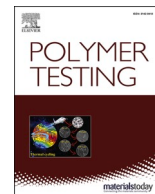


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Test Method

High strain rate compression testing of intra-ply and inter-ply hybrid thermoplastic composites reinforced with Kevlar/basalt fibers

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ABSTRACT

In this study, the influence of hybridization on the compression response of thermoplastic matrix-based composites under high strain rate loading was investigated. The intra-ply and inter-ply hybrid composites were manufactured with Kevlar/Basalt yarns as the reinforcements with Polypropylene as a matrix. Cylindrical composite specimens were laser cut from the flat compression moulded laminates. The composite specimens were loaded under high strain rate using split-Hopkinson pressure bar setup at strain rates ranging from 2815/s to 5481/s. The study revealed differences in the rate-dependent growth of peak stress, peak strain and toughness with the strain rate. Intra-ply hybrid composites with alternate weaving of Kevlar and basalt yarns exhibited highest peak stress as compared to the Inter-ply hybrid composites (alternate layers of Kevlar and basalt fabrics) and another intra-ply composite containing Kevlar in the warp and basalt in the weft direction. Whereas in inter-ply hybrid composite, with Kevlar as the loading face attained higher stress, while composite with Basalt as the loading face attained higher strain. SEM micrographs revealed that Kevlar on the loading face can bear the impact with lesser delamination as compared to the Basalt on the loading face. Damage studies revealed that Kevlar fiber surface loading results in higher stress as compared to basalt (brittle) surface loading with lower overall damage.

1. Introduction

Composite materials encounter loading rates from quasi-static in structural applications to shock in the case of the blast and ballistic applications. Particularly, in protective structures, aerospace and naval applications, they exhibit large deformation under impact load. Understanding of response of composites under high strain rates is necessary to analyse their dynamic response [1]. Furthermore, numerical modelling of composites under dynamic loading requires the knowledge of the variation of mechanical properties with an applied rate of loading [2]. Kevlar is an important reinforcement material in high velocity ballistic impact applications due to its lightweight, excellent specific stiffness and specific strength in comparison to conventional metals. These properties can be further improved through hybridization with less expensive fibers like basalt, glass and carbon [3]. Hybridization of high stiffness reinforcements with more ductile fibers like Kevlar combined with a ductile matrix like PP coalesces good mechanical properties with an excellent impact resistance [4]. The mechanical properties of a

hybrid composite can be varied by changing the stacking sequence, volume ratio and weaving of different yarns.

Split-Hopkinson pressure bar (SHPB) is one of the standard test methods that is used to obtain material properties at high strain rates [5, 6]. Various studies were carried out on high strain rate response of carbon/epoxy composites [7–9], glass/epoxy composites [10–13] and Kevlar/epoxy composites [14,15]. In these studies, it was reported that dynamic properties like peak stress and toughness increase with an increase in the strain rate. It is also reported that Kevlar with thermoplastic matrices enhances the impact response of the composites [16–19]. However, studies on high strain rate characterization of Kevlar reinforced thermoplastic matrices are very few [20]. Kapoor et al. [20] studied the high strain rate response of Kevlar/PP composites with different thicknesses. The laminate with the lower thickness (1.70 mm) exhibited a higher strain rate as compared to the higher thickness laminate (4.6 mm). It was observed that peak strain increases with an increase in the strain rate of Kevlar/Polypropylene (PP) composites due to the ductile nature of both fibers and matrix. Composites reinforced

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with single fiber material may not be suitable under different loading conditions during the service life [21]. Moreover, the implementation of Kevlar reinforced thermoplastic composites is more expensive than glass/carbon fibers [22]. Hybridization is a cost effective method which provides advantages of all the constituent material properties, while instantaneously alleviating their less appropriate qualities. Very few studies [21,23,24] investigated the high strain behavior of hybrid composites. In these studies, the hybrid combination used was glass/carbon and carbon/Kevlar composites with thermoset epoxy as a matrix. Naresh et al. [23] studied the dynamic response of carbon/glass reinforced epoxy composites at strain rates of 0.0016s^{-1} to 542s^{-1} . They reported that hybridization did not show a significant influence on the high strain rate response, however, combined advantages of both glass and carbon exhibited sensitivity to strain rate. Woo and Kim [24] studied high strain rate compressive response of carbon/Kevlar hybrid composites within the strain-rate range of $1002\text{--}1941\text{s}^{-1}$. The peak stress of hybrid composites was increased with strain rate while peak strain decreased. It was also reported that basalt is a good replacement for glass/carbon fibers due to its high strength coupled with brittle behaviour [25]. Sun et al. [26] studied high strain rate compression response of 2D and 3D basalt reinforced Vinyl ester composites within the strain rates of $0.001\text{--}3500\text{s}^{-1}$ and reported property enhancement as a function of the rate of loading.

From the above literature survey, it can be concluded that the dynamic characterization was carried out on thermoset composites either homogeneous [8,9,14] or hybrid [21,23]. Few studies reported the high strain rate response of thermoplastic composites [2,20]. It was also suggested that the combination of high stiffness basalt yarns with more ductile organic fibers like Kevlar improves the dynamic properties [4]. However, it was suggested for thermoset based composites. Also, it was suggested that the use of ductile PP with Kevlar [18] and a hybrid combination of Kevlar/basalt [19] improves the ballistic impact response of the composites. It was also reported that the intra-ply hybridization exhibits better static properties than the inter-ply hybridization [27,28]. However, for the implementation of these materials for high strain rate applications like protective structures, it is very much necessary to assess their response under high strain rate loading conditions. The high strain rate properties of Kevlar/basalt reinforced PP composites are not available in the open literature. Although mechanical properties of Kevlar or basalt/PP composites were reported, these studies were limited to either homogeneous or inter-ply hybrid composites. The type of hybridization also plays an important role in assessing high performance reinforcements for applications in protective structures. The hybridization at the yarn level highly influences the tailoring of properties with different combinations of reinforcement [3]. The need for research on the dynamic characterization with a combination of highly ductile Kevlar with high stiffness basalt fiber reinforced PP composites led us towards the present investigation. Also, a significant comparison between intra-ply and inter-ply hybridization helps to choose a correct form of hybridization for a particular application.

Therefore, the objective of the present study is to determine the high strain rate compression response of inter-ply and intra-ply hybrid Kevlar/basalt reinforced thermoplastic composites. Intra-ply and inter-ply hybrid composites were manufactured with thermoplastic polymer Polypropylene (PP) as a matrix. High strain rate compression tests were performed using SHPB setup and dynamic properties including peak stress, peak strain and toughness were evaluated. Dynamic failure modes under high strain rate loading were identified through SEM fractography and macroscopic analysis.

2. Experiments

2.1. Materials

2D-P fabrics were woven from Aramid (Kevlar) yarns of 1000 denier and basalt yarns of 2700 denier on a CCI make sample weaving machine.

Four different fabrics were produced; first, with Kevlar yarns (KPL), second with basalt yarns (BPL), third was a hybrid fabric with alternate placement of Kevlar and basalt yarns (HP-1) and the fourth was with basalt yarns in the warp direction and Kevlar yarns in the weft direction (HP-2). Surface images of produced fabrics are shown in Fig. 1. It may be noted that the purpose of the study is to investigate the behaviour of hybrid composite, for which alternate layers of Kevlar and basalt are used. For single fiber based composites, numerous studies are available in the literature [7–13,20]. Thermoplastic polymer PP of grade MI3530 was used as a matrix in the form of film. This PP film was produced using an in-house extrusion facility with a drawing speed of 5 mpm, die temperature of 205°C and an extruder pressure of 15 bar [18]. The interfacial property between Kevlar/basalt fabric and PP was improved by adding a coupling agent called, maleic anhydride grafted PP (MAG-PP) (Make: Pluss Polymers, Grade: Optim P-406) [18]. The main function of this coupling agent is linking of fibers to the polymer matrix and reducing the pull out while increasing the impact and tensile strength. The constructional parameters of different fabrics are presented in Table 1. The pure Kevlar and Basalt fabrics were used to manufacture inter-ply hybrid composites.

