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# Experimental and Numerical Investigation of High Strain Rate Mechanical Behavior of a [0/45/90/- 45] Quadriaxial E-Glass/Polyester Composite

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**Abstract**

Quasi-static ($10^{-3}$-$10^{-1}$ $s^{-1}$) and high strain rate (~900 $s^{-1}$) compression behavior of an E-Glass fiber woven fabric reinforced Polyester matrix composites was investigated by using a Shimadzu AG-I testing machine and a Split Hopkinson Pressure Bar apparatus in the Dynamic Testing and Modeling Laboratory of Izmir Institute of Technology. During the experiments, a high speed camera was used to determine deformation behavior. In both directions, modulus and failure strength increased with increasing strain rate. Higher strain rate sensitivity for both elastic modulus and failure strength was observed in the in-plane direction. Based upon these experimental data, a numerical model was developed using the commercial explicit finite element code LS-DYNA to investigate compressive deformation and damage behavior of composites. Excellent agreement was demonstrated for the case of high strain rate loading. Also, the fracture geometries were successfully predicted with the numerical model.



*Keywords:* High strain rate; Stress wave; Numerical simulation; LS-DYNA

## 1. Introduction

Determination of high strain rate mechanical properties and numerical modeling of glass fiber reinforced polymer matrix composite materials are especially important in different areas such as military, aerospace, and automotive applications. Dynamic and quasi-static mechanical properties should be determined to provide essential information about deformation and damage modes, and to generate necessary data for use in numerical modeling studies.

Several previous studies were prepared on characterization and numerical modeling of composites, some of their studies can be found in this paragraph. The compressive dynamic behavior of composites has been recently

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investigated by many authors [1-5]. In these dynamic compressive experiments, some investigators used servo hydraulic testing machines (for strain rates up to ~100 $s^{-1}$) and others used Split Hopkinson Pressure Bar apparatus for higher strain rate values (for strain rates varying in the range of 500-2000 $s^{-1}$). Most of the studies focused on damage modes and strain rate sensitive nature of these polymer matrix composites. In the determination of damage modes, post-mortem analysis was carried out. Quasi-static and high strain rate behavior of glass fiber reinforced composites was investigated by other researchers experimentally and numerically [6-8]. Brown et al. [9] simulated thermoplastic composites by using material model MAT-162 in LS-DYNA. They calibrated MAT-162 with data provided by quasi-static and dynamic tests.

In the present study, high strain rate compression behavior of an E-glass fiber reinforced polyester composite was determined. Composite plates were prepared in 0/45/90/-45 orientation by using VARTM, tested in Split Hopkinson Pressure Bar apparatus, and modeled with explicit commercial finite element code LS-DYNA [10] in Dynamic Testing and Modeling Laboratory of Izmir Institute of Technology. The material model was validated by comparing experimental and numerical results. In the experimental part, high-speed camera was also used to to determine operative failure modes and results were compared with those of numerical simulations. Damage modes and bar responses obtained from the numerical model showed good agreement with experimental results.

## 2. Experimental

E-glass fiber woven fabric (Quadriaxial [0/45/90/-45], 0.6 $kg/m^2$) – Crystic 702PAX polyester composite plates, 350x350x10 mm in dimensions, were prepared using vacuum assisted resin transfer molding method at the Dynamic Testing and Modeling Laboratory, Izmir Institute of Technology. Cylindrical specimens having ~9.75 mm in diameter were core-drilled from the composite plates in longitudinal, transverse and through–thickness directions.

Quasi-static tests were carried out at strain rates of $10^{-3}$, $10^{-2}$, and $10^{-1}$ $s^{-1}$ using a Shimadzu AG-I testing machine and high strain tests were conducted using a compression SHPB at an average strain rate of 900 $s^{-1}$. The particular SHPB used in experiments consists of CPM Rex76™ bars, a 350 mm long striker bar, a 3600 mm incident bar and an 1800 mm transmitter bar, all having a diameter of 20.35 mm. Multiple reloading of the samples in the SHPB was avoided by using a transmitter bar shorter than the incident bar.

