COMPRESSIVE SPLIT HOPKINSON PRESSURE BAR APPARATUS: PART II- EXPERIMENTAL RESULTS

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Abstract

Investigations on high strain rate behavior of a typical unidirectional glass / epoxy composite under compressive loading are presented. Compressive Split Hopkinson Pressure Bar (SHPB) apparatus was used for the studies. Compressive properties were evaluated along longitudinal, transverse and thickness directions in the strain rate range of 548 - 2645 per sec. It is observed that the compressive strength is enhanced at high strain rate loading compared with those at quasi-static loading. Studies were also carried out on 10° and 45° off-axis specimens. In-plane shear strength was determined based on 10° off-axis compressive results. It is observed that the in-plane shear strength is increased at high strain rate loading compared with that at quasi-static loading. But it remains nearly constant with increasing strain rate at high strain rates.

***Keywords**: Unidirectional glass / epoxy composite, Compressive properties, Strain rate effect, In-plane shear strength, Split Hopkinson Pressure Bar*

Introduction

With the increasing need for performance oriented material and structural systems, the design and development of advanced composite materials represents a new revolution in materials technology. Because of unique combination of mechanical, thermal and chemical properties, these materials are finding increasing uses in high performance applications as well as in day to day applications over the last four decades. Desirable properties such as high specific strength and high specific stiffness make it ideal for high performance applications like aerospace, navel, high speed transportation and space vehicles. Composite materials can be made to specific needs by tailoring the composition and process of manufacturing. Also composite materials have the distinct advantage of ease of manufacturing as compared to the conventional materials.

Over the service life, the structures undergo a variety of loading conditions such as static / quasi-static, dynamic, impact, blast and fatigue. Mechanical behavior of composite materials / structures depends up on the type of load applied. The behavior of such materials under static / quasi-static loading is well understood. For their effective use in high performance applications, the behavior of such materials at high strain rate loading should also be fully understood. Even though typical studies are available on the mechanical behavior of composite materials under high strain rate loading, the information is not complete.

When testing a material, it is important to know how quickly (or slowly) it is being deformed or loaded. One way to report this is the amount of strain induced per unit time, which is generally termed as the strain rate. The relationship between the magnitude of load and applied time plays an important role in resulting system response. As the loading time is shortened material inertia becomes important. Such an event is considered as high strain rate loading. In high strain rate loading, the material is subjected to rapid acceleration and rapid straining often accompanied by temperature increase.

A major concern in the use of composite materials is their susceptibility to damages resulting from effects of rapidly applied loads occurring over a short period of time. Since the material deformation and failure processes are greatly influenced by these loading conditions, the inherent multiphase structure of composites result in complex failure modes / fractures of constituent elements. The failure mechanisms are obviously more complex in composites than those in monolithic materials.

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Considering the importance of this discipline, i.e., the mechanical behavior of composite materials under high strain rate loading, there are typical studies on this subject. These studies are well documented in the form of review articles [1-3]. From these studies it is observed that, in most of the cases, mechanical properties increase at high strain rates compared with those at quasi-static loading. But some studies show decrease in mechanical properties at high strain rate loading. Specimen shape and size used in different studies are different.

State of Art

The early studies on testing materials at dynamic loads are presented in References [4-8]. These studies provided the foundation for the development of Split Hopkinson Pressure Bar (SHPB) or Kolsky apparatus. It is widely used for high strain rate testing of materials.

Design and development of a typical compressive SHPB apparatus is presented in Part I of this paper [9]. The objective of the present study is to investigate the compressive behavior of a typical unidirectional glass / epoxy composite under high strain rate loading. Further, studies are carried out on off-axis specimens also.

The SHPB has become a famous experimental technique to test the materials at high strain rates. Various studies were carried out on specimen design [10], stress uniformity [11] and stress wave reverberation [12,13]. It was observed that the loading pulse with larger rise time generates better stress uniformity than the loading pulse with lesser rise time [11,12]. Rise time of the incident pulse can be increased by placing a pulse shaper such as a small strip of soft material at impact end of the incident bar. Pulse shaper technique was used in SHPB experiments to obtain accurate stress-strain data at high strain rates for metals [14,15], composites [16-18] and elastic-plastic materials [19].

Various studies were carried out on high strain rate behavior of unidirectional and cross- ply glass composites [20-23] and woven fabric glass composites [17, 23-26] under compressive loading. The results are summarized and presented in Tables-1 - 4. Generally, it was observed that the compressive strength and modulus increase compared with those at quasi-static loading. It was observed that there is a significant scatter in the case of failure strain. Various studies were also carried out on high strain rate behavior of unidirectional and cross-ply carbon composites [27-32] and woven fabric carbon composites [33-36] under compressive loading (Tables-1 - 4). In this case also, it was observed that the compressive strength and modulus increase compared with those at quasi-static loading. It was observed that there is a significant scatter in the case of failure strain.

Based on the literature survey, an attempt is made to consolidate all the observations on the compressive behavior of composites under high strain rate loading. Accordingly, ranges of property change factors have been worked out for different cases and are presented in Table-5. Even tough, glass and carbon materials used, resin used and fiber volume fractions could be different for different studies, the consolidated information given in Table-5 gives an over view, regarding the behavior of composites under high strain rate compressive loading. It can be noted that the property change factor is generally more than one for compressive strength and Young's modulus. But property change factor varies in a wide range for different studies.

Property change factor is defined as the ratio of property at high strain rate loading to the property at quasi-static loading. If the property at high strain rate loading is more than property at quasi-static loading, property change factor would be more than one. For such cases, property change factor is termed as property enhancement factor. There may be typical cases where the property change factor could be less than one. This indicates that, for such cases, the property at high strain rate would be less than that at quasi-static loading.

