The Strain Rate Effect on Bending Properties of Basalt and Carbon Fibers Reinforced Phenolic Composites

M. Najafi *
Department of Mechanical Engineering,
South Tehran branch, Islamic Azad University, Tehran, Iran
E-mail: moslem.najafi85@yahoo.com
*Corresponding author

S. M. R. Khalili
Department of Mechanical Engineering,
K. N. Toosi University of Technology, Tehran, Iran
E-mail: smrkhalili2005@gmail.com

R. Eslami-Farsani
Department of Mechanical Engineering,
K. N. Toosi University of Technology, Tehran, Iran
E-mail: eslami@kntu.ac.ir

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Abstract: In this study, the strain rate effect on the bending properties of fiber reinforced composites for three types of polymer composites namely phenolic resin reinforced by woven basalt fibers, woven carbon fibers, and woven basalt/ woven carbon fibers at a total volume fraction of approximately 35% has been determined. Flexural tests have been conducted at low range of strain rates included 0.03 min^{-1}, 0.06 min^{-1} and 0.09 min^{-1}. Specimens with identical geometry have been used in all the tests. Experimental results showed that the strain rate has a significant effect on the material response in bending. Results showed that, both the flexural modulus and the ultimate flexural strength of the three types of composites are increased with the increasing in the strain rate. Also, the bending properties of composites reinforced with woven carbon fibers are very sensitive to the strain rate during the test.

Keywords: Basalt Fibers, Carbon Fibers, Strain Rate, Phenolic Resin

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Biographical notes: M. Najafi received his MSc in Mechanical Engineering at the Islamic Azad University, South Tehran Branch. He is interested in Mechanical Behaviour of Composite Materials, Fatigue and Fracture and Finite Element Methods. **S. M. R. Khalili** received his PhD in Applied Mechanics from Indian Institute of Technology (I.I.T), New Delhi, India 1992. He is currently Visiting Professor at Faculty of Engineering, University of Kingston, London, UK. **R. Eslami-Farsani** is an Assistant Professor of Mechanical Engineering at the K. N. Toosi University of Technology, Tehran, Iran. He received his PhD in Mechanical Engineering from K. N. Toosi University of Technology, Iran, 2005.

1 INTRODUCTION

In the last two decades, fiber-reinforced polymer (FRP) composites have generated considerable interest in various applications due to their unique and beneficial properties. Most of these applications require good performance over a range of deformation rates. Hence it has become important to know the effects of strain rate on the mechanical behaviour of FRP composites. Polymer composite structures undergo different loading condition during their service life and the mechanical response of these materials is sensitive to the rate at which they are loaded [1].

For the effective use of FRP composites their response under different loading rates should be clearly understood [2].Unlike metals, which have been studied extensively over a wide range of strain rates, only a limited amount of information is available with regard to the effect of strain rate on the response of fibrous composites [3].

Strain rate sensitivity of composite materials represents a primary aspect in mechanical behaviour of composite structures. Indeed, mechanical properties of composite materials are generally affected by strain rate as shown in Refs. [2-5]. In particular, the initial Young's modulus and failure stress increase as the strain rate becomes higher [4], [7]. The mechanical properties of some composite materials are rate sensitive at low range of strain rate [8]. It seems that the greater the strain rate and the loading velocity, the greater are the stiffness and ultimate strength of the composite materials. However a direct co-relation between the loading rate dependency of composite materials and those of the constituent phases may be difficult or rather complicated [9].

Carbon fibers have an excellent flexural strength and modulus, though they are much more expensive than other fibers. It is known that the basalt fibers have better tensile modulus than the E-glass fibers, have greater failure strain than the carbon fibers as well as good resistance to chemical attack, impact load and fire with less poisonous fumes [10].

Therefore, a woven hybrid composite of basalt and carbon fibers is reasonably priced with adequate mechanical, thermal and impact properties. However, it is not clear how the bending properties of the hybrid composite materials will be changed at different strain rates. In this paper, the flexural behavior of the basalt and carbon as well as hybrid basalt/carbon fibers reinforced phenolic composites is examined at three different strain rates.

