Chapter 5
Strain Rate and Temperature Effect on the Dynamic Tensile Response of Carbon/Epoxy Composite

Palak Bhagoria, Muddu Rahul Bharadwaj, Rohit Kumar, and Vikrant Tiwari

Abstract In high-performance applications such as aerospace and automotive sectors, the dynamic behaviour of materials are crucial as these are often subjected to both high strain rate and varying temperature. This paper discusses the dynamic tensile performance of plain weave carbon/epoxy composite at high and low temperatures. Carbon/epoxy composite laminates were fabricated using the resin transfer moulding technique. The high strain rate experiments were conducted on tensile Split Hopkinson Pressure bar (TSHPB) in the strain rate range of 900 - 2700 s^{-1}. A furnace and an in-house built environment chamber along with liquid nitrogen was utilised for conducting high and low temperature studies, respectively. The temperature range varied from -50 °C to 60 °C. The mechanical properties including strength and strain at peak stress is evaluated and their variation with varying strain rate and temperature is examined. The strength was observed to enhance with increasing strain rates, however it degraded with rising temperatures. Failure mechanisms such as fiber breaking and matrix cracking have been observed, indicating the dynamic response of plain weave carbon/epoxy composite.

Keywords High strain rate · Temperature · Hopkinson pressure bar

Introduction

Carbon-based polymeric composites have gained popularity in recent decades due to their exceptional properties such as lightweight characteristics, high strength, excellent chemical resistance, and superior thermal stability. The growing demand for high-performance materials necessitates a deeper understanding of the properties, behaviour, and applications of carbon-based polymeric composites.

Furthermore, numerous real-world applications are characterized by high strain rates as well as elevated or varying temperatures. For example, elements in the aerospace or automobile fields encounter coupled thermal and mechanical stresses, where both the rate of strain and temperature significantly influence the material's behaviour. Thus, several researchers have made efforts to study the mechanical behaviour of materials under the influence of varying temperatures and strain rate. Most of such components are made up of different composite materials and hence, it becomes a necessity to evaluate their performance under such extreme conditions.

Several researchers have analysed the effect of high strain rate on different composites utilising split Hopkinson pressure bar(SHPB) along with techniques such as digital image correlation [1–3] , however only few focussed on the coupled effect of strain rate and temperature. Hosur et al. [4] examined plain and satin woven fabric graphite/epoxy composite at high strain rate compression at ambient and high temperatures using SHPB. They found peak stress and modulus to increase with increasing strain rates at all temperatures. However, temperature reduced peak stress and dynamic modulus. Temperature, strain rate, and fabric architecture also affected failure modes. Zhang et al. [5] investigated the dynamic mechanical properties and failure characteristics of AFRP (Kevlar 29/49 fabric and epoxy composite) at various medium strain rates (25,50,100, and 200 s^{-1}) and temperatures (− 25, 0, 25, 50, and 100 °C) and potential coupling effects of strain rate and temperature. The Young's modulus and tensile strength of both kinds of AFRP increased from 25 to 50 s^{-1} but declined at 200 s^{-1}. For AFRP K29, a similar pattern between temperature and Young's modulus was noted. Nonetheless, AFRP K49's Young's modulus remained unaffected by temperature changes. Another researcher [6] focussed on the evaluation

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of the high strain rate compressive behaviour of cross-ply carbon/epoxy composite in the temperature range of 20 – 80 °C and observed marginal increase in ultimate compressive strength along with significant decrease in ultimate strain in the strain rate range of 10^{-3} to 10^{3} s^{-1} in all the three principal material directions. Also, the ultimate compressive strength decreased with increasing temperature. Similarly, other study [7] utilised SHPB experiments to analyse the dynamic mechanical performance of T700/BA9916 carbon/epoxy composite at high temperatures (25 – 200 °C). Elastic modulus and compression failure strength both declined with rising temperature, although maximum failure strain increased. Elastic modulus and compression failure strength both increased with increasing strain rates, while maximum failure strain decreased. Reis et al. [8] performed tensile experiments on glass fiber reinforced polymeric composite at various strain rates and temperatures and found that strain rate had a significant influence on ultimate tensile strength, but temperature had an effect only on modulus. Zhang et al. [9] examined the combined influence of temperature and strain rate on the tensile properties of basalt-fiber-reinforced polymers. The tensile strength remained unchanged at temperatures below 50 °C but dropped at 100 °C. Joshi et al. [10] conducted experimental study to characterize different composites under tensile loading for strain rates of 10^{-3}, 10^{-2}, and 10^{-1} s^{-1} and at temperatures 250 °C and 450 °C. The tensile behaviour of all the specimens indicated a significant influence of strain rate on ultimate tensile strength, whereas the temperature primarily affected the modulus.

