Research Article

Experimental and numerical investigations on dynamic behavior of CFRP laminates

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Abstract

Increased application of carbon fiber reinforced polymer (CFRP) composites to resist blast loadings necessitated investigating their dynamic behavior. It requires characterization of the CFRP laminates at high strain rates using split Hopkinson pressure bar or comparable device. In this investigation, tensile properties of the CFRP laminates subjected to high strain rates are studied experimentally and numerically. Experimental evaluation of tensile properties of the CFRP laminates using the Hopkinson bar is a tedious, time consuming, and costly exercise. Hence, upon conducting limited experimental evaluation, a numerical model is developed to characterize these composites at high strain rates. The developed numerical model of the Hopkinson bar technique is validated against the results obtained from the experiments conducted using crossbow system on the CFRP laminates. Full-scale tensile stress–strain curves are developed to study the effect of the strain rate on the ultimate tensile strength, elastic modulus, and energy absorption capacity of the CFRP laminates. It is observed that the CFRP laminates are sensitive to the strain rates and their ultimate tensile strength and energy absorption increases with the increase in the strain rate. Moreover, the effect of variation in thickness and length to width ratio for a constant stress pulse is insignificant.

Keywords CFRP · Crossbow system · Energy absorption · High strain rate · SHPB · Ultimate tensile strength

1 Introduction

The frequency of the ill-fated terrorist attacks across the globe has been increased drastically over the last few years. These attacks are mainly targeted towards vulnerable structures where considerable damage and loss of life takes place and these primarily include public/government buildings, bridges and similar strategically important structures. This necessitated the need for retrofit of the blast-resistant structures, as replacement of the existing vulnerable structures is not economically feasible. Thereby, blast retrofitting of the existing structures using advanced high-strength composite and lightweight materials is of prime importance. The carbon fiber reinforced polymer (CFRP) composites offer the advantages of high-strength and lighter weight, making them the most suitable choice for blast retrofitting purposes.

During a blast event, structural components of the buildings or bridges are typically subjected to high strain rates in the order of 1000–5000 s^{-1} or even more. Under such circumstances, the CFRP composites can be used to retrofit reinforced concrete (RC) structural elements such as columns, beams, walls and slabs, ensuring their survivability when subjected to such extreme loadings [8]. In early Harding and Welsh [12] investigated the mechanical properties of the uni-directionally reinforced CFRP composites and concluded that elastic modulus, fracture strength, and failure modes of the uni-directionally reinforced CFRP

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composites were independent of the strain rates. Based on finite element analysis (FEA), Al-Bastaki [1] studied the effects of strain rate on the Kevlar fiber reinforced plastic (FRP) using the ABAQUS™ software and showed good agreement with the experimental stress–strain response. Later on, Gilat et al. [7] studied the strain rate dependent behavior of the carbon/epoxy composites in tension by testing the resin and various laminate configurations at different strain rates. Tensile tests at lower and intermediate strain rates, conducted using hydraulic machine and split Hopkinson pressure bar (SHPB), revealed that stiffness increases with the increase in the rate of loading. Later, Gómez-Del Río et al. [10] investigated the effect of temperature on the tensile properties of the CFRP laminates at high strain rates using the SHPB device for different laminate configurations such as uni-directional (0° and 90°) and quasi-isotropic. They concluded that temperature and strain rate have insignificant influence on the tensile strength of uni-directional composites, if loaded in the fiber direction; whereas, strength of the uni-directional laminate increases appreciably in the transverse direction at low temperature and high strain rate. Further, they stated that temperature has a minor effect on the in-plane dynamic properties of the quasi-isotropic laminates. Moreover, a marginal increase in the tensile strength was observed under dynamic loading [10]. Deshpande [5] conducted an experimental study to determine the tensile properties of in-plane polymer matrix composite materials at quasi-static and high strain rates. He observed that unlike metals, polymer matrix composite materials do not exhibit persistent strain rate behavior at high strain rates. It was also observed that for different fiber orientations, strain rates vary for the same stroke rate as matrix material starts playing role at higher angles. Recently, Kimura et al. [14] conducted experiments under uni-axial tension at three different strain rates ranging from 10^{-5} to 10^{2} s^{-1} and observed that for quasi-static (10^{-5}) to intermediate (10^{-2} s^{-1}) strain rates, the stress–strain behavior of the CFRP material remained linear whereas, in the dynamic regime (10^{2} s^{-1}) stress–strain relation is nonlinear and an increase in the elastic modulus and tensile strength of the material is observed. Afterwards, Al-Zubaidy et al. [2] conducted experiments for the determination of tensile properties of the uni-directional CFRP (CF130), Araldite 420, and MBrace saturant adhesives at quasi-static and medium strain rates. A drop mass rig and an impact testing machine were used to conduct impact tests on the CFRP and epoxy materials. They concluded that the tensile properties of the CFRP and adhesives are indeed strain rate dependent. They presented an empirical relation for evaluating modulus of elasticity and uni-axial tensile strength as a function of strain rates. Dhaliwal and Newaz [6] investigated carbon fiber reinforced aluminum laminates under low velocity impact experimentally and conducted dynamic finite element method (FEM)-based transient simulations to predict their failure behavior. Their numerical material model successfully captured the peak load levels and ultimate central deflection for each impact energy level and compared well with the experimental results. Ćwik et al. [4] believed that further research is required in deeply understanding the importance of various parameters such as wave speeds and others, as well as the experimental data is crucial in validation of the numerical models subsequently used for such parametric investigation. On similar account, an experimentally validated FEM-based numerical analysis was performed by Pashmforoush et al. [16] on laminated fiber reinforced polymer (FRP) composites under low-velocity impact in an effort to minimize the damage. Such tensile stress–strain characterization of the advanced engineered composite materials [13] is essential in design of the members reinforced with it under quasi-static as well as dynamic loading conditions. In designing structural members against blast loading, in addition to the quasi-static tensile constitutive law, dynamic constitutive law for the materials is required.