2 MATERIALS AND FABRICATION OF SPECIMENS

Three kinds of specimens were prepared. The first specimen was a composite consisted of 8 plies of carbon fibers (AC220, Colan Products, Australia) and a phenolic matrix (Phenlam ® CL2000T, Huntsman Chemical Company, Australia). The second specimen consisted of 4 plies of basalt fibers (BAS 630, Basaltex™, Belgium) and the above said matrix. The third specimen consisted of 3 plies of basalt and 3 plies of carbon fibers, stacked alternatively and the above said matrix. The materials were fabricated in the form of plates with dimensions 400 mm × 400 mm × 2.5 mm. The fiber volume fraction of all composite specimens was 35% approximately. The laminates were fabricated by hand lay-up technique. The plates were fabricated at room temperature and relative humidity of 40% for 8 days. Physical and mechanical properties of the matrix and the fibers are presented in Table 1.

Table 1 Specification of the fibers and the resin

Specification	Basalt fibers	Carbon fibers	Phenolic resin
Thickness (mm)	0.56	0.25	…
Surface weight (g/m^2)	630	198	…
Density (g/cm^3)	2.70	1.75	1.2
Tensile strength (MPa)	3000	4210	24 - 45
Tensile modulus (GPa)	89	230	4
Elongation at break (%)	3.15	1.5	1 - 2
Gel time (min)	…	…	25

3 SPECIMEN PREPARATION

To avoid uncertainties related to size effects, the specimens in all the tests have the same geometry. Specimens were cut from the plates in the specified dimensions, 115 mm × 24 mm × 2.5 mm according to standard ASTM D 790 M, using a water jet cutting machine (Fig. 1). Each specimen was polished using sand paper. In this way, local surface cracks and local surface material heterogeneities were removed. After cutting to predetermined dimensions, the specimens were coded and their dimensions were measured. Specimens were divided into three groups: (1) basalt/phenolic group, (2) carbon/phenolic group, (3) basalt/carbon/phenolic group. All the specimens in each group were stored at room temperature until flexural testing.

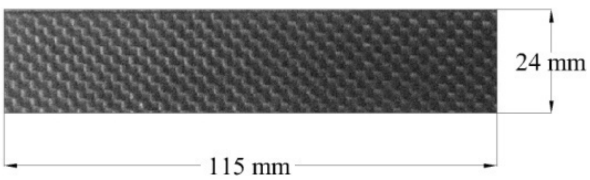


Fig. 1 Specimens preparation

4 FLEXURAL TESTING

Three-point bending tests were performed on a universal testing machine (Santam Co., Iran) according to ASTM D790M. Flexural tests have been conducted at low range of strain rates included low crosshead speed of approximately 2.35 mm/min (Strain Rate ~ 0.03 min^{-1}), intermediate crosshead speed of 4.7 mm/min (Strain Rate ~ 0.06 min^{-1}) and high crosshead speed of about 7 mm/min (Strain Rate ~ 0.09 min^{-1}) as shown in Fig. 2. The experiments were conducted at ambient temperature (+25 ^{o}C) and relative humidity (40%) conditions.

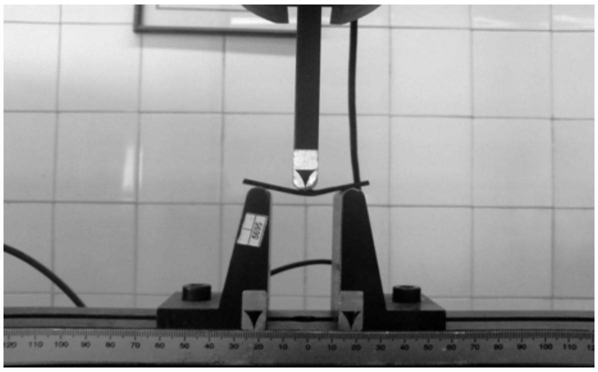


Fig. 2 Flexural testing process

5 RESULTS AND DISCUSSION

The objective of this research was to evaluate the effects of strain rate on bending properties of FRP composites. Typical flexural stress-strain curves of the three types of fiber reinforced phenolic composite materials are shown in Figs 3-5. Each figure contains the flexural stress strain curves from tests at various strain rates of one type of specimen. It is clearly observed that unlike basalt/phenolic composite and basalt/carbon/phenolic composite, which their flexural stress-strain curves are closely linear, the flexural stress-strain curves of carbon/phenolic composite is mostly non-linear. The carbon/phenolic specimens show a classical strain rate dependent response (Fig. 5). The stress strain curves at all strain rates have an initial linear response, a rounded transition to inelastic response followed by an inelastic range with a nearly constant low hardening rate. The effect of strain rate is clearly observed since the difference in the flow stress between the different strain rates is distinct and significant.