To the best of author's knowledge, the literature reflects a lack of comprehensive study performed on plain weave carbon/epoxy composite with regard to the influence of high strain rate and varying temperatures, and thus an effort has been made to understand the dynamic response of this material under such extreme conditions. The study is performed for high strain rate tensile loading condition combined with both low and high temperature utilizing tensile split Hopkinson pressure bar (TSHPB) along with furnace and an in-house built environment chamber for introducing temperature effects.

Composite Fabrication and specimen Preparation

The composite laminates of thickness 2 mm are fabricated using 12 layers of plain weave carbon fabric and epoxy resin system (EPOFINE®-1564 and FINEHARD-3486-2) utilizing Vacuum Assisted Resin Transfer Moulding machine. The laminate was cured at room temperature for 24 hrs followed by further curing at 70 °C for 16 hrs. Dog bone specimens of 2 mm thickness, and gauge length and gauge width as 4 mm each, are obtained from these laminates using water jet cutting.

Fig. 1 Dog-bone shaped specimen for high strain rate tensile experiments

Experimental Setup

The high strain rate tensile experiments are performed on tensile split Hopkinson pressure bar (TSHPB) setup available in Dynamic Material Response and Characterization Laboratory in Applied Mechanics department of IIT Delhi. An elaborative description of the complete setup is presented in [11, 12] .This setup works on the principle of one-dimensional wave propagation theory, which thereby is used for the calculation of variation of stress, strain rate and strain with respect to time using equations (1), (2) and (3), respectively [13]:

$$\sigma_s\,(t) = \frac{A_b\,E_b}{A}\varepsilon_t(t) \tag{1}$$

$$\dot{\varepsilon} = \frac{2C_b}{L}\varepsilon_r \tag{2}$$

$$\varepsilon = \frac{2C_b}{L}\int_0^t [\varepsilon_r\,(t)]\;dt \tag{3}$$

where A_b and A are the cross-sectional areas of bar and specimen, respectively. C_b and E_b are the elastic wave speed and elastic modulus of bar. ε_r and ε_t are the strains of the reflected and transmitted pulse, respectively.

In order to perform experiments with flat specimens, the setup was modified by utilizing adapters made up of same material as the bar. The details of these adapters are well described in [14]. Aluminium tabs are pasted on the gripping length of the specimen to prevent any slippage and to protect specimen from any damage when fitted in the adapters.

The current study also included evaluation of the influence of varying temperatures, for which number of iterations for time versus temperature cycle were performed. These iterations, as shown in fig. 2, were utilised to perform experiments at desired temperature at a particular time. For attaining high temperatures, the specimen was heated in furnace at 100 °C for 1 hr and then subjected to high strain rate at different time instants. The low temperature experiments were conducted utilizing an in-house built environment chamber along with liquid nitrogen.

The study initiated by performing time versus temperature studies wherein the specimen is mounted in the adapter within the chamber and using K-type thermocouple, the variation of temperature with respect to time is noted. Number of iterations, as shown in fig. 2, were performed to evaluate the time at which the desired temperature is attained.