The use of the SHPB device is a well-established technique for the dynamic characterization of the metallic materials; however, for the polymeric materials several challenges exist in obtaining reliable results. In the tests conducted using the SHPB device, several factors, such as longitudinal wave dispersion, impedance mismatch between bar and specimen materials, instrumentation and similar influence the accuracy and reliability of the experimental results. Recent developments in this area to understand dynamic behavior of such advanced material composites included finite element (FE)-based simulation technique to determine the dynamic stress–strain curve numerically for particular strain rates, which are experimentally verified with reduced the sources of error and experimental costs [9].

Based on the literature review, it is inferred that no general agreement exists on the dynamic behavior of the CFRP laminates at high strain rates. Further, it is also noted that no full-scale numerical solution has yet been reported for these composites. Although, Suga et al. [17] proposed a numerical solution for the CFRP laminates, their investigation mainly focused on the impedance mismatch between the bars and specimens for different laminate configurations and they provided a solution of using long duration stress pulses as loading for the cases having high impedance mismatch. Based on this review, in the present investigation a numerical model of the tensile SHPB testing for the CFRP laminates has been reported, which has effectively developed the full-scale stress–strain curves and duly verified through experiments conducted using a crossbow system on the CFRP laminates.

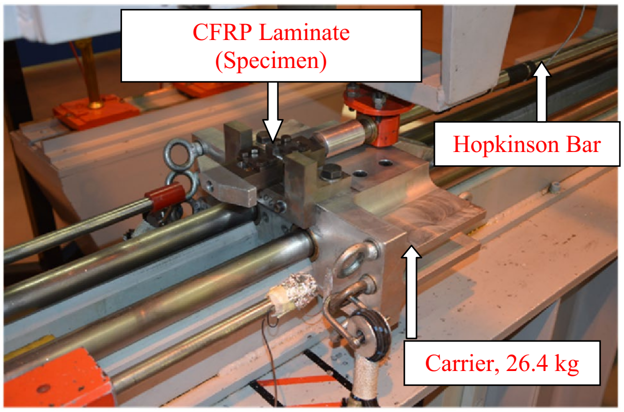

Fig. 1 Experimental setup of crossbow system used

2 Experiment methodology

In the present investigation, commercially available Goldbond®-Superplate CFRP laminates were used. The quasi-static and dynamic properties of the CFRP laminates in longitudinal direction of the fibers were evaluated in this study for PAN-based Carbon Fiber (CF) of grade 1450 reinforced in epoxy matrix. Herein, fiber areal weight was 200 g/m^2 and fiber density was 1.8 g/m^3. The design tensile strength as per ASTM D-3039 was 2380.95 N/mm^2 and modulus of elasticity, *E* being 176.5 GPa. The quasi-static and dynamic tests of these CFRP laminates were conducted. The high strain rate testing of the CFRP laminates was carried out using crossbow system, as shown in Fig. 1. It is to be noted that the crossbow system is an alternative to the conventional SHPB device and it provides data for the same range of strain rates; however, it is a more compact device and has a potential of producing higher impact energies leading to higher strain rates [11, 15]. Moreover, the conventional SHPB device essentially requires high-pressure gas for the gas-gun used to launch the heavy projectile, occupying a large space, which can be eliminated in the crossbow system. Such requirement of high-pressure system and large floor area sometimes restricts the limit of strain rate which otherwise could be achieved under the given test conditions. In the crossbow system, long length striker bar is replaced by a heavy carrier mass to produce high-energy impacts, making it a compact version of the SHPB device. In the crossbow system, projectile can be launched conveniently with energy up to 800 J. Thus, the crossbow system is considered to be an offshoot of the blend between the standard SHPB device and the direct impact Hopkinson bar.

In the current investigation, the experimental setup consisted of a carrier with a mass of 26.4 kg, Hopkinson bar of 6 m length and 30 mm diameter and the CFRP specimen to be tested. The Hopkinson bar is made of Malvar steel having material constants, elastic modulus, $E = 190{,}125$ MPa, Density, $\rho = 7800$ kg/m^3, and Poisson's ratio, $\nu = 0.3$. One end of the specimen is fixed to the Hopkinson bar using screws by applying lateral pressure and on the other end it is fixed to an arrow type geometry that is left free in space (Fig. 1). Closer view of the CFRP specimen placed in the crossbow system for testing is seen in Fig. 2a. Further, an indicative sketch of the crossbow system is represented in Fig. 2b for better understanding of the mechanism employed for the high strain rate tensile testing system for the CFRP specimen.

The setup was attached with high-speed video cameras Photron FASTCAM to capture the dynamic response of the CFRP specimen in the axial direction by capturing 30,000 s^{-1} images of 256 × 128 pixel^2 resolution during the experiment of duration 2.18 s. The CFRP specimens were painted with white color and marked with random black dots. Pictures taken by the video cameras before and during the tests were analyzed using ICASOFT software for determination of the dynamic displacement of the CFRP specimen and dynamic strains induced in it.

The strain gauges attached to the Hopkinson bar measure the stress time history of the specimen when subjected to impact loading. The carrier mass of 26.4 kg is made to impact on the specimen at measured velocity of 10.4 m/s. The velocity of the carrier mass was measured using non-intrusive technique of laser guns. Strain gauges were connected on the Hopkinson bar approximately at 1 m from the impact end in order to ensure that the recorded signals are least affected by the changes in the loaded area as the deformation proceeds and that the effect of heating at the impact end does not alter the baseline voltage of the gauges. These strain gauges were bonded at the opposite sides of the bar and connected in series to cancel out asymmetrical bending waves.