## 3. Numerical Modeling

Finite element modeling of dynamic experiments is important to provide proper material model data which can further be used in other problems such as blast, impact, etc.. In this study, the LS-DYNA 971 commercial finite element code was used to model Split Hopkinson Pressure Bar experiments of composites. In the analysis, MAT-162, a progressive failure model was used to model damage initiation and progression in composites. This model is based on the principle of progressive failure of Hashin [11] and damage mechanics of Matzenmiller et al. [12] which controls strain softening behavior after failure.

In the analysis it was found that, when damage parameters AM1 and AM2 were set to the value of 2, post-failure behavior was represented well. From the through-thickness compression test model to represent fiber failure observed in the experiments, damage parameter, AM3, was found to be 0.5. A value of 0.35 for AM4, reported in [13], was used in the present analysis. Some other properties also have to be fine tuned by comparing the numerical results with experiments. The parameters that need to be calibrated are out-of-plane fiber strength, matrix shear strength and delamination constant. In an experimental work conducted on plain-weave E-glass/epoxy composite [14], interlaminar shear strength was measured to be 29.4 MPa at an average strain rate of 1000 $s^{-1}$. In this research, 30 MPa was used for interlaminar shear strength. The through-thickness tensile strength of the composite was estimated to be 50 MPa. Experimental results revealed that the through-thickness tensile strength of the composite is usually lower than the tensile strength of the polyester matrix material. The interlaminar shear stress concentration was studied by Pahr et al. [15] and the stress concentration was reported to be 1.21. In this study, a value of 1.2 was used for the delamination constant.

The effect of strain rate on the strength and elastic modulus of composite layer is modeled by strain rate dependent functions with four parameters. Based on the experimental data, values of $C_1 = 0.02048$, $C_2 = 0.030135$ and $C_4 = 0.050517$ for E-glass/polyester composite were calculated and used in the present paper as baseline strain rate sensitivity constants. A 0.024 value of $C_3$ was calculated from the experimental data given in

[14]. The eroding parameters, E_LIMIT; maximum allowable axial tensile strain, E_CRSH; minimum allowable compressive volume strain, and EEXPN; tensile volume strain were obtained from fine tuning them to get the bar responses and damaged shapes. The material properties used in the simulation for the bars and the composite specimen are shown in Table 1.

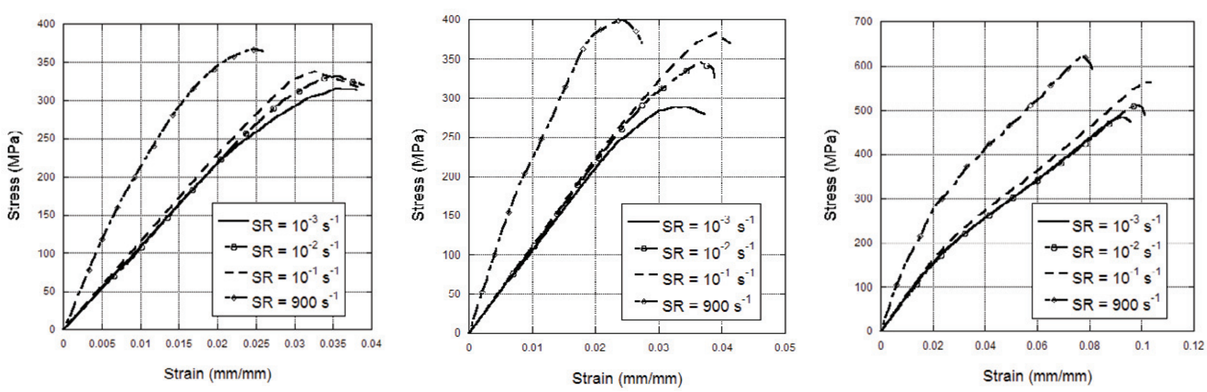
Table.1. Material properties used in numerical investigation