2.2. Manufacturing of composites

Eight layer composite laminates were manufactured using vacuum-assisted compression molding. Four different composite laminates were manufactured, including two intra-ply and two inter-ply hybrid composites. Schematics of the stacking sequence for different hybrid composites are shown in Fig. 2.

Eight layers of 2D-woven fabric with alternate matrix films were stacked and compacted to produce composite laminates using compression molding. The laminates were kept at a molding pressure of 10 bar pressure at a temperature of 200°C for 10 min. Vacuum at 550 mm of Hg was maintained to avoid voids and air entrapment. After completion of the molding time, the mold platens were water cooled to bring laminates to ambient temperature under pressure. Cylindrical specimens of diameter 11.47 ± 0.04 mm were cut from the laminate using computer aided fiber laser cutting machine. Physical properties of manufactured composite laminates such as density and fiber volume fraction were measured by water displacement method as per ASTM D792 and burn off test as per ASTM D2584 standards, respectively. The physical parameters measured for the manufactured laminates are presented in Table 2.

2.3. Split-Hopkinson pressure bar test

High strain rates tests in the compression direction of the specimens were performed using SHPB apparatus available at Indian Institute of Technology Delhi, India. This SHPB set-up comprises of three Titanium (Ti6Al4V) bars of 16 mm diameter; a striker bar of length 240 mm, an incident bar of length 1200 mm and a transmission bar of length 1200 mm. The properties of titanium bars were: density $\rho = 4430$ kg/m³, Young's modulus = 113.8 GPa and elastic wave speed = 5068 m/s. To obtain the adequate dynamic equilibrium in the SHPB test, a pulse shaper of 1.3 mm thick and 3.1 mm diameter Linatex (natural rubber) was used between the striker and incident bar [29]. The schematic of the SHPB set-up is shown in Fig. 3.

The specimen was kept between the incident bar and the transmission bar. When the pressurized nitrogen gas is released, the striker bar accelerates and impacts the incident bar. This impact produces a constant amplitude elastic compressive wave in the incident bar. When this elastic wave crosses the midsection of the incident bar, the strain induced is recorded in the form of change in voltage due to a change in the resistance of the strain gage. When the wave reaches the bar/specimen interface, a part of the stress wave is reflected to the incident bar as a tensile wave, and partly transmitted to the transmission bar as a compressive wave. The voltage signal that is received from the incident

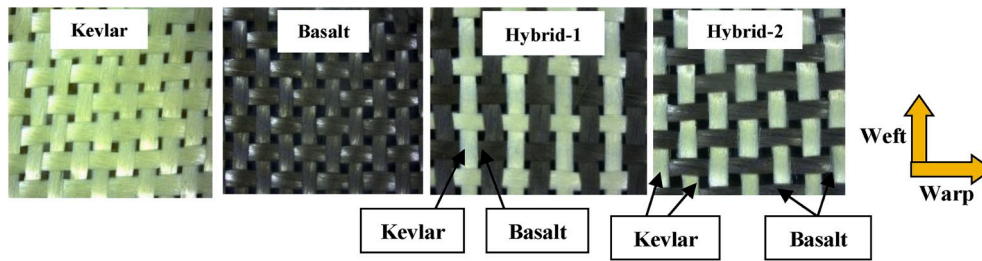


Fig. 1. Surface photographs of different 2D-P fabrics.

Table 1
Constructional and dimensional parameters of different fabrics.

Fabric	Abbreviations	Warp yarns/inch (EPI)	Weft yarns/inch (PPI)	Thickness (mm)	GSM (g/m ²)
Kevlar 2D	KPL	15	15	0.29	145
Basalt 2D	BPL	15	15	0.50	370
Hybrid-1	HP-1	15	15	0.40	250
Hybrid-2	HP-2	15	15	0.40	250

EPI = Ends per inch and PPI = Picks per inch.

bar is responsible for strain induced in the specimen and strain rate. The voltage recorded from the transmission bar is a measure of stress induced in the specimen. Further details on measurement theory and instrumentation are well described in Refs. [6,30]. The high strain rate compressive properties including stress (σ), strain (ϵ) and strain rate ($\dot{\epsilon}$) were obtained based on the following equations [31,32]:

$$\sigma = \frac{E_b A_b}{A_s} \epsilon_t(t) \tag{1}$$

$$\epsilon = \frac{-2C_e}{L_s} \int_0^t \epsilon_r(t) dt \tag{2}$$

$$\dot{\epsilon} = \frac{-2c_e}{L_s} \epsilon_r(t) \tag{3}$$

where, E_b is the modulus of the bars, A_b is the cross-sectional area of the bar, A_s is the cross-sectional area of the specimen, C_e is the wave velocity in the bar, L_s is the length of the specimen, $\epsilon_r(t)$ is the reflected strain gage signal and $\epsilon_t(t)$ is the transmitted strain gage signal.

For the calculation of strain rate of homogenous materials slope of strain rate-time curve serves the purpose. However, in the case of the dynamic loading of composites, stress wave attenuation is substantial. Therefore, in this case, the scheme suggested in the known literature

[33] for materials showing stress wave attenuation is used. The strain rate in this work is calculated by dividing the area under the strain rate-strain curve up to maximum strain under loading by the maximum strain.

The failure characterization of specimens was performed at macroscopic and microscopic levels. The macroscopic analysis was performed by capturing the fractured specimens using a high definition camera. Microscopic failure analysis was performed using SEM. For SEM the images were captured along the edge (thickness side) of the specimen.

3. Results and discussion

Dynamic compression tests were carried on the intra-ply and inter-ply hybrid composites at strain rates ranging from 2820/s to 5481/s. An example of dynamic compression responses in the HP-1 specimen at 1.2 and 1.4 bar pressures is shown in Fig. 4. The strain waves detected by strain gages mounted on the incident and transmission bars of the SHPB setup are shown in Fig. 4. The green line represents the signal from the incident bar and the blue line represents the signal from the transmission bar. Due to impact of the striker bar on the incident bar, the stress wave propagates in the incident bar and separates into two parts when reaches the interface between the incident bar and the specimen. One part is reflected to the bar and the other part is transmitted into the specimen. Then, the remaining pulse reaches the interface between the specimen and transmission bar.

Again, a part of the pulse is reflected into the specimen and the remaining part is continuously transmitted to the transmission bar. The incident and transmitted waves were compressive and the reflected

Table 2
Measured physical parameters of the laminates [19].

Parameter	HP-1	HP-2	HP-B	HP-K
Density (g/cc)	1.44	1.37	1.37	1.36
Fiber volume fraction (%)	52.17	53.45	53.41	54.15
Thickness (mm)	1.70 ± 0.04	1.72 ± 0.05	1.74 ± 0.02	1.72 ± 0.02

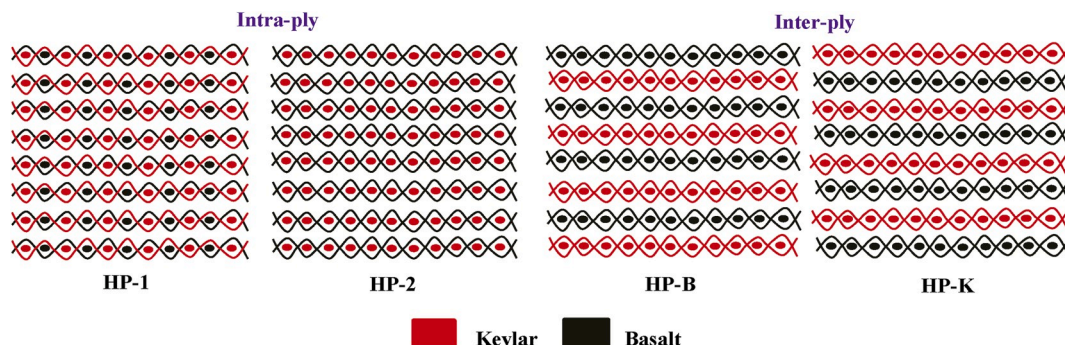


Fig. 2. Schematics of stacking sequence in manufacturing process.

