain the Young's modulus by curve-fitting the initial part of the stress-strain curve.

Figure 5 illustrates the predicted major Young's modulus of the IM6G/3501-6 carbon/epoxy material as a function of strain rate and waviness parameter A/L. It is shown that the major Young's modulus degrades seriously as the fiber waviness increases. It increases moderately as the strain rate increases for the same waviness parameter A/L.

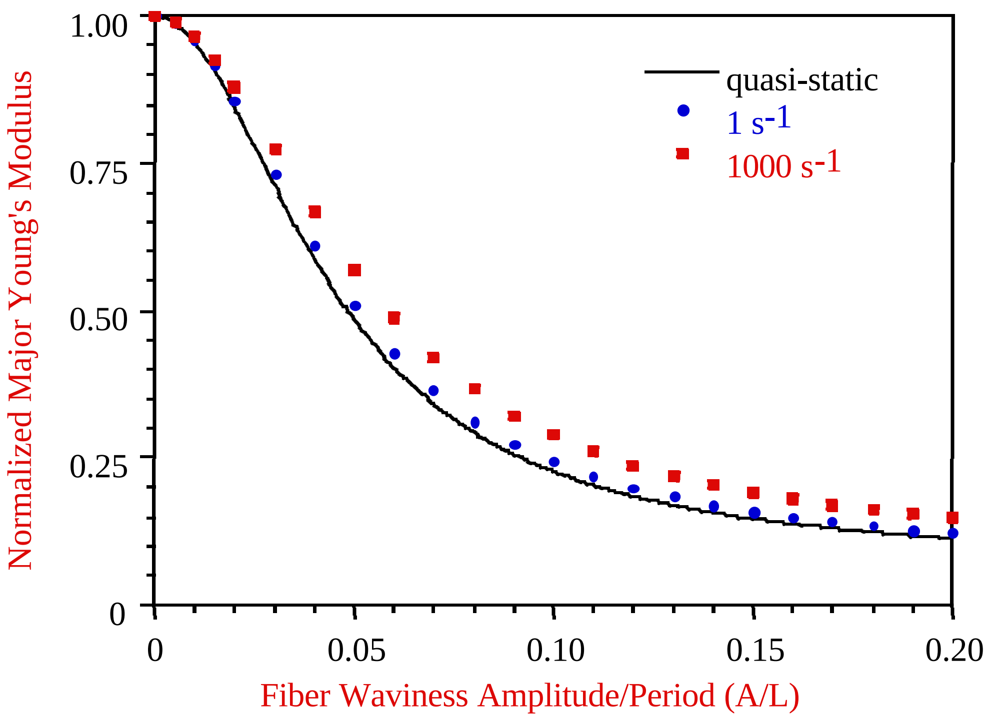

Fig. 5: Predicted major Young's modulus as a function of strain rate and waviness parameter A/L for unidirectional composite with uniform fiber waviness

Figure 6 illustrates the predicted stress-strain curves (for A/L = 0.075) under uniaxial compressive loading σ_x for various strain rates. It is shown that strong nonlinearity exists due to fiber waviness. The nonlinear stress-strain curve stiffens significantly as the strain rate increases due to the shear component involved. Figure 7 shows a comparison between predicted and experimental stress-strain curves obtained under quasi-static and high strain rate compressive loading for specimens with uniform fiber waviness (A/L = 0.043). The specimens failed prematurely due to spallation of the unsupported portions. The observed strain rate effect is not significant up to the premature failure load. However, if the load is increased above this level, a strong strain rate effect is expected.