The quasi-static tests on the CFRP laminate specimens were carried out using universal testing machine (UTM) as per the procedure suggested in the ASTM D3039/3039M-14. The specimens were dimensioned to a gauge length of 141 mm, width of 31 mm, and with one uni-directional (0°) CFRP lamina having a single ply of 1 mm thickness as shown in Fig. 3. For the effective application of the tensile force to the specimen and preventing premature failure, aluminum grips were attached to the laminate using high-strength epoxy. The grips were assembled into the holders and lateral pressure was applied to avoid the slip at the grips. The strain gauges attached to the specimen and load cell of the machine facilitated obtaining the stress–strain plots to understand quasi-static behavior of the CFRP laminates.

Figure 4 shows the average stress–strain curve obtained from the quasi-static tests on five specimens of the uni-directional CFRP laminates. It can be observed from the

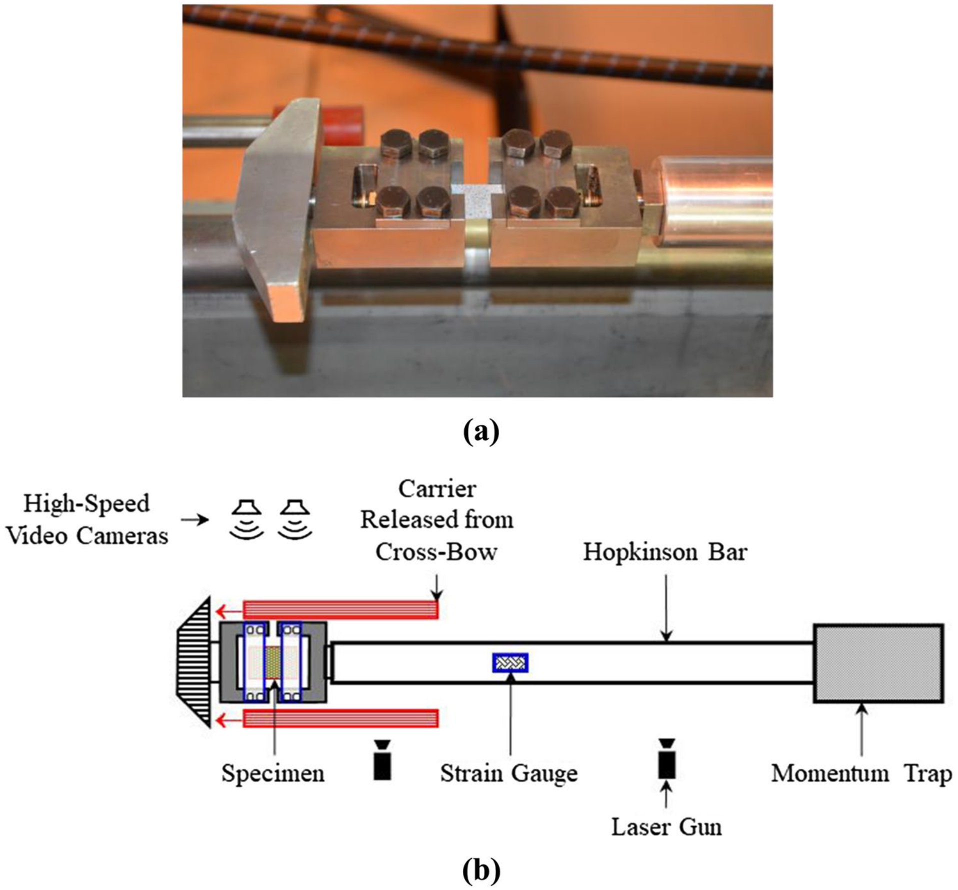

Fig. 2 **a** Experimental setup of crossbow system with CFRP specimen in position, **b** typical sketch of the crossbow configuration employed for high strain rate tensile testing

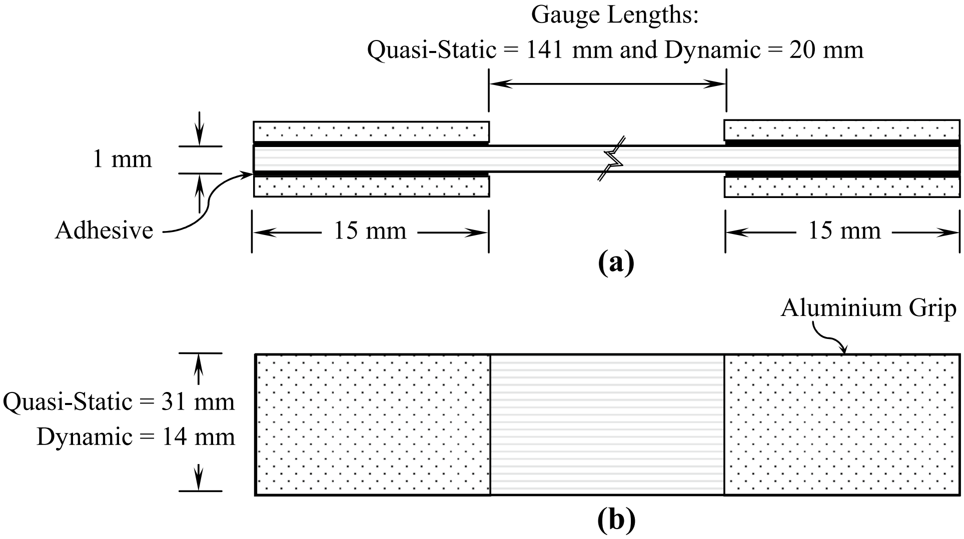

Fig. 3 Quasi-static and dynamic test specimen: **a** section and **b** plan

stress–strain curve that the uni-directional CFRP laminates behave in a linear elastic manner until reaching its ultimate rupture. The rupture at ultimate load was observed to be sudden explosive with loud sound. Such mode of failure is attributed towards rapid release of the high strain energy accumulated across the specimen length during the test. The CFRP laminates broke into small longitudinal pieces. The material properties, such as elastic modulus and Poisson's ratio, were computed as per the ASTM D3039/3039M-14 (Table 3) at 1000 and 3000 με and were evaluated to be 176.515 GPa and 0.37, respectively. The density of the CFRP specimen used for the tests was