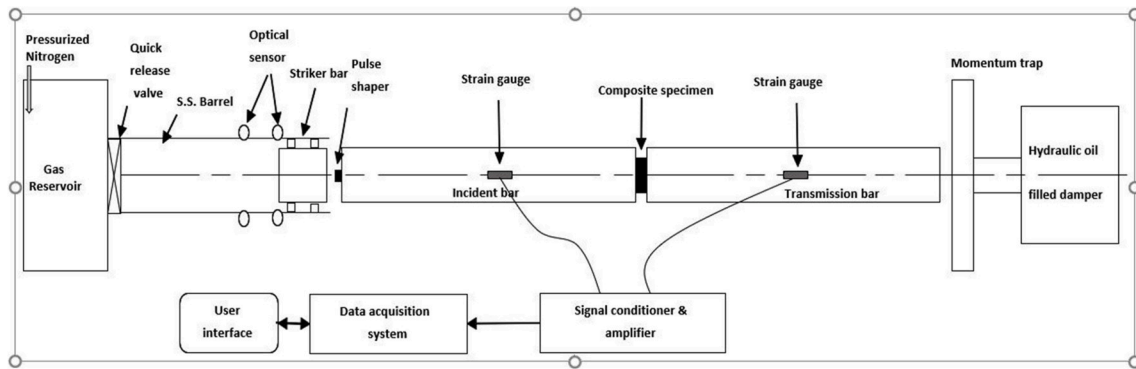


Fig. 3. Schematic SHPB set-up for compression tests.

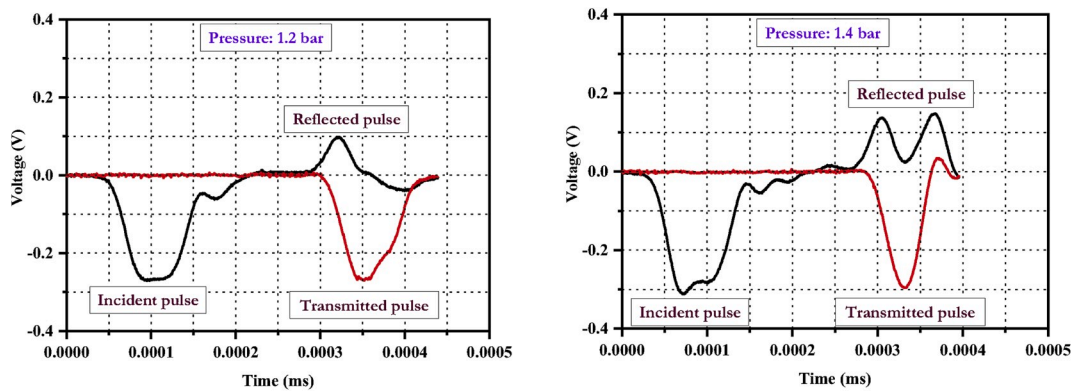


Fig. 4. Typical dynamic compressive responses from strain gages showing voltage versus time curve.

wave was tensile. The transient data for each specimen tested under a high strain rate was recorded in terms of incident, reflected and transmitted waves. Shortening of the transmitted pulse and a second peak in the reflected pulse indicates the occurrence of macroscopic damage [34–37]. At an impact pressure of 1.2 bar, there was no second peak in the reflected curve while for 1.4 bar it was present. A similar scenario was observed for the remaining specimens. The strain gage signal from the transmission bar is converted into the stress and reflected strain pulse from the incident bar is converted to strain and strain rate using Eqs. (1)–(3), respectively. Strain rate versus time and stress versus time response were saved, then these data were superimposed to obtain dynamic stress-strain response.

For each loading condition, a minimum of three tests was carried out for each specimen at the same impact pressure and the same environmental conditions to ensure reproducibility. The dynamic in-plane compressive response and dynamic compressive properties including peak stress, strain at peak stress, the slope of the stress-strain response and the toughness values were measured and discussed in the following sections. Table 3 presents the impact pressures applied and the corresponding strain rates for all the hybrid specimens.

3.1. High strain rate stress-strain response

Through-the-thickness dynamic compression tests were performed on intra-ply and inter-ply hybrid composites within the strain rate regime of 2820–5481/s. Initial strain rates of all the specimens were very close (Refer Table 3) i.e. $\sim 2820 \pm 18.7/s$ at a pressure of 1.0 bar. The dynamic stress-strain response of intra-ply hybrid composites (HP-1, HP-2) was explained first followed by inter-ply hybrid (HP-B and HP-K) composites. Later, the dynamic response of intra-ply and inter-ply composites was compared at their initial strain rates. The maximum stress value of the stress-strain response before softening was considered

Table 3
Impact pressures and measured strain rates.

Impact pressure (bar)	Strain rate (s^{-1})			
	HP-1	HP-2	HP-B	HP-K
1.0	2820 \pm	2800 \pm	2815 \pm	2845 \pm
	25.21	23.65	19.63	30.23
1.2	3590 \pm	3570 \pm	3588 \pm	3586 \pm
	32.70	18.27	25.81	24.98
1.4	4953 \pm	4990 \pm	4611 \pm	4687 \pm
	12.76	30.26	24.75	22.16
1.6	5085 \pm	5429 \pm	5463 \pm	5481 \pm
	26.05	24.62	20.36	27.63

as the peak stress and the corresponding strain was considered as the peak strain. The toughness was obtained by measuring the area under the stress-strain response.

Typical high strain rate compression stress-strain responses of intra-ply hybrid composites are shown in Fig. 5. The strain rates of HP-1 and HP-2 specimens were approximately the same. However, the stress-strain response varied depending on the structure of the composite. The initial linear elastic region was followed by a region of the inelastic region, until yielding occurred, beyond which specimens failed due to shear. Then, the stress was decreased attributing the strain softening. At lower strain rates (2820/s for HP-1 and 2800/s for HP-2), the samples were undamaged with minimal plastic deformation, indicated by the recovery curve towards the end of the stress-strain curve. As the strain rate increased, the specimens underwent deformation exhibiting different failure behaviors depending on the structure of the specimens. The stress increased with an increase in the strain rate until a threshold strain rate was reached. Beyond the threshold point, increasing strain rate resulted in catastrophic specimen failure. However, it may be noted

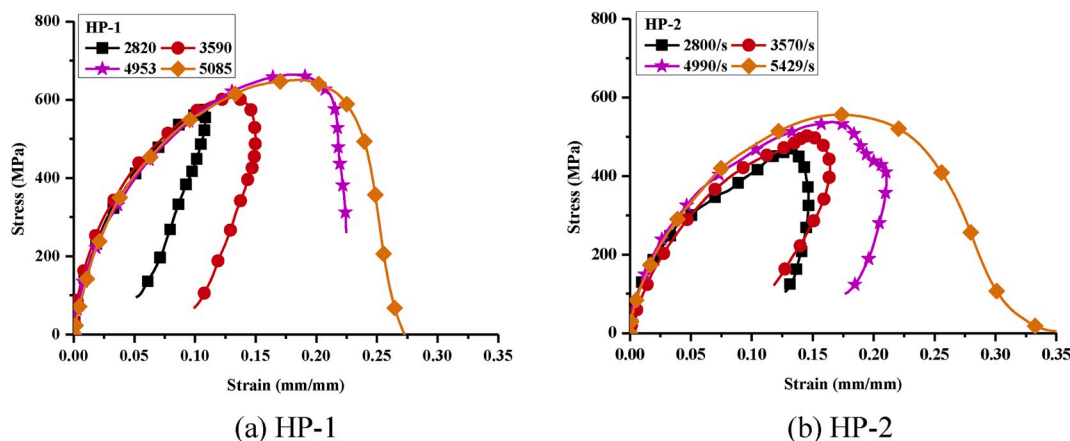


Fig. 5. Dynamic stress-strain response of intra-ply hybrid composites.

that after failure strain rate the peak stress lies in close range of stress, indicating the limiting value of stress beyond which the composite system is not capable of showing significant enhancement in strength characteristics as a function of enhancing strain rate.