| E-glass/polyester composite | | | |
|---|---|---|---|
| Density, ρ, (kg $m^{-3}$) | 1850 | Fiber crush, $S_{FC}$, (GPa) | 0.6 |
| Tensile modulus, $E_a, E_b, E_c$ (GPa) | 12.2, 13.05, 8.014 | Matrix mode shear strength, $S_{AB}$, $S_{BC}$, $S_{CA}$, (GPa) | 0.04 |
| Poisson's ratio, $\vartheta_{ab}, \vartheta_{bc}, \vartheta_{cb}$ | 0.08, 0.14, 0.15 | Residual compressive scale factor, SFFC, (GPa) | 0.3 |
| Shear modulus, $G_{AB}$, $G_{BC}$, $G_{CA}$, (GPa) | 1.79, 1.52, 1.52 | Friction angle, PHIC, (GPa) | 10 |
| In-plane tensile strength, $S_{AT}$, $S_{BT}$, (GPa) | 0.4 | Delamination, S_DELM | 1.2 |
| Compressive strength, $S_{AC}$, $S_{BC}$, (GPa) | 0.366 | Fiber shear, $S_{FS}$, (GPa) | 0.2 |
| Incident and transmitter bars | | | |
| Density, ρ, (kg $m^{-3}$) | 8255 | | |
| Young's modulus, E, (GPa) | 214 | | |
| Poisson's ratio, $\vartheta$ | 0.3 | | |

In the damage analysis of the composite specimen, a full (no symmetry definitions) numerical model was used with appropriate boundary conditions. The model has three components in contact: the incident bar 3600 mm and transmitter bar 1800 mm in length, and the specimen. Experimentally measured stress pulse is used as an input to the face of the incident bar that striker bar impacts and all other boundaries are traction-free. Incident and transmitter bar models are composed of 180000 elements. Through-thickness and in-plane composite specimens were modeled with 60000 and 20000 elements, respectively. Eroding single surface contact was defined between composite layers and eroding surface-to-surface contact was used between composite and both of incident and transmitter bars.

## 4. Results and Discussion

In Figs. 1(a-c) stress strain curves of longitudinal, transverse, and through-thickness specimens can be seen for four different strain rates. Three of these strain rates are in the quasi-static range; $10^{-3}$, $10^{-2}$, $10^{-1}$ $s^{-1}$ and one of them is in the dynamic range; 900 $s^{-1}$.

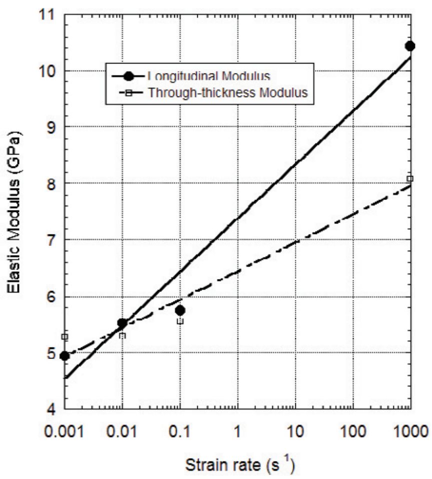



(a) (b) (c)

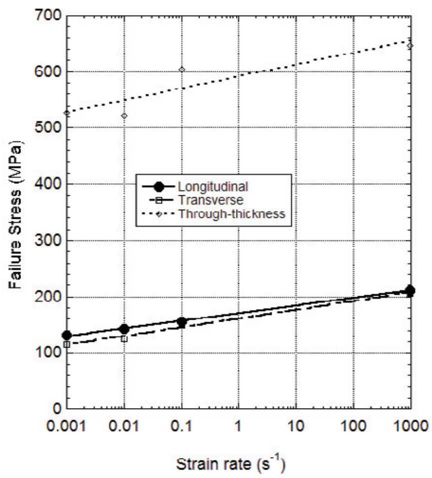
Fig. 1. Stress-Strain curves of the composite in the (a) longitudinal, (b) transverse, and (c) through-thickness directions.