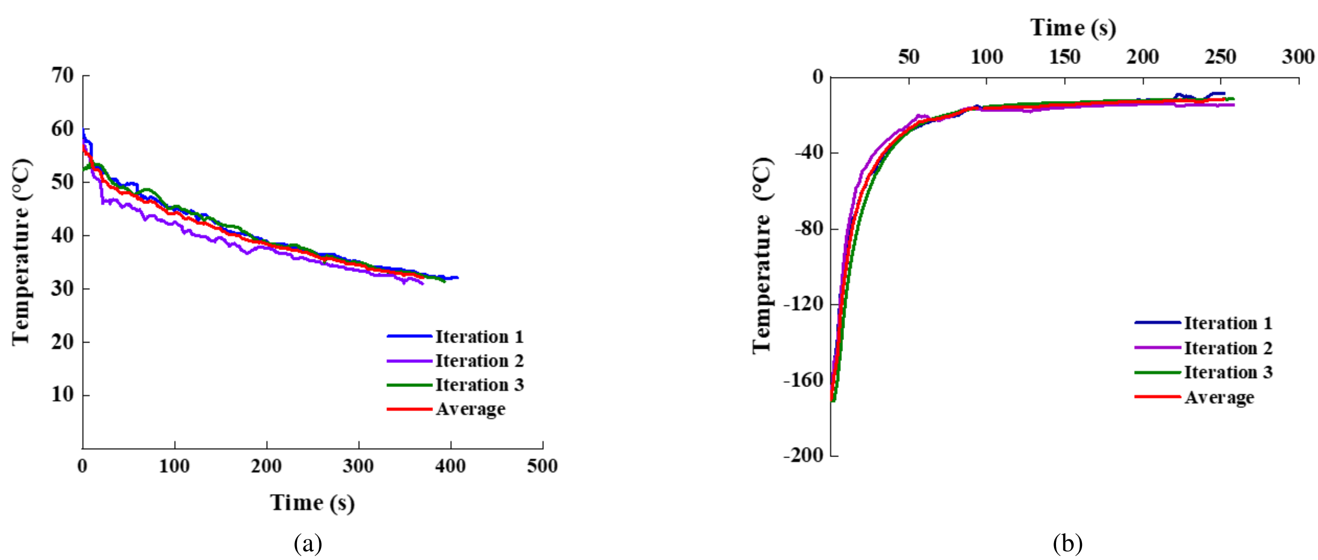


Fig. 2 Time versus Temperature curves for (a) High temperature, (b) Low temperature studies

Results and Discussion

High strain rate tensile experiments for plain weave carbon/epoxy composite were performed utilizing tensile split Hopkinson pressure bar in the strain rate range of 900-2700 s^{-1} at temperatures of − 45 °C, − 25 °C, 25 °C (room temperature), 35 °C and 45 °C. Fig. 3 represents the true stress versus true strain plots for plain weave carbon/epoxy composite corresponding to different temperatures for various strain rates. Table 1 enlists the strength and strains at peak stress obtained at these strain rates and temperatures. It can be noted that at any temperature, the strength and strain at peak stress increase with increasing strain rate, indicating strain rate sensitivity of plain weave carbon/epoxy composite (Fig. 4). The table also shows