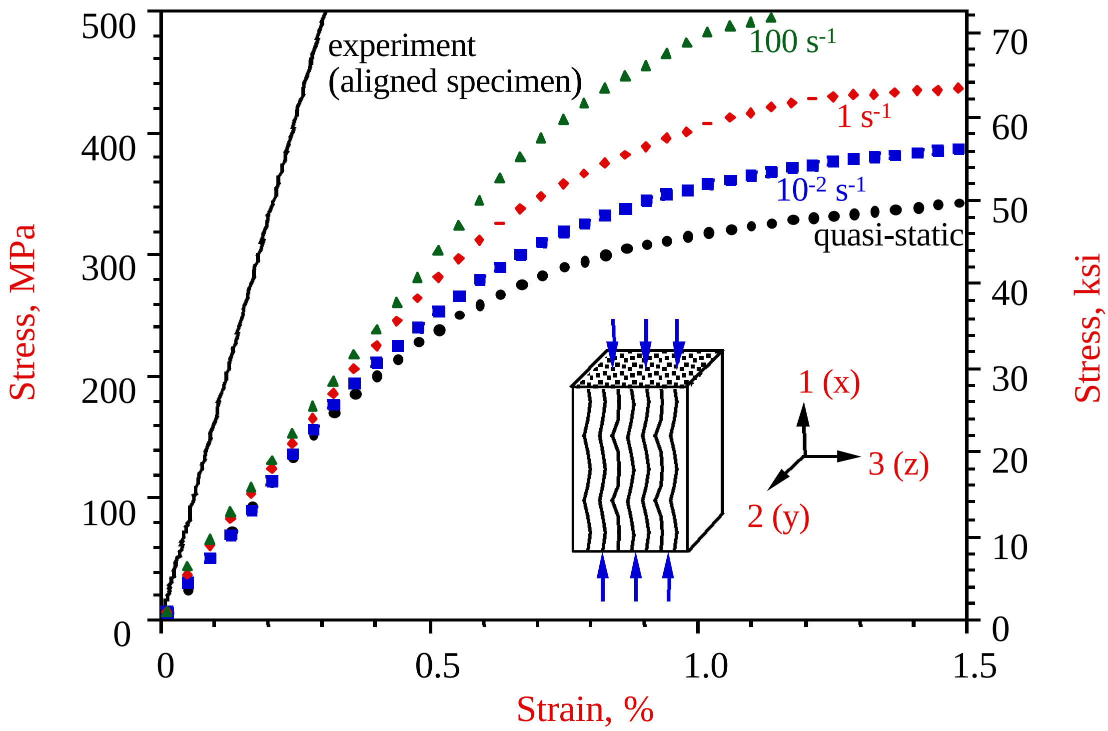

Fig. 6: Predicted stress-strain curves for unidirectional composite with uniform fiber waviness under uniaxial compression in the x direction (waviness parameter A/L=0.075)