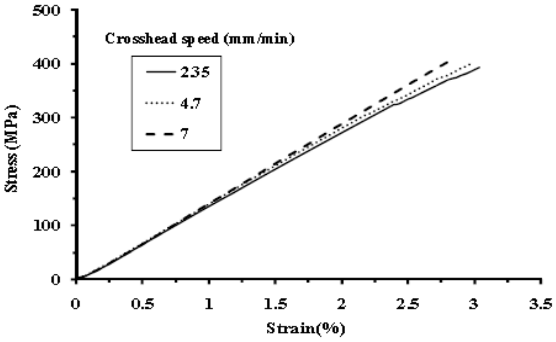


Fig. 3 Flexural stress-strain curves of basalt/phenolic composite at 2.35, 4.7 and 7 mm/min crosshead speeds

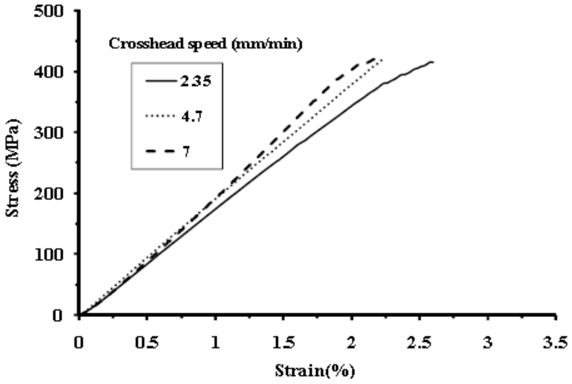


Fig. 4 Flexural stress-strain curves of basalt/carbon/phenolic composite at 2.35, 4.7 and 7 mm/min crosshead speeds

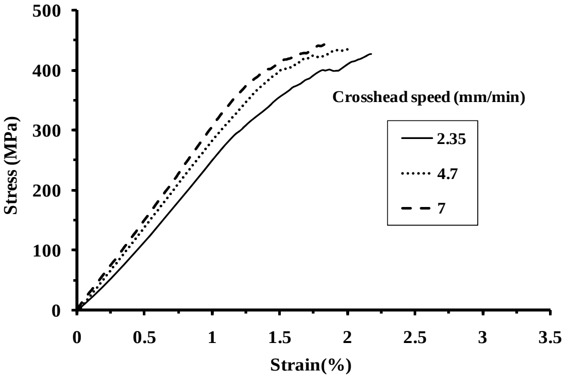


Fig. 5 Flexural stress-strain curves of carbon/phenolic composite at 2.35, 4.7 and 7 mm/min crosshead speeds

The comparative results shows that the values of bending properties are increased more for carbon/phenolic composites at higher strain rates. It may be assumed that the failure mechanisms are loading rate sensitive phenomenon. A summary of the bending property values at three strain rates are given in Tables 2- 4. From Tables 2- 4, it can be concluded that these FRP composites are the strain rate sensitive materials.

Moreover, the results indicate that the bending properties of these FRP composites tend to increase with increasing strain rate. In general, a stiffer material response (stress strain curve increases more rapidly) is observed with increasing strain rate, where higher maximum stresses are associated with deformation at higher strain rates.