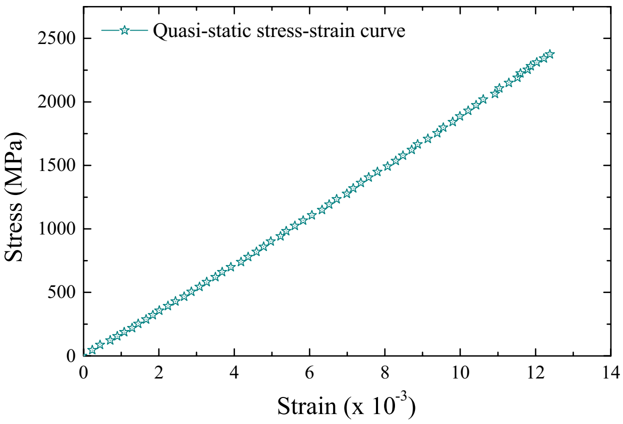

Fig. 4 Stress-strain curve at quasi-static rate for uni-directional CFRP laminate

1800 kg/m^3. The ultimate strength of the laminate was calculated as 2380.95 MPa at the fracture strain of 0.0124.

In ASTM D3039/D3039M-14 standard, Clause 11.9 deals with failure mode; accordingly, the mode and location of failure of the specimens were recorded. From the standard description given in the ASTM D3039/D3039M-14 standard for the three-part failure mode code, for the quasi-statically tested CFRP laminates in this experimentation, the following failure mode and location were observed and noted. Failure type: longitudinal splitting (S) in an explosive manner (X); failure area: multiple areas (M) within the gauge (G); and failure location: middle (M).

3 Numerical modeling of crossbow system

Standard test procedure recommended by the ASTM in D3039/D3039M-14 was used for conducting the quasi-static tests to obtain material constants for the CFRP specimen and to confirm the datasheet provided by the supplier. This test method determines the in-plane tensile properties of the high-modulus fibers reinforced by polymer matrix composite materials. A thin flat strip of material having a constant rectangular cross-section is mounted in the grips of a mechanical testing machine and monotonically loaded in tension while recording the force. The ultimate strength of the material is determined from the maximum force carried before failure. When the coupon strain is monitored with strain or displacement transducers, the stress–strain response of the material is determined, from which the ultimate tensile strain, tensile modulus of elasticity, Poisson's ratio, and transition strain is derived.

The material properties such as elastic modulus and Poisson's ratio are calculated as suggested in the ASTM D3039/3039M-14 (Table 3) at 1000 and 3000 $\mu\varepsilon$ and are found to be 176.5 GPa and 0.37, respectively. The density of the CFRP specimen used for the tests was 1800 kg/m^3. The ultimate strength of the laminate is obtained as 2380.95 MPa at failure strain of 0.0124. The failure of the laminate is considered at the point when any slippage between the fiber and the matrix occurs. The material properties assigned to the finite elements of the CFRP laminate are those obtained from the experimental results.

Evaluating tensile properties of the CFRP laminates experimentally using the Hopkinson bar is a cumbersome, lengthy, and expensive affair. Therefore, to be able to conduct extensive parametric investigation, a numerical model is developed to mimic the Hopkinson bar testing for characterizing the CFRP composites at high strain rates, upon conducting few dynamic tests. The numerical model of the crossbow experimental setup is prepared in a commercially available finite element (FE) code ABAQUS™ version 6.11. The numerical model is validated against the experimental results obtained on the crossbow system. The model consists of the Hopkinson bar and the CFRP laminate specimen. The dimensions of the four CFRP laminate specimens tested in the Hopkinson bar apparatus were as shown in Fig. 3. The function of the carrier mass (26.4 kg) in the experimental setup is simulated using a loading pulse in the numerical model which is applied at the free end of the Hopkinson bar. One end of the specimen is attached to the Hopkinson bar while the other end is fixed. The dimensions and material properties of the model are considered the same as that of the experimental setup described earlier. Further, a strain cutoff failure criterion is used to model the failure as per ABAQUS. The Hopkinson bar is modeled as an elastic bar to serve the intended purpose. The boundary conditions of the numerical model are modeled such that movement is allowed only in one-longitudinal direction. Three-dimensional (3D) solid brick elements with reduced integration and hourglass control (C3D8R) are used to model the bar. These elements take into consideration the large mesh distortion without affecting the results due to the volumetric locking. The CFRP laminate is meshed using eight node quadrilateral, in-plane, general-purpose continuum shell element with reduced integration and hourglass control (SC8R), which takes into consideration the finite element strain. Based on a mesh convergence study, the laminate is meshed using a global seed of 0.5 mm and the bar is meshed using a global seed of 5 mm. It is to be noted that the FE analysis using the numerical model is conditionally stable for time increments that are smaller than the Courant's time limit, $\Delta t = l/C$, where l is the smallest element dimension and C is the speed of wave in the medium in which it travels. The material properties assigned to the finite elements of the CFRP laminate are those obtained from the experimental results. Figures 5 and 6 respectively