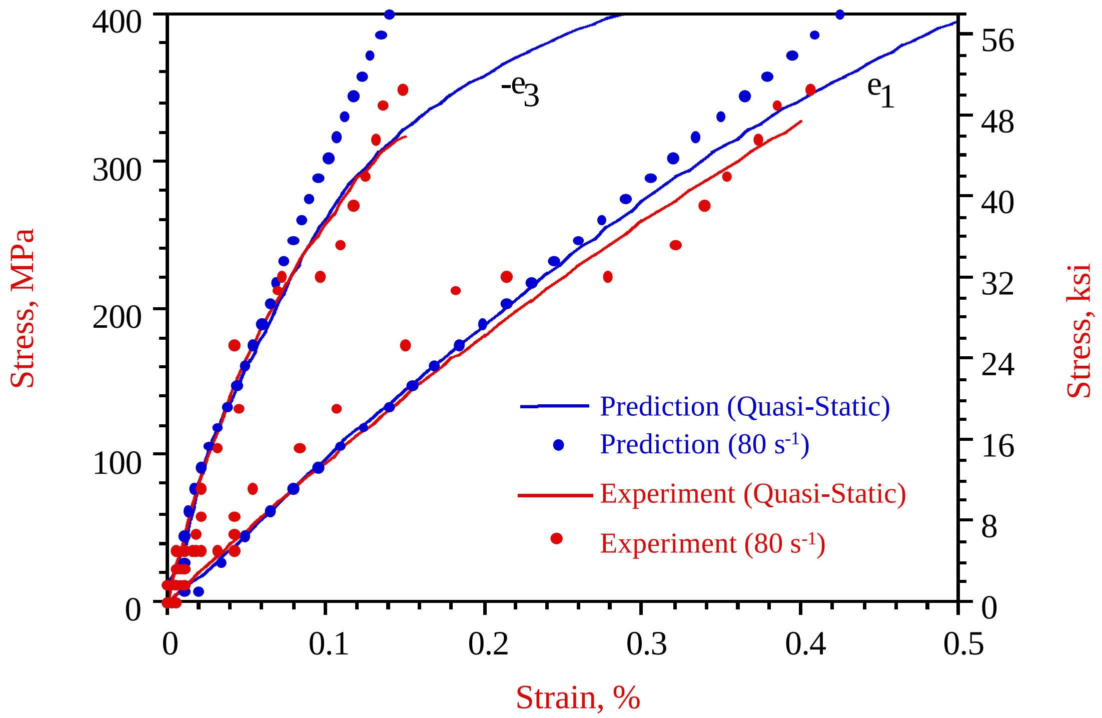

Fig. 7: Comparison between predictions and experiments on stress-strain curves for 150-ply unidirectional IM6G/3501-6 carbon/epoxy with uniform fiber waviness under quasi-static and high strain rate compressive loading in the x direction (A/L=0.0425)

CROSSPLY LAMINATES

Crossply carbon/epoxy laminates of $[(0_8/90_8)_2/0_4]_s$ layup were first fabricated without layer waviness and tested under quasi-static and high strain rate axial compressive loadings. The resulting stress-strain curves are shown in Fig. 8 and appear to be very similar to those of the unidirectional composite under longitudinal compression (see Fig. 3). The behavior of the crossply laminate is governed primarily by that of its 0° plies, with a nearly constant initial modulus and strength and ultimate strain increasing significantly with strain rate. One characteristic difference is that the ultimate strains in the crossply specimens are higher than those of the 0° material at the same strain rates. This can be attributed to the fact that the 0° layers in the crossply specimen are supported laterally by the adjacent 90° layers and thus can sustain higher stresses and strains before failure.

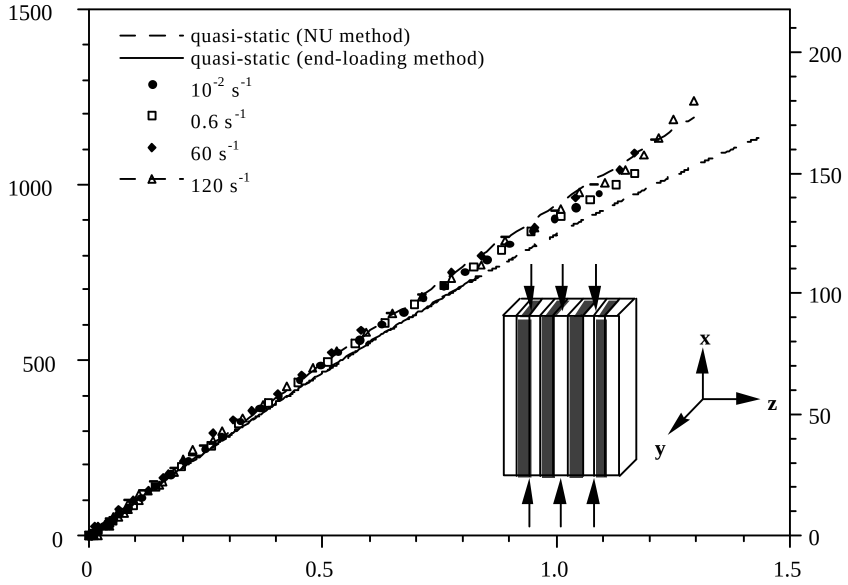

Fig. 8: Stress-strain curves of $[(0_8/90_8)_2 0_4]_s$ crossply carbon/epoxy laminate under quasi-static and high strain rate compressive axial loading