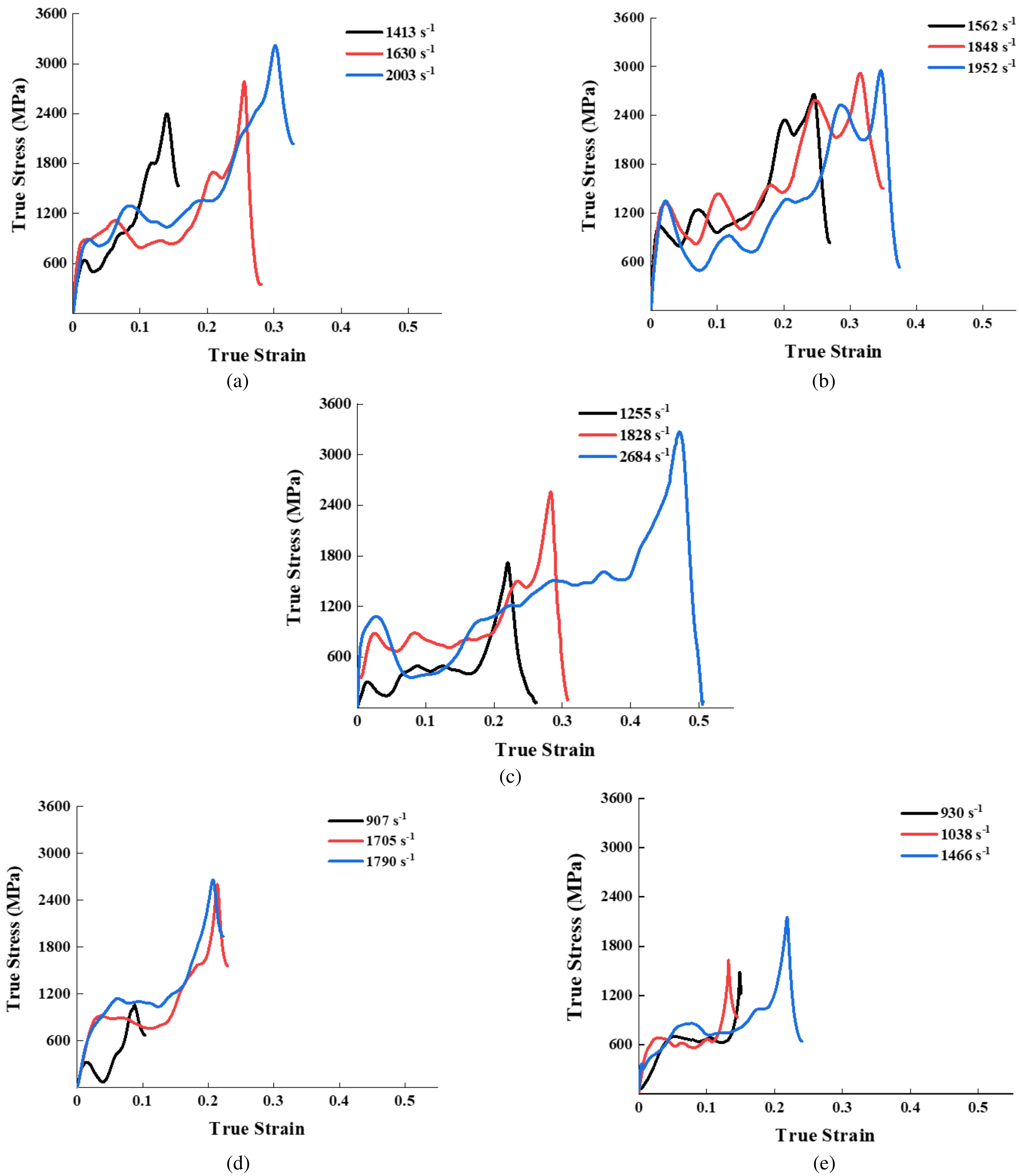
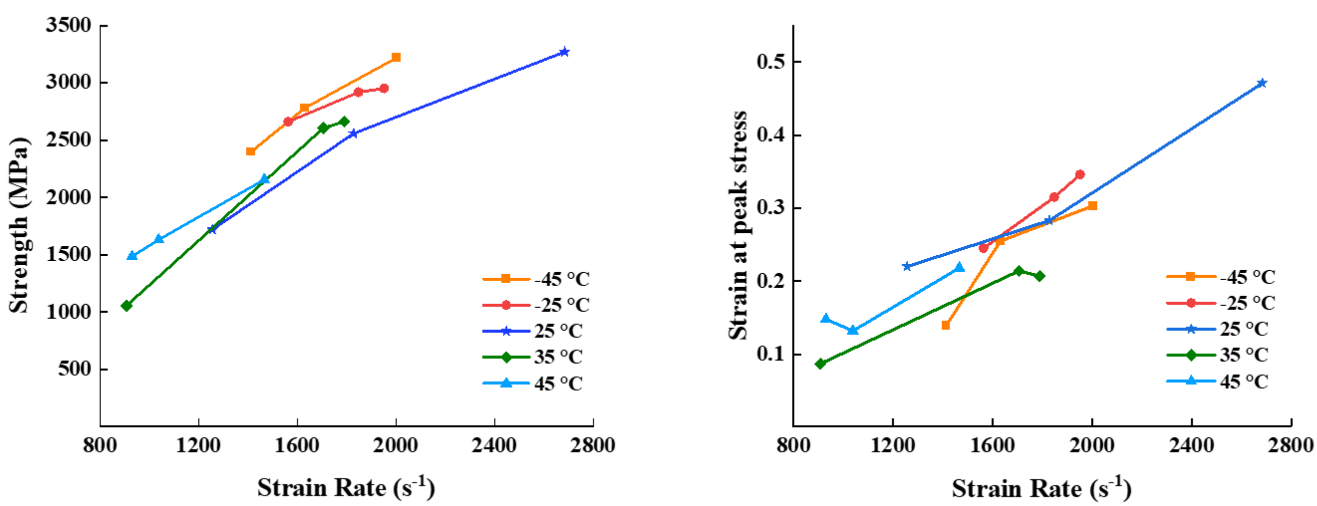


Fig. 3 True stress versus true strain plots for carbon/epoxy composite at various temperatures for different strain rates

Table 1 Mechanical properties of plain weave carbon/epoxy composite at various strain rates and temperatures