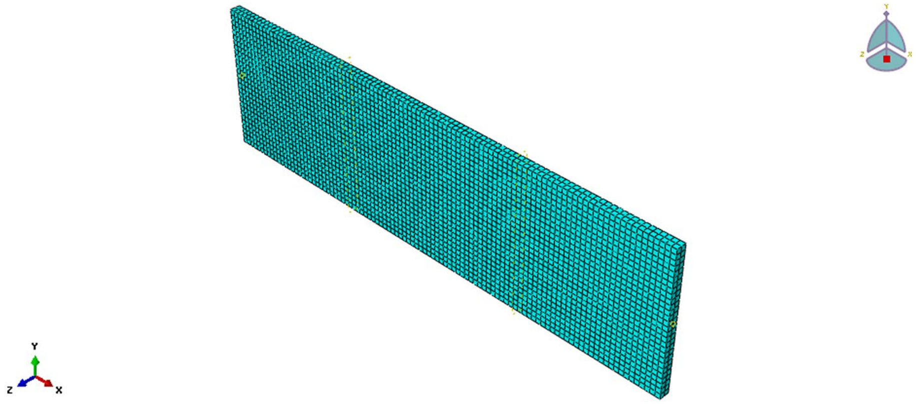

Fig. 5 Finite element (FE) model of uni-directional CFRP laminate

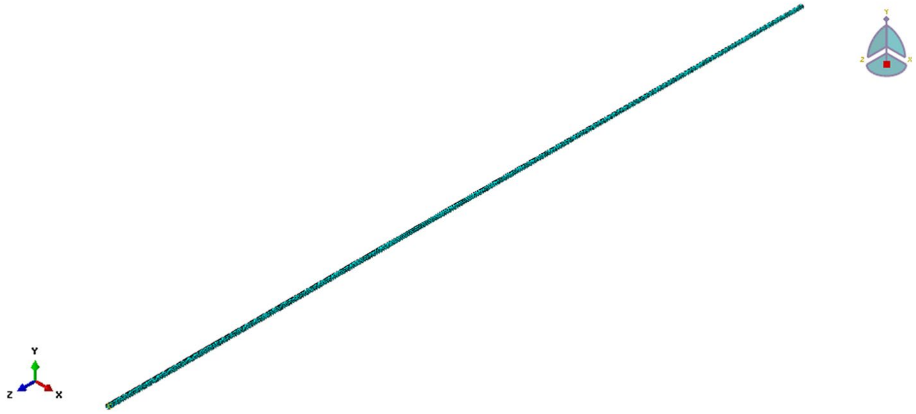

Fig. 6 Finite element (FE) model of Hopkinson bar

show the FE models of the CFRP specimen and bar developed using ABAQUS.

In order to simulate the function of strain gauges used in the laboratory tests, reference points are selected on the Hopkinson bar and on the CFRP laminate to measure the data of the incident and reflected pulses. These pulses are used to compute the stress–strain response of the CFRP laminates. The tensile loading pulse is applied at the free end of the Hopkinson bar, which travels all along its length, then through the laminate length, and thereafter reflects back as a compressive pulse based on the impedance difference between the bar and the CFRP laminate. Figure 7 shows the tensile stress (σ) pulse time history used in the simulation, which represents the effect of the carrier mass (26.4 kg) striking at an average velocity of 10.4 m/s to induce the impact on the CFRP laminate in the tests.

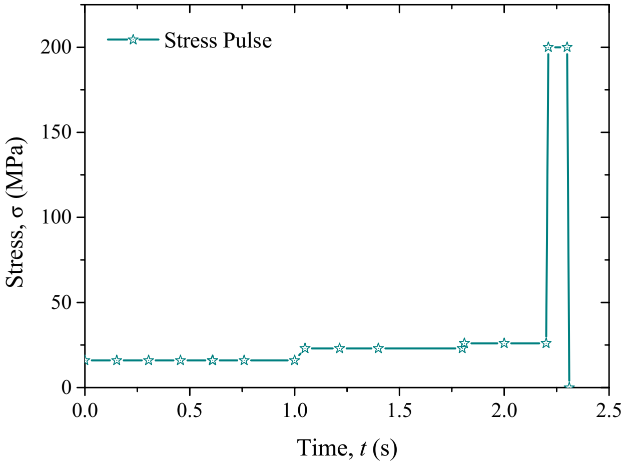

Fig. 7 Stress pulse used in the numerical simulations

The comparison between the time histories of the strain obtained along ε_{11} direction (0° direction) from the numerical simulation and the dynamic tests is shown in Fig. 8. The theoretical results obtained from the numerical simulation are found to be replicating the dynamic test results obtained from the crossbow system, by subjecting the CFRP laminate with an average impact velocity of 10.4 m/s using a carrier of 26.4 kg mass. The duration of the strain time history curve shows the high energy impact created by the carrier mass which is equivalent to the long length striker bar in the conventional SHPB device. It can be observed from Fig. 8 that the numerically predicted and experimental results are in good agreement quantitatively and qualitatively,