It can be seen from Fig. 1 that longitudinal and transverse specimens show linear behavior in the beginning of deformation and show a slight deviation from linearity before final failure. As can be seen from Fig.1(a), both in quasi-static and high strain rates, as strain rate increases failure stress increases and strain decreases. On the other hand for transverse specimen (Fig.1(b)), in the quasi-static range, as strain rate increases, both failure stress and failure strain increase. When the strain rate increases to the dynamic range, failure stress increases while failure strain decreases. It can be seen that, in longitudinal direction, the composite has a lower failure stress value than it has in transverse direction. It is also worth to note that, strength values in longitudinal and transverse directions are highly dominated by mechanical properties of matrix material.

Through-thickness test results show slightly different behavior as can be seen in Fig.1(c). The behavior becomes nonlinear at larger strains, indicating stress induced damage and its accumulation with increasing strain. In the quasi-static range it is seen that, as strain rate increases, both failure stress and failure strain increase. On the other hand, when strain rate increases to dynamic range, failure stress increases but failure strain decreases. It is also worth noting that, in the through-thickness direction, failure strain is considerably higher than in other directions, both in quasi-static experiments and dynamic experiments.




(a)



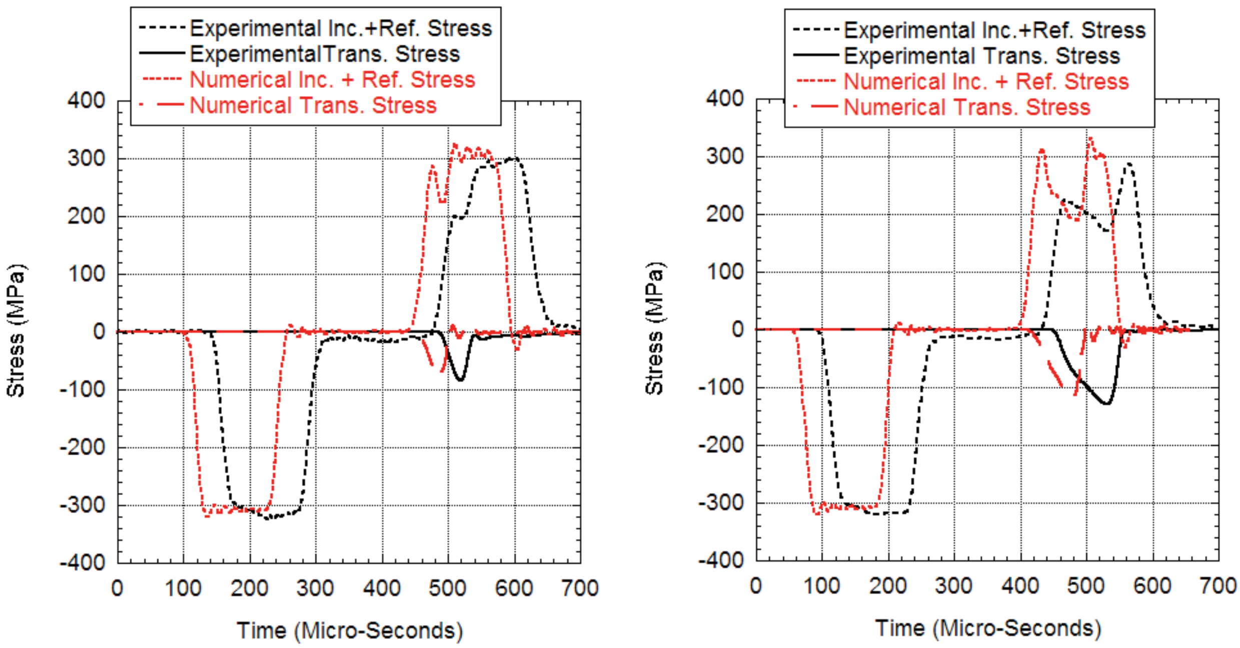

(b)

Fig. 2. Strain rate dependency of (a) moduli, (b) failure stresses in three directions.

Elastic moduli of the composite were calculated using quasi-static and dynamic test results for different strain rates. Then those values were fitted to strain rate dependency functions of the material model, CERATE's. Strain rate dependency of longitudinal, transverse, and through-thickness moduli, and also failure stresses in three directions can be seen in Figs. 2(a) and (b). Although in quasi-static tests, composite has nearly same modulus in axial and transverse directions. Transverse modulus has higher rate sensitivity and dynamic transverse modulus is quite higher. Through-thickness and longitudinal modulus have nearly same rate dependency.