The HP-1 (Fig. 5a) specimens exhibited a region of the inelastic region approximately from a strain of 0.0125. At strain rates of 2820/s and 3590/s, the rate of increase in the stress of HP-1 specimens was nearly the same and specimens were intact following a hysteresis loop in stress-strain response. At a strain rate of 4953/s, the specimen exhibited a maximum peak stress value showing microscopic damage. Beyond this strain rate, the specimens exhibited catastrophic failure, hence, limiting the strain rate for HP-1 specimens was 4953/s. The peak stress decreased slightly after the threshold strain rate while the peak strain was increasing. An interesting phenomenon at limiting strain rate is a nearly vertical drop of stress curve at failure, whereas the same was followed by the recovery curve of lower strain rates and increasing total strain for further higher rates of loading.

The HP-2 specimens (Fig. 5b) were subjected to strain rates of 2800/s, 3570/s, 4990/s and 5429/s. Unloading was observed until the strain rate of 4990/s, beyond which the specimen failed. At lower strain rates, the rate of increase in the strain was higher than that of the HP-1 specimen. It may be due to the lower inter-yarn friction between yarns [38]. As the strain rate increased, the peak stress and peak strain were increased. The threshold strain rate for the HP-2 specimen was 4990/s and resulted in peak stress of 537.55 MPa at 16.65% strain.

Though both the intra-ply hybrid (HP-1 and HP-2) and interplay (HP-B and HP-K) specimens withstand identical threshold rate, which may be attributed to the identical areal density of both the fabrics. However, in the case of HP-1 composite, in which Kevlar and basalt yarns were alternately woven in both the warp and weft direction, resulted in better performance of the composite system. HP-2 composite had basalt yarns in the warp direction and Kevlar yarns in the weft direction. Though the number of yarns in the HP-1 and HP-2 composites were the same, the type of weaving influenced the high strain rate properties of intra-ply hybrid composites. At limiting strain rates of approximately 4971/s (average of limiting strain rates of HP-1 and HP-2), the peak stress of the HP-1 specimen was 19.07% higher than the HP-2 specimen, indicating the influence of weaving. Hence, the placement of identical yarns by a common fabrication process may lead to the difference in final properties, is an indicator of the benefits of optimal hybridization.

Fig. 6 shows the dynamic stress-strain responses of inter-ply hybrid composites when impact face was of Basalt and Kevlar respectively. It may be noted that simply changing the face of the composite to the loading from basalt to Kevlar had a significant effect on the high strain rate performance of a given composite. The linear elastic region followed a similar trend in each case, whereas stress was increasing with an increase in the strain rate. Up to the limiting strain rates of HP-B (4611/s)

and HP-K (4687/s) specimens, the specimens were macroscopically undamaged. Therefore, the response of these strain rates was exhibiting unloading of stress. Beyond the limiting strain rates, the specimens exhibited macroscopic damage. The peak stress and peak strain values were increased with an increase in the strain rates. In inter-ply hybrid composites, the stacking of layers influenced the peak stress and peak strain values. HP-K specimens had the highest peak stress and peak strain values than the HP-B specimens.

Two identical composite specimens machined out from single laminate having four alternate layers of basalt and Kevlar fabrics exhibited different properties as impact face was changed. Changing the face of the loading from basalt to Kevlar resulted in the improvement of peak stress by 11.64–15.13% within the strain rate regime of 2815/s to 5481/s. Also, a lower total strain was noted for the same. This indicates the importance of impedance mismatch between bars and specimen and relative hardness and associated brittle behavior of fiber. Since, the basalt face is relatively a hard face, it undergoes brittle fracture irrespective of matrix behavior. Therefore, it may be noted from this simple experimentation, proper attention should be given to the face, which is responsible for the successful entry of energy into the composite, else, even a healthy composite system may result in non-satisfactory performance.

3.2. Comparison of high strain rate response between intra-ply and inter-ply composites

The dynamic stress-strain responses of intra-ply and inter-ply composites were compared at initial strain rates i.e for pressures of 1 bar and 1.2 bar (Refer Table 3). If the strain rate values at these pressures are averaged, they were i.e $\sim 2820 \pm 18.7/s$ and $\sim 3854 \pm 9.40/s$ for pressures of 1.0 bar and 1.2 bar, respectively. Fig. 7 shows the comparison between the stress-strain response of intra-ply and inter-ply hybrid composites at a similar strain rate. Alternate weaving of Kevlar and basalt yarns (HP-1) exhibited higher peak stress as compared to the remaining composites. It may be due to the presence of both high stiffness basalt and high ductile Kevlar yarns in a single layer. Higher peak stress and lower strain may be noted as a function of intra ply hybridization. This indicates the importance of hybridization at fiber level. When the incident bar strikes the specimen, Kevlar yarns tries to dissipate the energy in the form of transverse stress waves, while basalt yarns undergo brittle failure. Due to this hybrid effect, the strength increased. Though HP-1 specimens had a lower peak strain, the rate of increase in strain was higher.

The inelastic region of HP-2, HP-B and HP-K specimens was similar. In the case of HP-2 specimens, placing basalt yarns in the warp direction and Kevlar yarns in the weft direction increased the peak strain. Though both the yarns were present in the loading direction, the addition of the

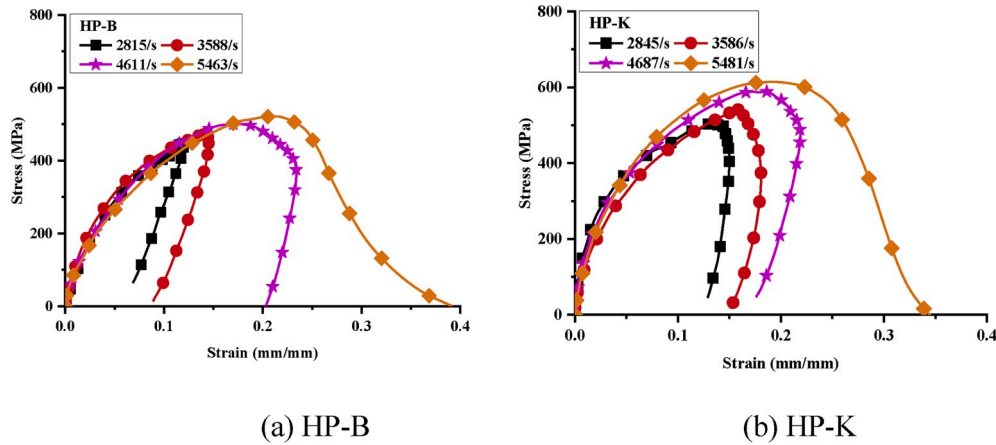


Fig. 6. Dynamic stress-strain response of inter-ply hybrid composites.

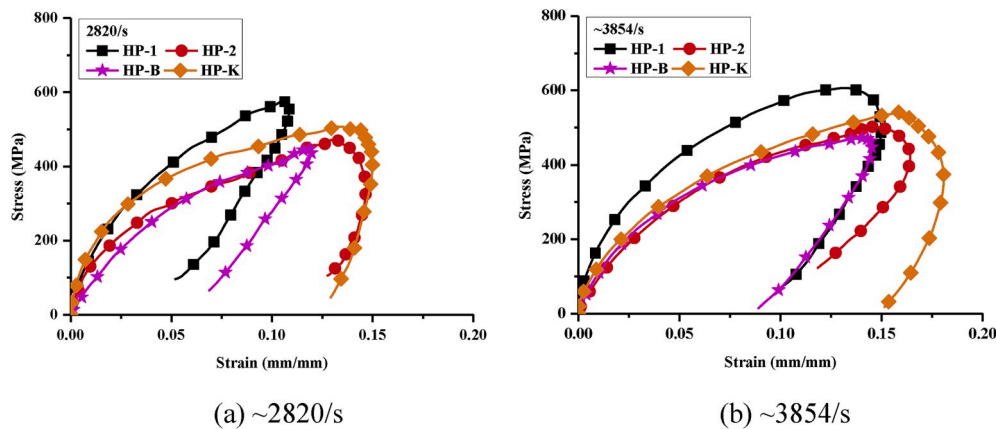


Fig. 7. Dynamic stress-strain response: intra-ply vs inter-ply hybrid composites.