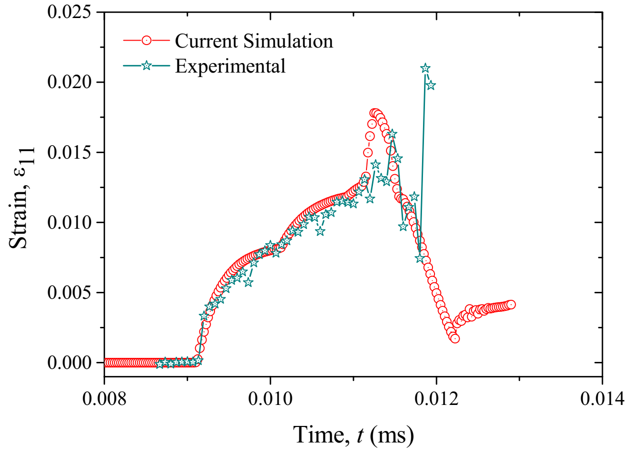

Fig. 8 Validation of numerical results with experimental results

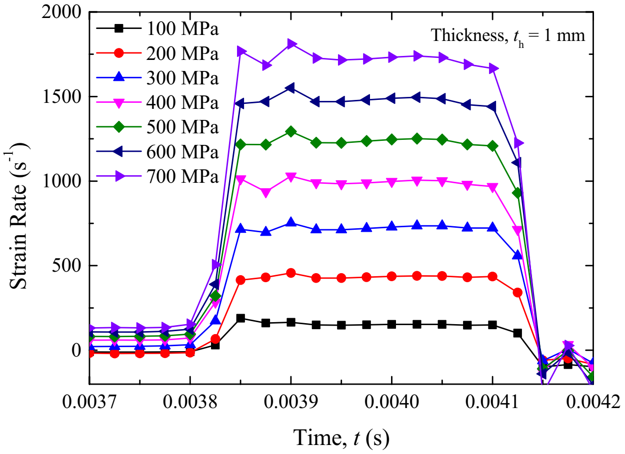

Fig. 9 Strain rate variation with respect to different stress impulses

thus validating the numerical scheme developed in the present investigation.

4 Results and discussion

Figure 9 shows the strain rate time histories for different magnitudes of the maximum stress pulses (analogous to the impact velocities). It is observed that as maximum stress pulse magnitude is varied from 100 to 700 MPa, the strain rate to which the laminate is subjected increases from 180 to 1750 s^{-1}, respectively. Hence, by using high magnitudes of the stress pulses, high intensity or high strain rate loadings can be simulated as accomplished in the present investigation.

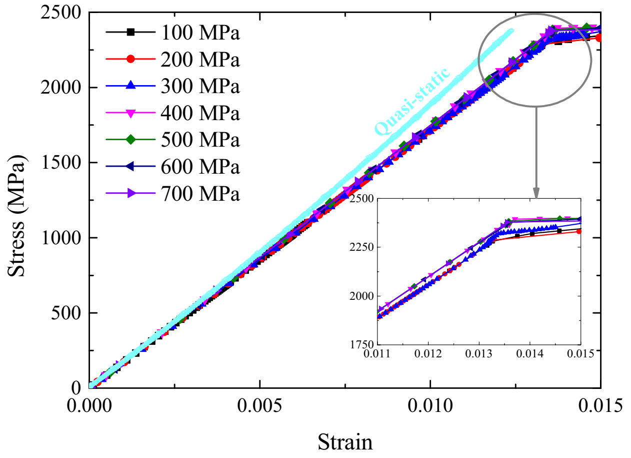

Fig. 10 Stress-strain plots for different maximum stress impulse magnitudes

4.1 Effect of variation of stress pulse

Upon validation of the present numerical scheme, the FE model is used for conducting parametric investigation by varying magnitude of the stress pulses representing different carrier impact velocities. Figure 10 shows the stress–strain behavior of the uni-directional CFRP laminates for varying maximum tensile stress pulse magnitudes from 100 to 700 MPa along with the quasi-static experimental results. The composite material shows linear elastic behavior till rupture followed by a sudden explosive failure. It can further be observed from the plots that the elastic modulus of the laminate is invariable to the intensity of the impact velocity, whereas there is some increase in the ultimate strength of the CFRP laminate with increasing impact velocity as seen within the inset. Earlier, some high strain rate tests were performed by Taniguchi et al. [18, 19] on the unidirectional carbon/epoxy composites on a specimen similar to that used in the present investigation (Fig. 3). They concluded that (a) the tensile modulus is independent of the high strain rate; however (b) strain rate dependency of the dynamic tensile strength in these two studies is reported differently. Nevertheless, from the present investigation it is concluded that the elastic modulus of the uni-directional CFRP laminates is strain rate insensitive; however, the ultimate tensile strength of the CFRP laminates is marginally strain rate sensitive. The increase in ultimate tensile strength of the CFRP laminates due to the increased rate of loading has been observed to be about only 1% for the strain rate of 1750/s applied in the tests conducted in this study in comparison with the quasi-static study.

The variation in the ultimate tensile strength and energy absorbed by the uni-directional CFRP laminates against maximum stress pulse magnitudes (carrier impact

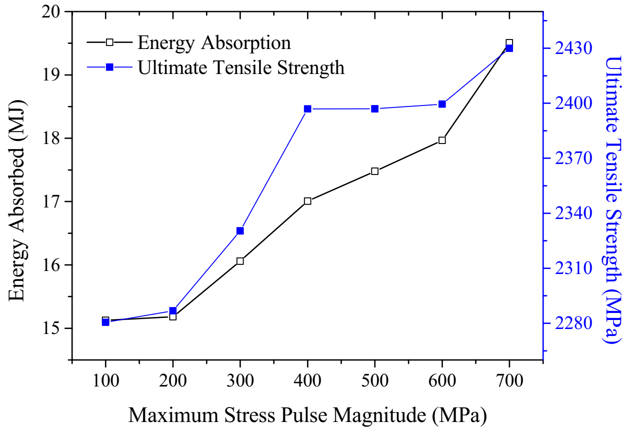

Fig. 11 Strength variation in uni-directional CFRP laminates with respect to strike rate

velocities) is shown in Fig. 11. The maximum tensile stress pulse magnitudes considered are: 100, 200, 300, 400, 500, 600, and 700 MPa. It is observed from the plots that with the increase in the impact velocity, the ultimate tensile strength, and energy absorption increase significantly. This increase in the energy absorption at higher impact velocities shows the advantage of using the CFRP laminates in the structures subjected to the impulsive blast loads wherein materials are subjected to high rate of loading. Further, it is observed that there is a marginal increase in the ultimate strength with the variation in the stress pulse from 400 to 600 MPa. However, significant increase in the ultimate strength is observed when the stress pulse is increased to 700 MPa as shown in Fig. 11. The energy absorbed is increased almost 1.3 times for high impact stresses (700 MPa) than that at the lower impact stresses (100 MPa).