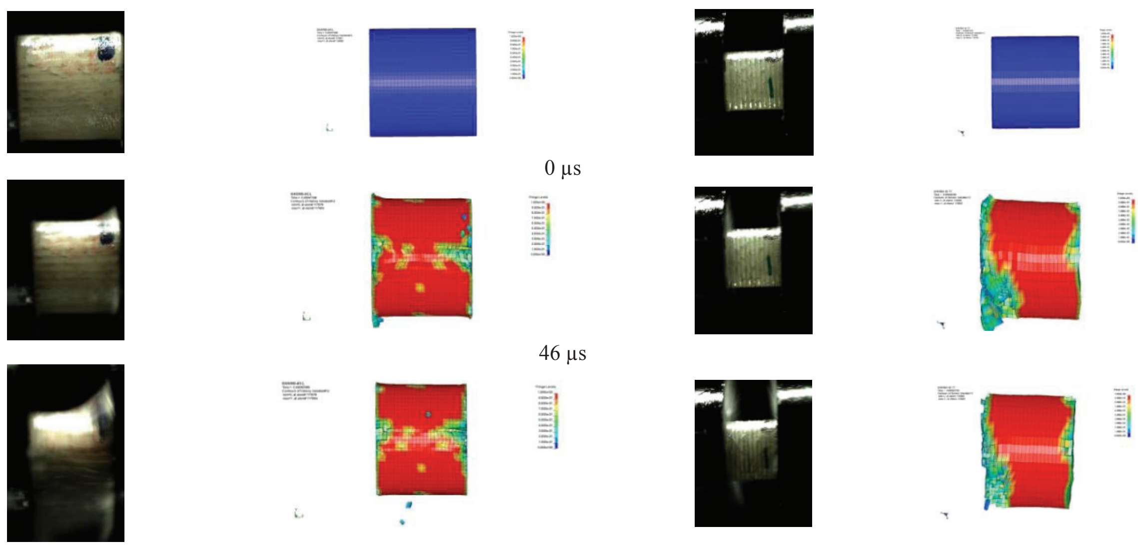
Composite show similar rate sensitivity of failure stresses in all three directions. Averaging three values obtained from fits, CERATE1, strain rate dependency of failure stress, was found to be 0.02048.

In Figs. 3(a) and (b) experimental and numerical bar responses of the composite are given. Numerical data was intentionally time-shifted for clarity. It is clear that the numerical data show very similar behavior to the experimental data and, hence, confirm the validity of the model. From Fig. 3(b), the amplitude of the reflected wave is seen to increase as a function of time from zero to a local maximum before decreasing gradually: this is followed by a sharp rise indicating that the specimen has been extensively damaged or has failed.




(a) (b)

Fig. 3. Experimental and Numerical bar responses in the (a) longitudinal and (b) through-thickness directions.




(a) (b) (c) (d)

Fig. 4. Damage sequences of composite; in longitudinal direction (a) experimentally and (b) numerically, in through-thickness direction (c) experimentally and (d) numerically.

In Fig. 4 experimentally obtained and numerically calculated damage sequences of composite can be seen in longitudinal and through-thickness directions. In experiments, a high-speed camera was used to obtain the images. In figures, first pictures show the instant that incident bar strikes the specimen. The images were taken with an interframe time of 46 μs. Numerical simulation results are shown with the contours of delamination mode history variable of MAT-162 (History variable #12, [10]).

## 5. Conclusions

In this study quasi-static and high strain rate compression behaviors of an E-glass/polyester composite were determined in longitudinal, transverse, and through-thickness directions. At higher strain rates an increased modulus and failure strength were observed in all directions. Higher strain rate sensitivity for elastic modulus was observed in the transverse direction. A numerical model has been developed to investigate deformation and fracture of the composite. Excellent agreement has been demonstrated for the case of high strain rate loading by comparing high-speed camera images with images from the numerical model. In addition, the fracture geometries were successfully predicted with the numerical model.

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