Additional crossply laminates were fabricated with a controlled degree of waviness of the central 0° layer. Special techniques were developed and used for the purpose [11]. Figure 9 shows an ultrasonic C-scan of a 72-ply $[(0_8/90_8)_2\overline{0}_{8w}]_s$ crossply carbon/epoxy composite with central layer waviness. Pulse echo scanning was used with an unfocused 5 MHz transducer and with the gate of the received signal placed at the back surface. The period of waviness can be detected and measured very easily from the C-scan.

Specimens with wavy layers were tested under quasi-static and high strain rate loadings. The resulting stress-strain curves are shown in Fig. 10 and compared with corresponding curves for specimens without layer waviness. Layer waviness produces a certain amount of softening under quasi-static loading but no noticeable difference at the high strain rates of 100-120 s^{-1}. The effect of high strain rate is the opposite, it tends to stiffen the material response for both the aligned and wavy specimens. Thus, it is seen in Fig. 10 that the stress-strain curve of the wavy specimen at the high strain rate is stiffer than the quasi-static curve of the aligned specimen. Layer waviness has a deleterious effect on strength and ultimate strain under both quasi-static and high strain rate loadings as seen in Fig. 10. This is due to the fact that waviness induces other failure mechanisms, such as transverse tension and delamination, which cause earlier failures.

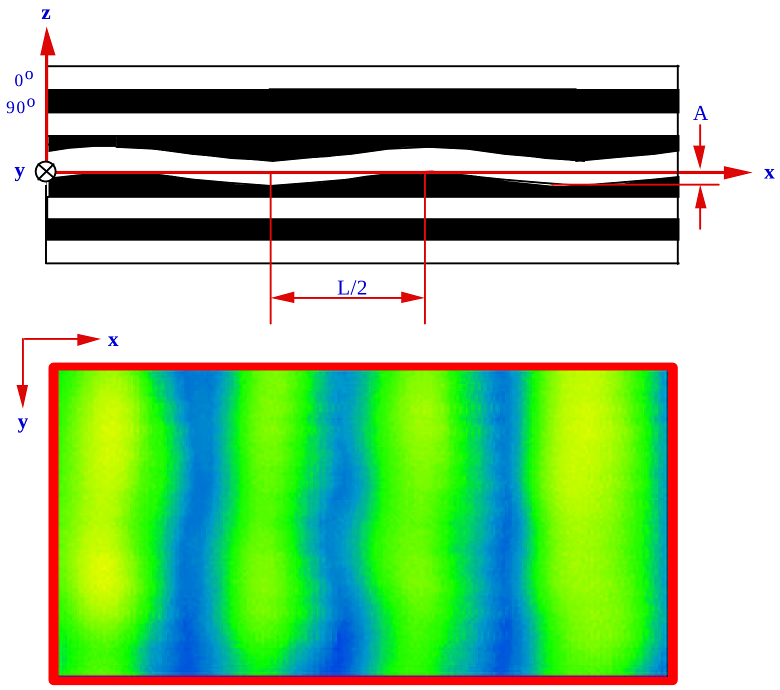

Fig. 9: Ultrasonic C-scan image of a 72-ply crossply composite with embedded layer waviness