4.2 Effect of CFRP specimen thickness

In order to understand the effect of the thickness (t_h) of the specimens on the stress–strain behavior of the CFRP laminates, an investigation under a stress of 400 MPa with varying thickness is carried out. Figure 12 shows the results of the effect of variation in the thickness of the specimen for the length (L) to width (W) ratio of 1.43. It can be observed from these plots that before rupture of the CFRP laminate, there is almost no effect of the variation in the thickness, $t_h = 1$, 2, and 3 mm. However, when stress in the CFRP laminate increased beyond 1000 MPa, marginal effect of the variation in the thickness of the CFRP is observed. It is found that with the increase in thickness from 1 to 2 mm, there is marginal increase in the stress (variation being less than 5%); however, from 2 to 3 mm there is insignificant change in this stress level. Hence, based on these observations, it is concluded that the effect of variation in the thicknesses investigated here on the stress level is insignificant. Figure 13 shows the corresponding strain rates with three thicknesses, $t_h = 1$, 2, and 3 mm for the length to width ratio, $L/W = 1.43$. It is noticeable that the strain rates induced in the CFRP specimen are sensitive to its thickness.

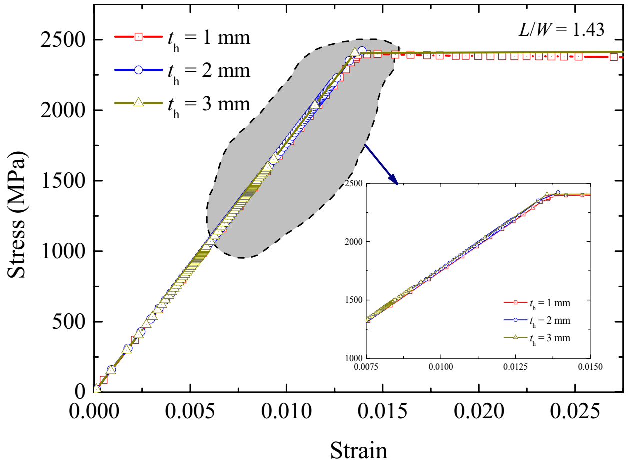

Fig. 12 Effect of variation of thickness (t_h) for a peak impulse of 400 MPa and $L/W = 1.43$

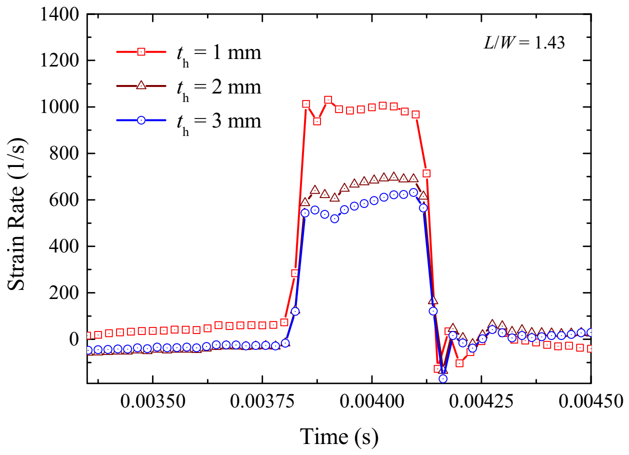

Fig. 13 Strain rates for three thicknesses of the CFRP laminates under a constant stress pulse

4.3 Effect of length to width (L/W) ratio

In order to understand the effect of the length to width ratio (L/W) of the specimens on the stress–strain behavior of the CFRP laminates, an investigation under a stress of 400 MPa with varying L/W ratio is carried out. Figure 14 shows the results of the effect of the variation of the L/W ratio of the CFRP specimens. It can be observed from these

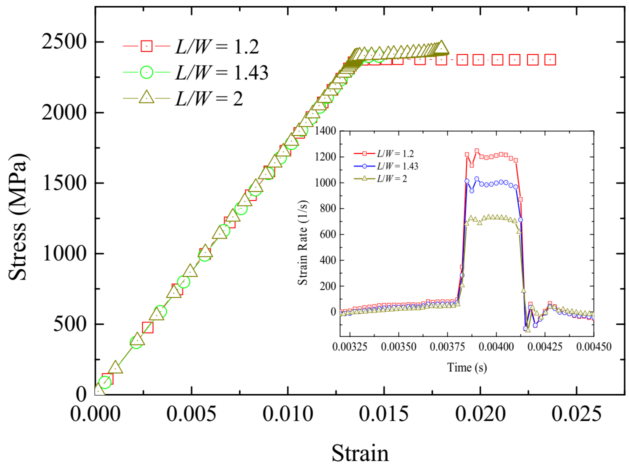

Fig. 14 Effect of variation of *L*/*W* ratio and corresponding strain rates for CFRP laminates under a constants stress pulse

plots that before rupture of the CFRP laminate there is almost no effect of variation of *L*/*W*. However, when stress in the CFRP laminate increased beyond 1500 MPa, marginal effect in the variation of the *L*/*W* is observed. It is found that with the increase in the *L*/*W* from 1 to 1.43 there is marginal increase in the stress (variation being less than 3%), however from 1.43 to 2 mm there is no change in the stress level; hence, based on these observations, it is concluded that the effect of variation of the length to width ratio on the stress level is insignificant under present investigation for considered simulation parameters.