PP matrix increased the failure strain. In the alternate stacking of basalt and Kevlar fabrics with basalt layer on the impact side, exhibited lower peak stress.

3.3. Influence of strain rate on dynamic properties

From the above dynamic stress-strain response it was observed that there was a dependency of material properties on the strain rate. Therefore, in this section, the sensitivity of dynamic properties including peak stress, peak strain and toughness with respect to strain rate was discussed. Fig. 8 shows the influence of strain rate on the dynamic compressive properties of intra-ply and inter-ply hybrid composites. The peak stress was increased with an increase in the strain rate in a linear fashion in each composite (Fig. 8a). The peak stress of intra-ply HP-1 specimens was higher while inter-ply HP-B was lower. The lower peak stress of HP-B may be due to the major role played by the front face basalt fabric which underwent brittle failure as soon as impact initiated. Within the strain rate regimes of 2820–5481/s, the percentage increase in peak stress with respect to strain rate was 15.30%, 17.73%, 16.30% and 21.09% for HP-1, HP-2, HP-B and HP-K composites, respectively.

In Fig. 8b, the peak strain of all the hybrid composites increased linearly with the strain rate. Although these composites consist of basalt yarns, the presence of ductile Kevlar yarns and PP matrix increased the peak strain. At lower strain rates, intra-ply hybrid composites had a lower peak strain than the inter-ply hybrid ones, however, with an increase in the strain rate, the peak strain of intra-ply hybrids was increased. Overall, at lower strain rates ($\sim 2820/s$ and $\sim 3854/s$), there was a difference of 2.86% in the peak strain of all the composites. At

limiting strain rates of all the specimens, it was reduced to the 1.81% peak strain.

The toughness of the hybrid composites increased linearly with the strain rate. At lower strain rates, the toughness of intra-ply hybrids was lower as compared to the inter-ply HP-K composites. With an increase in the strain rate above $\sim 3583/s$, the toughness of intra-ply HP-1 was increased. The increase in the toughness within the strain rate regime (2800–5481/s) was 182.93%, 120.18%, 177.13% and 86.33% for HP-1, HP-2, HP-B and HP-K composites, respectively. The increase of toughness in the case of intra-ply HP-1 composites was higher as compared to the remaining composites. The dynamic compressive properties of all the hybrid composites are presented in Table 4.

3.4. High strain failure analysis

Failure mechanisms of hybrid composites under high strain rate loading at different high strain rates are analyzed using macroscopic images and SEM fractography. The macroscopic analysis was carried out by capturing the surface images of failed specimens after performing tests. SEM fractography was performed in the through-thickness direction of the specimens to identify various failure modes under dynamic loading.

3.4.1. Macroscopic analysis

Macroscopic images of intra-ply hybrid specimens following dynamic tests at various strain rates are shown in Fig. 9. In the case of HP-1 specimens, till the limiting strain rate, the failure was superficial with small deformation along the thickness direction. Beyond limiting strain

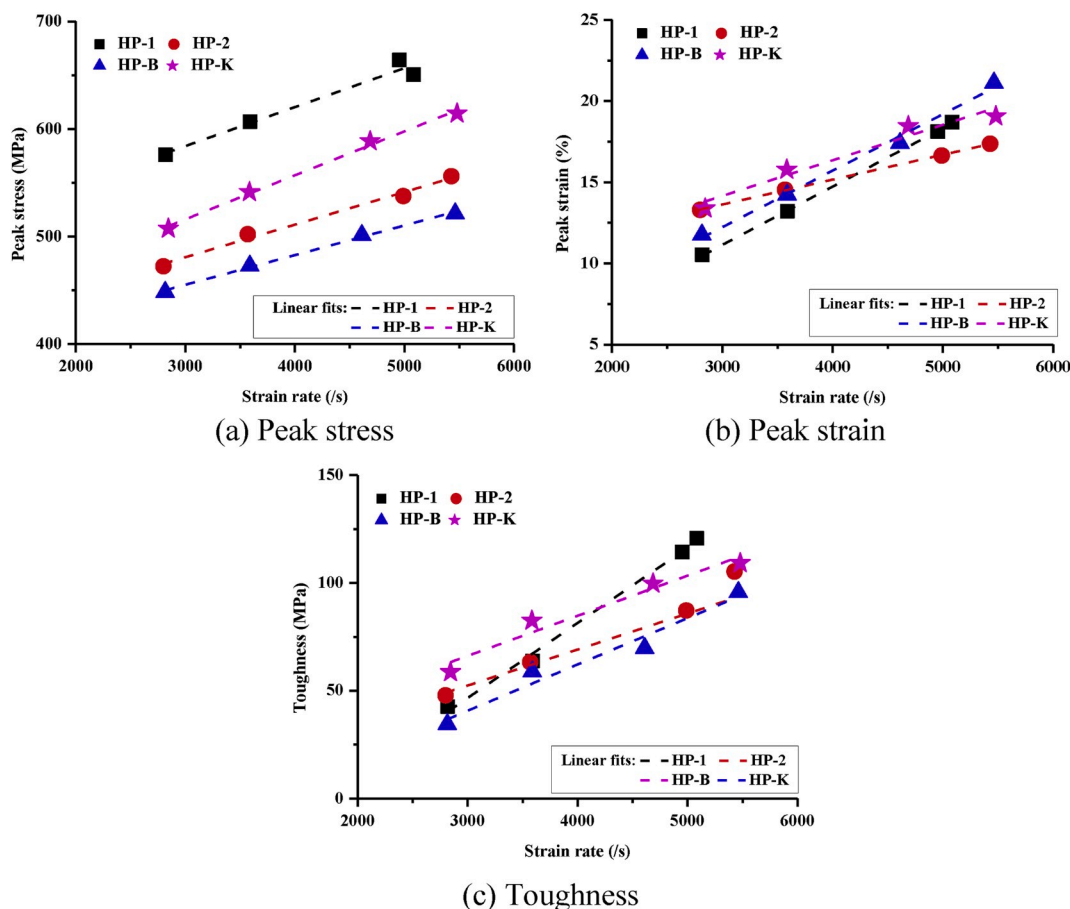


Fig. 8. Strain rate effect on compressive properties.

Table 4
Dynamic compressive properties of intra-ply and inter-ply hybrid composites.

Specimens	Strain rate (s ⁻¹)	Peak stress (MPa)	Peak strain (%)	Toughness (MPa)
HP-1	2820	576.11	10.53	42.65
	3590	606.86	13.21	63.81
	4953	664.26	18.12	114.27
	5085	650.51	18.70	120.67
HP-2	2800	472.36	13.30	47.81
	3570	502.21	14.54	63.28
	4990	537.55	16.65	87.13
	5429	556.13	17.37	91.27
HP-B	2815	448.40	11.77	34.51
	3588	472.89	14.23	58.92
	4611	501.26	17.41	69.76
	5463	521.51	21.13	95.64
HP-K	2845	507.48	13.39	58.61
	3586	541.49	15.78	82.53
	4687	588.68	18.46	99.67
	5481	614.51	19.07	109.21

rate (4953/s) yarns were busted out normal to the loading direction along with matrix crack and yarn breaks on the surface of HP-1 specimens. Similarly, HP-2 specimens were intact until the limiting strain rate and exhibited minor failure on the surfaces with significant local delamination. HP-2 failed after limiting strain rate (4990/s) exhibiting the involvement of multiple failure modes like an inter yarns failure, matrix cracking and shear failure. However, it may be noted that though macroscopic damage was recorded higher for HP-2, (indicating energy absorption), but the resulting properties are better for HP-1 as far as strength and toughness is concerned.