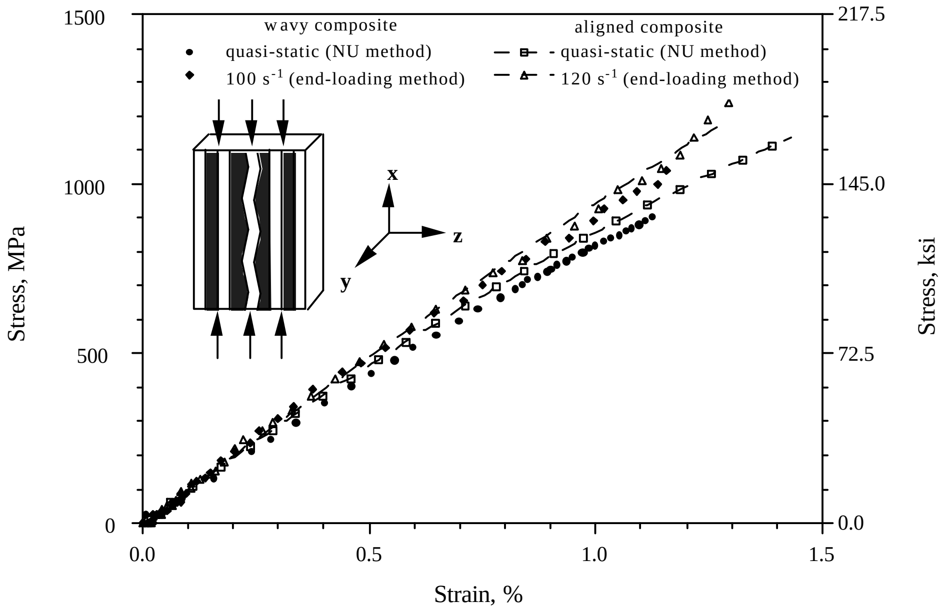

Fig. 10: Stress-strain curves for $[(0_8/90_8)_2\bar{0}_{8w}]_2$ crossply composite with central layer waviness under quasi-static and high strain rate compressive loading

CONCLUSIONS

Falling weight impact and Split-Hopkinson Pressure Bar systems were used to characterize a unidirectional carbon/epoxy composite at high strain rates under longitudinal and transverse compressive loadings and under in-plane shear. The 90-degree properties, which are governed by the matrix, show an increase in modulus and strength over the static values but no significant change in ultimate strain. The stress-strain curve stiffens as the strain rate increases. The shear stress-strain behavior, which is also matrix-dominated, shows high nonlinearity with a plateau region at a stress level that increases significantly as the strain rate increases. The initial transverse and shear moduli vary in the same manner with strain rate, showing an increase of approximately 35% over seven decades of strain rate. The transverse and shear strengths also vary together but in a more pronounced way, showing an almost two-fold increase over seven decades of strain rate. Longitudinal stress-strain curves were also obtained at various strain rates. The initial modulus does not change with strain rate, however, the compressive strength and ultimate strain increase significantly with strain rate by almost 70% over seven decades of strain rate. This can be attributed to the fact that the longitudinal compressive strength is related to the shear behavior of the material which is a matrix dominated property.

Falling weight and Hopkinson bar tests were also conducted on crossply carbon/epoxy laminates of $[(0_8/90_8)_2/0_4]_s$ layup. Stress-strain curves to failure were obtained at different strain rates. The behavior of the crossply laminate is governed primarily by that of its 0° plies, with a constant initial modulus and ultimate strain and strength increasing significantly with strain rate. One characteristic difference is that the ultimate strains of the crossply specimens are higher than those of the 0° material at the same strain rates. This can be attributed to the fact that the 0° layers in the crossply specimen are better supported by the adjacent 90°layers and allowed to develop higher stresses and strains before failure.

The combined effects of strain rate and fiber waviness were investigated for unidirectional and crossply laminates. The results of the high strain rate characterization of the unidirectional material were used in an incremental analysis to predict high strain rate behavior of composites with fiber waviness. Longitudinal stress-strain curves for a material with a specified degree of uniform fiber waviness were obtained at various strain rates. The nonlinear stress-strain curve stiffens significantly with increasing strain rate because of the strain-rate sensitive shear component involved. The study was extended to the case of crossply laminates containing a wavy layer at the center. Layer waviness under quasi-static loading reduces the strength of the crossply laminate significantly but reduces the stiffness only slightly. Both stiffness and strength increase at high strain rates for the laminate with a wavy layer with the ultimate strain remaining relatively unchanged.

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