5 Conclusions

In the present investigation, tensile properties of the uni-directional carbon fiber reinforced polymer (CFRP) laminates subjected to high strain rates is studied experimentally using crossbow system and the test results are used to validate a numerical model developed. Moreover, the quasi-static tests were conducted in universal testing machine (UTM) from which the material constants of the uni-directional CFRP laminates are calculated. It is found that the uni-directional CFRP laminates show linear elastic behavior till the rupture followed by a sudden failure. The dynamic characterization of the CFRP laminates is done using the Hopkinson bar crossbow system and the numerical model developed based on it is used for conducting parametric investigation on the ultimate tensile strength and energy absorption properties of the CFRP laminates along with specimen's geometric parameters. Based on these experimental and numerical investigations the following conclusions are arrived at.

1. The elastic modulus of the CFRP laminates from the dynamic analyses is obtained almost the same as that from the quasi-static test and it does not vary with the impact velocity; hence, it is concluded that the elastic modulus of the uni-directional CFRP laminates is strain rate insensitive.
2. The variation of the ultimate tensile strength against carrier impact velocities showed that the uni-directional CFRP laminate shows higher strengths with the increase in the strain rates and the variation is considerable for the uni-directional laminates considered in the present investigation. Hence, it is concluded that the ultimate tensile strength of the CFRP laminates is reasonably strain rate sensitive. The increase in ultimate tensile strength of the CFRP laminates due to the increased rate of loading has been observed to be about only 1% for the strain rate of 1750/s applied in the tests conducted in this study in comparison with the quasi-static study.
3. The energy absorbed is increased almost 1.3 times for high impact stresses (700 MPa) than that at the lower impact stresses (100 MPa). The significant increase in the energy absorption shows the advantage of using the uni-directional CFRP composite materials for structures subjected to high strain rates such as that during the blast events.
4. The effect of variation of thickness and length to width ratio on the dynamic behavior is insignificant for the parameters considered in the present investigation.

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Compliance with ethical standards

Conflict of interest The authors declare no potential conflicting interests in the submission of this journal manuscript in terms of authorship of the research conducted and presented.

References

1. Al-Bastaki NMS (1998) Design of fiber reinforced composite structures subjected to high strain rates using finite element analysis. Appl Compos Mater 5:223–236
2. Al-Zubaidy H, Zhao XL, Al-Mahaidi R (2013) Mechanical characterization of the dynamic tensile properties of CFRP sheet and adhesive at medium strain rates. Compos Struct 96:153–164

3. ASTM D3039/D3039M-14 (2014) Standard test method for tensile properties of polymer matrix composite materials. American Society for Testing and Materials (ASTM), West Conshohocken
4. Ćwik TK, Iannucci L, Curtis P, Pope D (2017) Design and ballistic performance of hybrid composite laminates. Appl Compos Mater 24:717–733
5. Deshpande AB (2006) Characterization of CFRP and GFRP composite materials at high strain rate tensile loading. Master of Science Thesis, College of Engineering and Faculty of Graduate School, Wichita State University (WSU), USA
6. Dhaliwal GS, Newaz GM (2016) Modeling low velocity impact response of carbon fiber reinforced aluminum laminates (CARALL). J Dyn Behav Mater 2(2):181–193
7. Gilat A, Goldberg RK, Roberts GD (2002) Experimental study of strain-rate-dependent behavior of carbon/epoxy composite. Compos Sci Technol 62(10–11):1469–1476
8. Goel MD, Matsagar VA (2014) Blast resistant design of structures. Pract Period Struct Des Constr Am Soc Civ Eng (ASCE). https://doi.org/10.1061/(ASCE)SC.1943-5576.0000188
9. Goel MD, Matsagar VA, Gupta AK, Marburg S (2013) Strain rate sensitivity of closed cell aluminum fly ash foam. Trans Nonferrous Met Soc China 23:1080–1089
10. Gómez-Del Río T, Barbero E, Zaera R, Navarro C (2005) Dynamic tensile behavior at low temperature of CFRP using a split Hopkinson pressure bar. Compos Sci Technol 65(1):61–71
11. Hamdan S, Swallowe GM (1996) A crossbow system for high-strain-rate mechanical testing. Measur Sci Technol 7:1068–1072
12. Harding J, Welsh LM (1983) A tensile testing technique for fiber reinforced composites at impact rates of strain. J Mater Sci 18:1810–1826
13. Ju M, Lee S, Park C (2017) Response of glass fiber reinforced polymer (GFRP)-steel hybrid reinforcing bar in uniaxial tension. Int J Concr Struct Mater. https://doi.org/10.1007/s40069-017-0212-9
14. Kimura H, Itabashi M, Kawata K (2012) Mechanical characterization of uni-directional CFRP thin strip and CFRP cables under quasi-static and dynamic tension. Adv Compos Mater 10(2–3):177–187
15. Masson I, Guégan P, Lesaffre AS, Quirion Y, Poitou A (2006) Dynamic compressive testing under confining pressure on a quasi-brittle material. J Phys IV 134(1):707–712
16. Pashmforoush F, Fotouhi M, Sarhan AAD (2017) Experimental-numerical study on minimizing impact induced damage in laminated composites under low-velocity impact. J Reinf Plast Compos. https://doi.org/10.1177/0731684417737166
17. Suga K, Okamoto K, Takagi K, Nakatani H, Ogihara S, Kikuchi M (2012) Numerical validation of split Hopkinson pressure bar technique for evaluating tensile mechanical properties of CFRP laminates. Adv Compos Mater 21(3):221–232
18. Taniguchi N, Nishiwaki T, Kawada H (2007) Tensile strength of unidirectional CFRP laminate under high strain rate. Adv Compos Mater 16(2):167–180
19. Taniguchi N, Nishiwaki T, Kawada H (2008) Experimental characterization of dynamic tensile strength in unidirectional carbon/epoxy composites. Adv Compos Mater 17(2):139–156