Macroscopic failures of inter-ply hybrid specimens are shown in

Fig. 10. In both the HP-B and HP-K specimens, though the impact faces were different, failure of specimens till the limiting strain rate was microscopic with crushing on the impact face and minor deformation. Beyond limiting strain rate, failure was catastrophic. Both the HP-B and HP-K specimens were failed with fragmenting of yarns, matrix crack, shear failure and busting of yarns.

3.4.2. SEM fractography

Failure on the cylindrical surface of impacted intra-ply and inter-ply hybrid composites was compared at a strain rate of ~2820/s. At this strain rate, all hybrid specimens were intact and exhibited microscopic failure. Therefore, SEM micrographs were compared. Fig. 11 shows the SEM micrographs of intra-ply and inter-ply specimens at a strain rate of ~2820/s. HP-1 specimen exhibited matrix shedding with minor delamination and small shear fracture. Delamination in HP-1 specimens was in the middle of the specimens. However, in HP-2 specimens, delamination was extended to the bottom surface. This can be attributed to the higher peak stress and toughness of HP-1 specimens as compared to HP-2 specimens. At the same strain rate, HP-2 experienced high dynamic load and underwent major yarn deformation along with extensive delamination and shear fracture as compared to HP-1 specimen. In the case of HP-B specimens, multiple shear fractures were evident with delamination and brittle failure of basalt yarns. On the impact face of HP-B specimens, delamination with the shedding of yarns was also observed. On the impact face of HP-K specimens, fragmentation of fabrics with both Kevlar and basalt yarns failure was observed. In addition, yarn kinking, shear fracture and yarn deformation were observed. However, delamination in HP-K specimens was lower than the HP-B specimens. This implies that macroscopic damage had delamination in between.

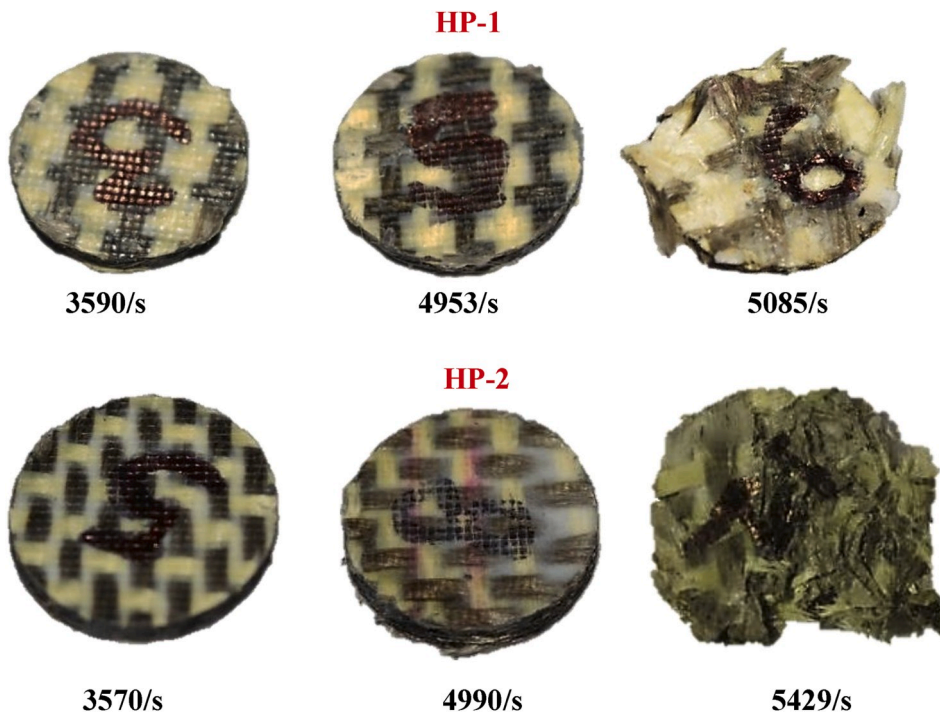


Fig. 9. Macroscopic failure of intra-ply hybrid specimens.

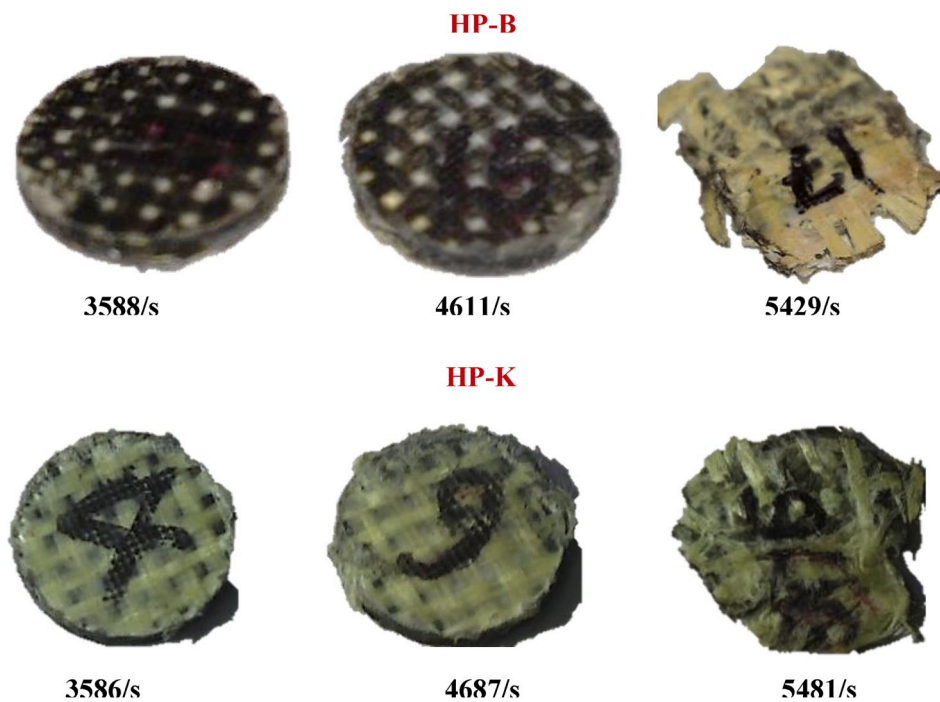


Fig. 10. Macroscopic failure of inter-ply hybrid specimens.

3.5. Comparison of the results

It is very difficult to find the studies on the same reinforcement type, resin, manufacturing and loading conditions to compare the present findings. However, very few studies are available in the open literature, which reported the high strain rate response of Kevlar/epoxy [14], basalt/epoxy [26], Kevlar/PP [20] and 3D Kevlar/basalt with PP [37]. High strain rate properties with a combination of 2D Kevlar/Basalt with PP are not available in the open literature. Therefore, the present results

were compared with the results reported in Refs. [20,37], which are close to the present study. The present study shows the enhancement of high strain rate properties due to hybridization.