Temperature (°C)	Strain Rate (s^{-1})	Strength (MPa)	Strain at Peak stress
	2003	3219.057±3.121	0.303
- 45	1630	2781.013±5.431	0.255
	1413	2397.694±5.565	0.139
	1952	2951.927±1.233	0.346
- 25	1848	2917.760±4.632	0.315
	1562	2658.971±3.101	0.245
	2684	3269.564±3.060	0.471
25	1828	2556.910±3.557	0.283
	1255	1719.870±2.110	0.22
	1790	2661.967±6.812	0.207
35	1705	2604.910±5.205	0.214
	907	1055.401±4.273	0.087
	1466	2153.979±8.615	0.218
45	1038	1631.597±6.202	0.132
	930	1484.318±4.931	0.148



(a) (b)

Fig. 4 Variation of (a) strength and (b) strain at peak stress of plain weave carbon/epoxy composite with strain rate at different temperatures

that with decreasing temperature, the strength of the carbon/epoxy composite increases which can be attributed to matrix stiffening and strain rate hardening. At lower temperatures, the epoxy matrix stiffens, allowing more stress to be transferred to the carbon fibers and decreasing fiber pullout. From fig. 3, it can be observed that at elevated temperatures, the matrix demonstrates enhanced ductility, facilitating improved stress transfer among fibers, resulting in a more gradual increase in stress and greater overall strain prior to failure.

The stress-strain curve also displays presence of some fluctuations before reaching ultimate stress. These fluctuations reduce when the composite specimen is subjected to higher temperatures. The presence of such fluctuations indicates that the composite laminate experienced initiation and progression of damage and cracks [15]. With decrease in temperature, the epoxy matrix becomes more brittle leading to matrix cracking. These cracks induce abrupt stress drops and generates stress wave reflections, which thereby introduces fluctuations in the stress -strain curve. The stress is further increased since the load is redistributed to the area surrounding the failed region [16]. The ductility of matrix and energy dissipation are enhanced at elevated temperatures, which thus reduces the severity of these fluctuations.

The images of fractured specimens are depicted in fig. 5 corresponding to temperature of 45 °C and – 45 °C. Figure 5 (a) depicts the deformed specimen when subjected to a temperature of 45°C at high strain rate of 1466 s^{-1}. The figure shows some fiber pull-out along with stepped pattern indicating interlaminar shear failure. This can be attributed to the fact that at moderate temperatures, epoxy softens slightly, reducing brittleness. Furthermore, fig. 5 (b) clearly shows that at cryogenic temperature of $-$ 45 °C and strain rate of 1630 s^{-1}, carbon/epoxy composite experiences fibre breakage indicating characteristics of brittle fracture. This is further confirmed from fig. 3 (a), that demonstrates a sudden drop in stress following the peak stress. Thus, it can be concluded, that with increasing temperature, the carbon/epoxy composite experiences a transition in its failure mode from brittle fiber breakage to a failure mode that is a combination of shear failure and fiber pull out. This is also confirmed from the stress strain curves in fig. 3, with increase in failure strain and more gradual stress drop after peak stress.

(a) (b)

Fig. 5 Deformed specimens when subjected to (a) $\dot{\varepsilon} = 1466\ s^{-1}$ at 45 °C and (b) $\dot{\varepsilon} = 1630\ s^{-1}$ at -45 °C

Conclusion

The current study focusses on the effect of temperature and high strain rate under tensile loading conditions on plain weave carbon/ epoxy composite laminates. The high strain rate experiments were conducted in the range of 900-2700 s^{-1} at temperatures of $-$ 45 °C, $-$ 25 °C, 25 °C, 35 °C and 45 °C utilizing tensile split Hopkinson pressure bar. Following are the conclusions drawn from the current study:

1. The strength and strain at peak stress of carbon/epoxy composite increases with increasing strain rate, indicating its strain rate sensitivity.
2. The decrease in temperature leads to increase in strength of carbon/epoxy composite, indicating thermal sensitivity of carbon/epoxy composite laminate. The strength increased by approximately 11% and decreased by 30%, when the temperature was varied to $-$ 45 °C and 45 °C respectively, from room temperature (25 °C).
3. With decrease in temperature, matrix cracking occurs in the carbon/ epoxy composite due to brittleness of epoxy, leading to fluctuations in stress before attaining ultimate strength.
4. The variation in temperature influences the failure mode of the laminate.
5. With decrease in temperature, the failure mode of carbon/epoxy composite undergoes transition from fiber pull-out and shear failure to fiber rupture.

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