Table 2 Variations of ultimate flexural strength of composites at 2.35, 4.7 and 7 mm/min crosshead speeds

Composite type	Ultimate Flexural Strength (MPa) 2.35 mm/min	4.7 mm/min	7 mm/min
Basalt/phenolic	392.2	399.85	401.83
Basalt/carbon/phenolic	414.10	419.06	423.79
Carbon/phenolic	427.03	436.48	442.79

Comparison of the values in Tables 2-4 shows that, the ultimate flexural strength values at 7 mm/min crosshead speed are 2.24%, 2.15% and 3.69% higher than those calculated at 2.35 mm/min for basalt/phenolic, basalt/carbon/phenolic and carbon/phenolic composites, respectively. Also the flexural modulus values at 7 mm/min are 5.43%, 9.51% and 15.90% higher than those calculated at 2.35 mm/min for basalt/phenolic, basalt/carbon/phenolic and carbon/phenolic composites, respectively. However, the inverse effect of strain rate on the failure strain of all composites is relatively noticeable for three strain rates investigated.

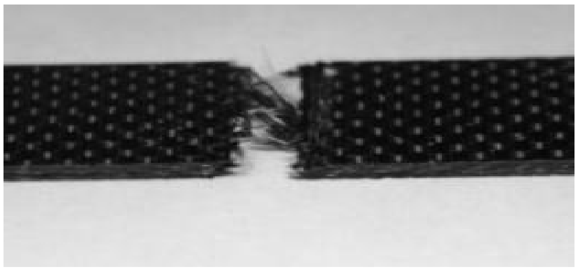
Table 3 Variations of flexural modulus of composites at 2.35, 4.7 and 7 mm/min crosshead speeds

Composite type	Flexural Modulus (GPa) 2.35 mm/min	4.7 mm/min	7 mm/min
Basalt/phenolic	13.79	14.24	14.54
Basalt/carbon/phenolic	17.87	19.09	19.57
Carbon/phenolic	25.72	28.12	29.81

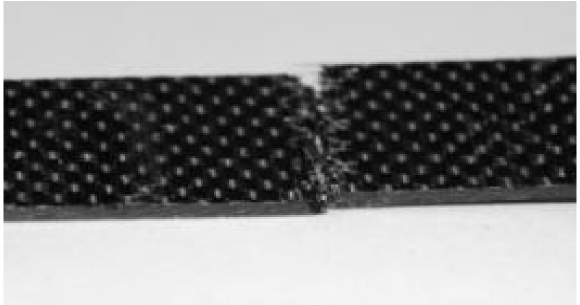
Table 4 Variations of failure strain of composites at 2.35, 4.7 and 7 mm/min crosshead speeds

Composite type	Failure Strain (%) 2.35 mm/min	4.7 mm/min	7 mm/min
Basalt/phenolic	3.03	2.98	2.79
Basalt/carbon/phenolic	2.59	2.22	2.19
Carbon/phenolic	2.17	2.01	1.84

Fig. 6 shows the fractured surfaces of carbon/phenolic specimens. Figure 6(a) represents the fracture patterns of the specimens at 2.35 mm/min crosshead speeds and figure 6(b) indicates the failure pattern at 7 mm/min crosshead speed. It is important to note that a change in the strain rate can change failure modes. The failure mode changes from fiber pull-out and fiber breakage to brittle fracture with considerable matrix damage as the crosshead rate increases [11].



(a)



(b)

Fig. 6 Fracture patterns of carbon/phenolic composite at (a) 2.35 and (b) 7 mm/min crosshead speeds

6 CONCLUSION

The objective of the presented research activity has been the investigation of the bending properties of the phenolic resin reinforced by woven basalt fibers and woven carbon fibers at three different strain rates. The main outcomes of the conducted activities are the following:

1. Overall the experimental results show that the strain rate significantly affects the response of the basalt and carbon fibers reinforced phenolic composites.

2. The results indicated that the both flexural modulus and ultimate flexural strength of the composites tend to increase with increasing strain rate.

3. Only a small increase in the maximum stress with increasing strain rate was observed in the basalt/phenolic and basalt/carbon/phenolic specimens and more significant effect of the strain rate on the maximum stress was observed in carbon/phenolic specimens. In particular, for the highest investigated strain rate, at 7 mm/min crosshead speed (0.09 min^{-1}), the failure stress arrived up to nearly 3.69% higher than those calculated at 2.35 mm/min (0.03 min^{-1}) for carbon/phenolic specimens.

4. Observation of the smooth fractured surfaces of carbon/phenolic specimens indicated the brittle fracture due to debonding at the interface between fibres and the matrix at high strain rates.

It is hoped that the data presented here will be helpful to others for development of studies.

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