Woo and Kim [14] reported that pre-pegged Kevlar-woven fabrics with thermoset resin show a reduction in the failure strain as a function of rising stress which in turn is a function of increasing rate of loading. Typically this confirms the brittle material behaviour. Whereas in the present study, the use of PP polymer exhibited ductile behaviour and it was evident from the increase of failure strain with the strain rate. In

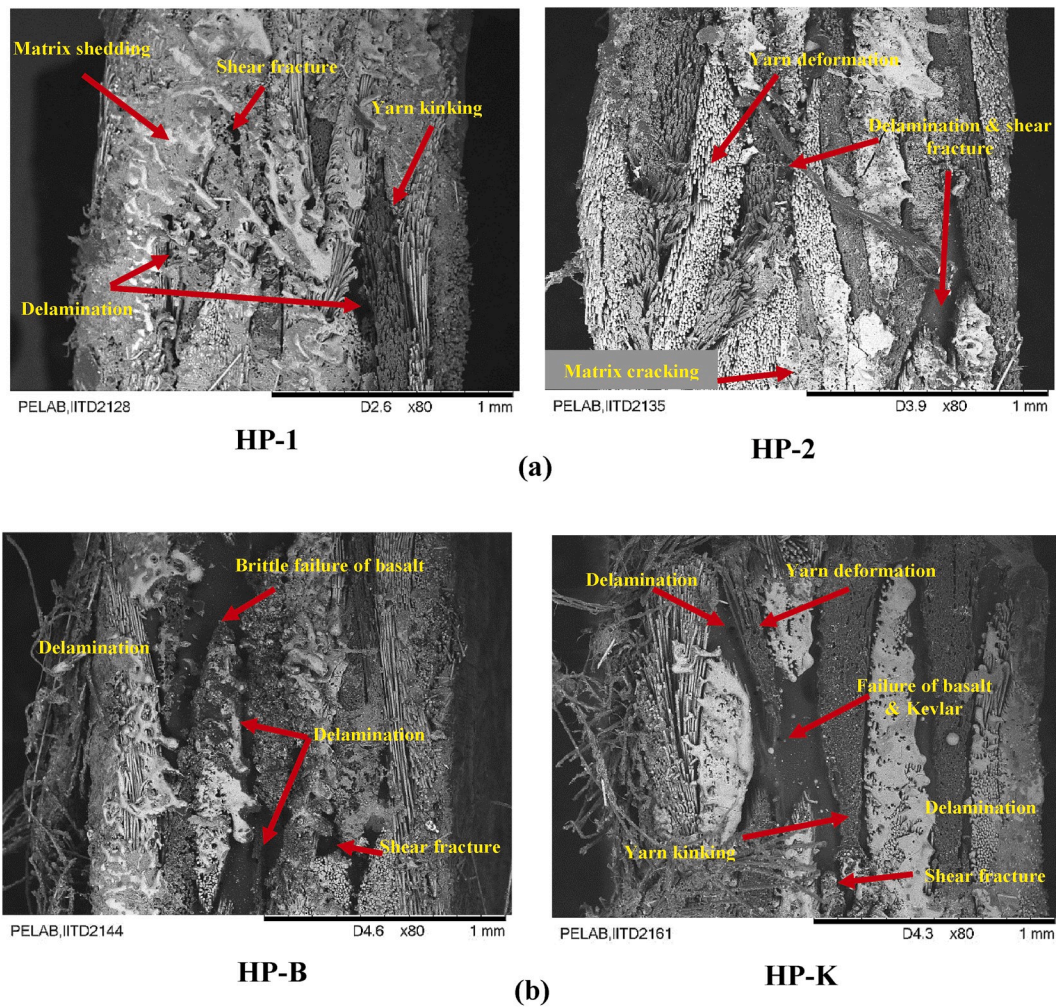


Fig. 11. SEM micrographs of different composites at $\sim 2820/s$: (a) intra-ply, (b) inter-ply.

addition, an interesting phenomenon depicted due to the hybridization of Kevlar and Basalt is the increment of all the material properties like stress, strain, strain rate and toughness.

Sun et al. [26] studied the high strain rate response of basalt reinforced Vinyl ester resin composites in which the brittle behaviour was the major failure due to the high strain rate. However, in the present study, the brittle damage behaviour is significantly controlled due to the presence of Kevlar and PP. The addition of Kevlar and PP resulted in increment of both stress and strain in a hybrid composite system, whereas it is not the same with a composite comprising only brittle basalt fibre.

In Ref. [20], they reported the dynamic response of eight-layer Kevlar/PP composites under strain rates between 1370/s and 6066/s. At a pressure of 1.6 bar, the strain rate reported for Kevlar/PP was 5335/s with peak stress of 407.98 MPa. In the present study, the strain rate obtained at a pressure of 1.6 bar was 5085/s, 5429/s, 5463/s and 5481/s for HP-1, HP-2, HP-B and HP-K, respectively. At these strain rates, the peak stress of present hybrid composites was 27.82–37.28% higher than the pure Kevlar/PP [20], indicating the major role played by the hybridization. Also, the areal density of the hybrid fabrics was 31.31% lower than the Kevlar fabric. Not only peak stress, but also the peak strain and toughness of the present hybrid composites were 2.13–19.54% and 33.58–49.76% higher than the Kevlar/PP composites reported [20]. Fig. 12 shows the comparison of the present study dynamic properties with the literature [20]. This comparison indicates that, with a lower areal density of the hybrid fabrics, enhanced dynamic properties can be achieved.

Bandaru et al. [37] studied the high strain rate response of 3D homogeneous and hybrid composite laminates manufactured with Kevlar, basalt fabrics and PP as a resin. They reported that the tailoring of Kevlar and basalt yarns through intralayer hybridization improved the damage resistance within in the strain rate regime of 3633/s to 5235/s. The materials in Ref. [37], are closely related to the present study, however, the areal density of these fabrics was higher (Table 5) than the fabrics studied in the present study. At a pressure of 1.4 bar, the strain rates of 3D fabrics were 4.68–7.94% higher than that of the 2D hybrid laminates of the present study. It was due to the structure of the fabrics, which provided an additional in-plane stiffness in the compression direction. However, the peak stress of HP-1 laminates was 25.39%, 7.13% and 16.31% higher than that of K3D, B3D and H3D laminates, respectively [37]. Similarly, HP-2, HP-B and HP-K laminates exhibited 7.80%, 1.12% and 15.80% higher peak stress as compared to the K3D laminates in Ref. [37]. Also, the peak strain of present 2D hybrid laminates was 7.84–36.21% and 27.68–34.77% higher than the B3D and H3D laminates of Ref. [37]. It indicates that a higher areal density 3D fabric can be replaced by a lower areal density 2D hybrid fabric which reduces the effort made during the weaving of 3D fabrics and the material wastage. Fig. 13 shows a comparison of dynamic properties between present 2D hybrid composites and 3D composites from the literature. Table 5 presents the comparison between the high strain rate properties of the present study with the literature.

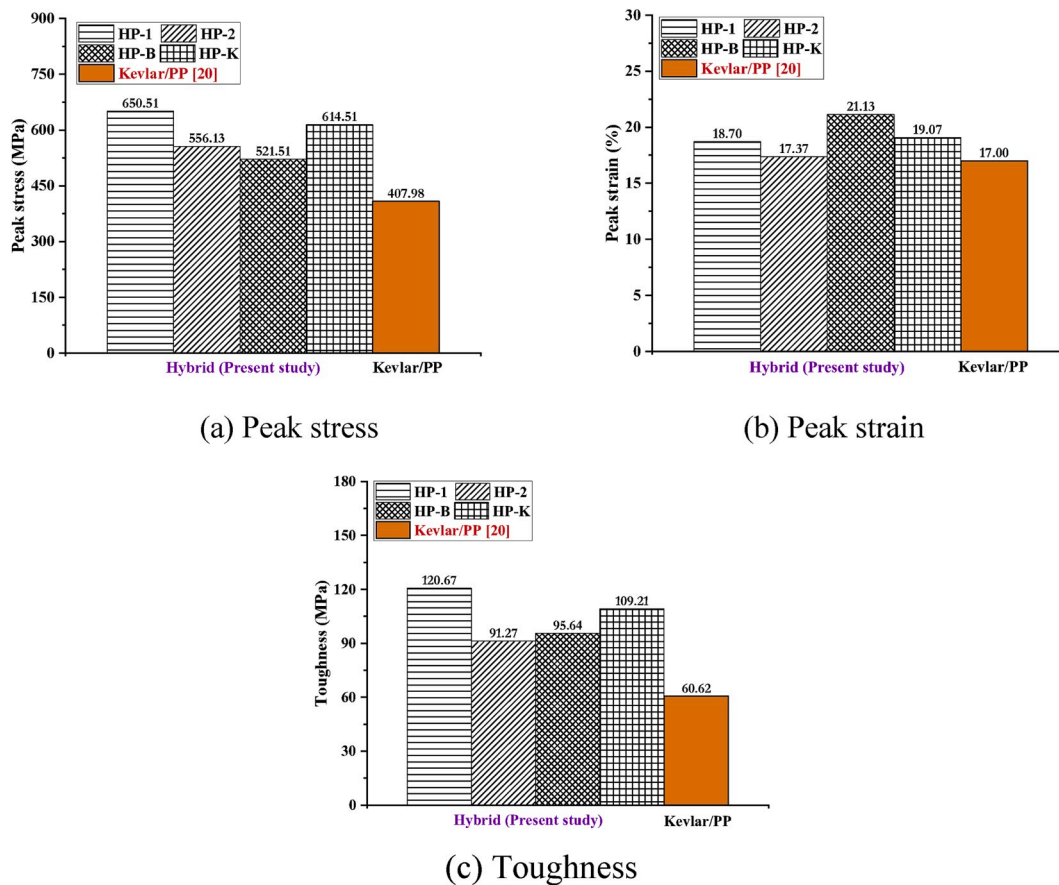


Fig. 12. Comparison of high strain rate properties.

Table 5
Comparison of high strain rate properties with the literature.

Pressure (MPa)	Specimen	Areal density (g/m ²)	Strain rate/s	Peak stress (MPa)	Peak strain (%)	Toughness (MPa)
1.6	HP-1	250	5085	650.51	18.70	120.67
	HP-2	250	5429	556.13	17.37	91.27
	HP-B	-	5463	521.51	21.13	95.64
	HP-K	-	5481	614.51	19.07	109.21
	Kevlar/PP [20]	364	5335	407.98	17.00	60.62
1.4	HP-1	250	4953	664.26	18.12	114.27
	HP-2	250	4990	537.55	16.65	87.13
	HP-B	-	4611	501.26	17.41	69.76
	HP-K	-	4687	588.68	18.46	99.67
	K3D [37]	580	5235	495.61	19.09	60.50
	B3D [37]	1450	5009	616.89	10.62	88.80
	H3D [37]	930	5230	555.88	12.04	79.12

4. Conclusions

Studies were carried out on intra-ply and inter-ply thermoplastic Kevlar/basalt hybrid composites under high strain rate compression loading. The high strain rate tests were performed using SHPB in the through-thickness direction of composites. The composites were tested in the strain rates ranging from 2800/s to 5481/s. Failure mechanisms were characterized by digital images and SEM. Based on the dynamic performance of thermoplastic hybrid composites, the influence of hybridization on high strain rate response of these composites was inferred by drawing following conclusions:

- Tailoring of 2D fabrics with a combination of Kevlar and basalt fabrics indicated that intra-ply hybridization of lightweight 2D fabrics are an alternative to the heavy weight 3D fabrics in applications like protective structures.
- Scheme of hybridization showed a significant influence on the dynamic response of composites. Intra-ply hybrid composites could withstand higher strain rates as compared to the inter-ply hybrid composites.
- Though the scheme of hybridization is different for each composite, the dynamic response in terms of peak stress, peak strain and toughness increased with an increase in the strain rate.
- Among intra-ply hybrid composites, composite with alternate weaving of Kevlar and basalt yarns (HP-1) had higher peak stress as compared to the composite with basalt yarns in the warp and Kevlar yarns in the weft directions (HP-2). At lower strain rates (~2820/s and ~3854/s), the toughness of HP-2 was higher than the HP-1 composite. However, the phenomenon changed at higher strain rates.
- In the case of inter-ply hybrid composites, alternate layers of Kevlar and basalt fabrics with Kevlar layer on the loading face (HP-K) exhibited higher strain rate sensitivity and higher peak stress values as compared to the composite with basalt as loading face (HP-B).
- On comparing the intra-ply and inter-ply hybrid composites, intra-ply HP-1 composite had higher peak stress as compared to the inter-ply (HP-B and HP-K) composites while having lower peak strain. It indicates that HP-1 specimens had higher stiffness as compared to all other composites under consideration. The lower peak strain was increased with a change in the placement of yarns (HP-2).
- The failure mechanisms were almost similar in both the intra-ply and inter-ply hybrid composites. A combination of brittle basalt yarns

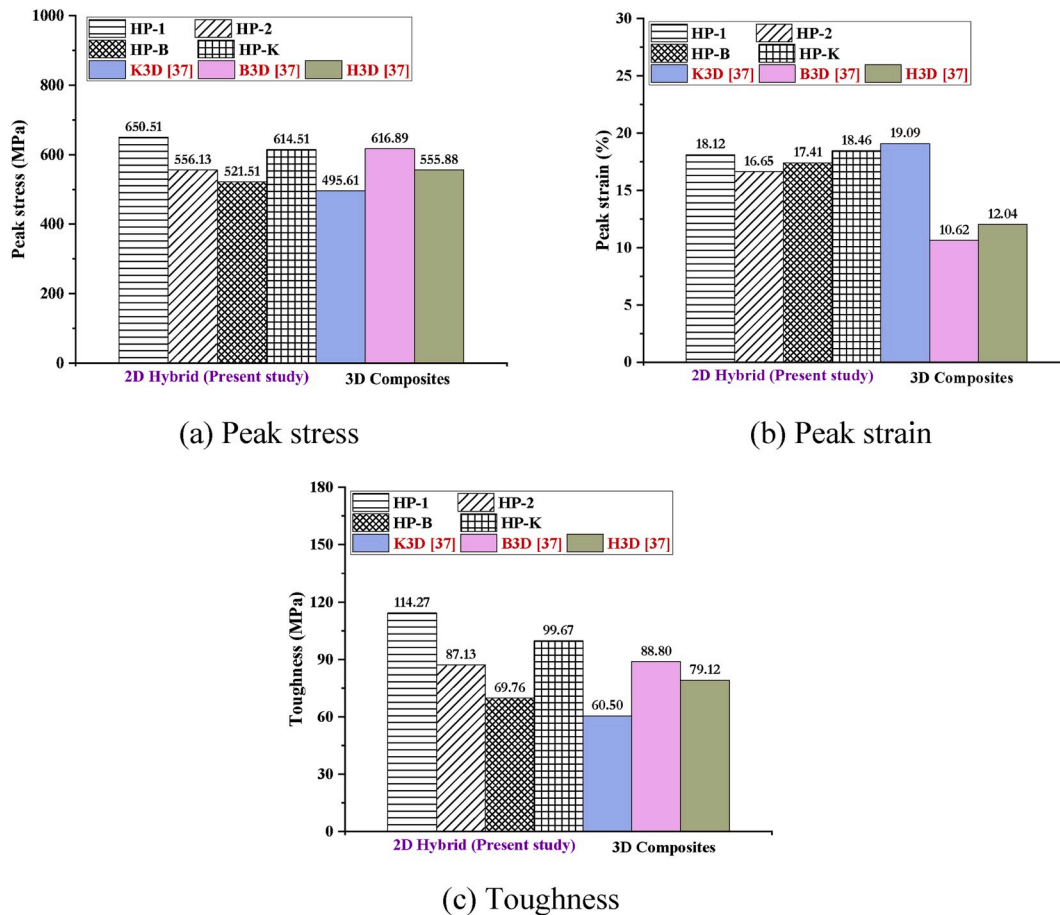


Fig. 13. Comparison of dynamic properties between 2D and 3D composites.

with ductile Kevlar yarns underwent multiple failures, including brittle and ductile damage. Intra-ply composites predominantly failed due to matrix crack, yarns deformation with minor delamination while inter-ply hybrid composites failed primarily due to the delamination and multiple shear fractures.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study for the development of ballistic resistant materials.

CRediT authorship contribution statement

Aswani Kumar Bandaru: Conceptualization, Methodology, Investigation, Data curation, Validation, Writing - original draft, Writing - review & editing. **Hemant Chouhan:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Validation, Writing - original draft, Writing - review & editing. **Naresh Bhatnagar:** Conceptualization, Resources, Investigation, Supervision, Writing - review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.polymertesting.2020.106407>.

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