Even though there are typical studies on the compressive behavior of composites under high strain rate loading, the properties with respect to all the principal directions, i.e., along longitudinal, transverse and thickness directions for a variety of materials are not available.

The objective of the present study is to determine the behavior of a typical unidirectional glass / epoxy composite under high strain rate compressive loading. Compressive strength, modulus and ultimate strain were evaluated and are presented along longitudinal, transverse and thickness directions. Quasi-static properties are also presented for comparison. Force verses time plots based on strain gauge signals obtained from incident bar and transmitter bar are derived and compared.

Table-1 : Behaviour of unidirectional composites / laminated composites made of unidirectional layers under high strain rate compressive loading - property change factor (from literature)

Material	Along	Strain rate (per sec)	Static properties			Property change factor, HSR/QS			Reference
			σ^{ult} (MPa)	E (GPa)	ε^{ult} (%)	for σ^{ult}	for E	for ε^{ult}	
Glass / Epoxy	L	2020	758	54.2	0.90	2.00	1.92	2.66	Jenq and Sheu (1993)
	Z	3142	146	17.1	0.80	1.08	2.40	4.12	
Carbon / Epoxy	L	110	965	-	0.61	1.81	-	1.74	Hsiao and Daniel (1998)
	T	120	268	-	3.18	1.42	-	1.17	
Carbon / Epoxy (CP)	I	120	759	98.6	0.83	1.66	1.03	1.56	Hsiao et.al (1998)
Carbon / Epoxy	L	110	987	171	1.16	1.79	1.01	0.93	
	T	1800	269	10.0	3.49	1.94	1.37	1.04	
Graphite / Epoxy	L	2400	665	69.0	1.34	0.87	5.80	0.18	Li and Lambros (1999)
	T	1324	109	4.06	1.78	1.14	-	1.32	
	Z	1975	103	3.70	3.80	1.74	-	0.46	
Carbon / Epoxy	T	1800	269	10.0	3.49	1.94	1.37	1.04	Hsiao et.al (1999)
E-glass / Vinylester (V_f = 50%)	L	3000	591	37.7	-	1.43	1.40	-	Oguni and Ravichandran (2001)
E-glass / Vinylester (V_f = 30%)	L	2000	468	30.6	-	1.27	-	-	
Graphite / Epoxy	L	800	666	-	-	1.48	-	-	Vinson and Woldesenbet (2001)
Carbon / Epoxy (CP)	I	817	387	9.66	5.20	1.00	1.57	0.57	Hosur et.al (2001)
	Z	817	778	5.06	18.9	0.81	1.10	0.63	
Carbon / Epoxy	L	817	504	11.5	5.80	1.26	1.87	0.57	
	T	817	149	3.95	4.90	1.25	1.50	0.81	
Graphite / Epoxy	L	1100	580	26.6	-	1.93	3.04	-	Jadhav et.al (2003)
	T	1400	125	5.28	-	2.70	1.58	-	
S2 glass / Epoxy	T	2000	170	-	3.3	1.94	-	0.84	Vural and Ravichandran (2003)
S2 glass / Vinylester	L	1232	201	6.00	3.20	2.04	4.26	0.56	Haque and Ali (2005)
	T	1231	80	2.50	3.02	1.94	0.84	0.59	

L : Longitudianl, T : Transverse, Z : Thickness, I : In-plane, HSR : High Strain Rate, QS : Quasi-Static, CP : Cross-Ply

Table-2 : Behaviour of woven fabric composites under high strain rate compressive loading - property change factor (from literature)

Material	Along	Strain rate (per sec)	Static properties			Property change factor, HSR/QS			Reference
			σ^{ult} (MPa)	E (GPa)	ε^{ult} (%)	for σ^{ult}	for E	for ε^{ult}	
Plain weave Glass / Epoxy	W	860	410	20.8	2.23	1.40	1.39	1.26	Harding (1992)
Woven CFRP T300/915	F	600	507	-	0.93	1.80	-	1.83	Hou and Ruiz (2000)
Plain weave S2 - glass/Vinylester	F Z	705 675	292 690	- -	1.20 5.20	1.41 1.35	- -	2.21 1.36	Gama et.al (2001)
Woven S2 - glass	W Z	840 800	265 600	- -	2.40 4.55	1.92 1.16	- -	1.13 1.57	Song et.al (2003)
Plain weave carbon / epoxy	W	1039	196	8.3	3.90	2.27	4.24	0.38	Hosur et.al (2003)
Satin weave carbon / epoxy	W F	1092 1079	227 237	11.1 11.7	3.40 3.00	2.31 2.36	4.05 3.90	0.44 0.53	
Plain weave graphite / epoxy	W	930	196	8.3	3.90	2.50	4.90	0.38	Hosur et.al (2004)
Satin weave graphite / epoxy	W F	945 977	227 237	11.0 11.0	3.40 3.00	2.40 2.43	3.90 3.90	0.51 0.54	
Satin weave carbon / epoxy	W F	1092 1390	312 358	4.70 4.87	9.40 10.7	1.33 1.46	4.63 5.62	0.27 0.23	Hosur et.al (2004)
Plain weave S2 - glass/Vinylester	F	1149	180	5.00	3.60	1.75	3.30	0.61	Haque and Ali (2005)

CFRP : Carbon Fiber Reinforced Plastics, W : Warp, F : Fill, Z : Thickness

Table-3 : High strain rate behaviour of unidirectional composites / composites made of unidirectional layers - compressive loading (from literature)

Material	Along	Strain rate (per sec)	High strain rate properties			Reference
			σ^{ult} (MPa)	E (GPa)	ε^{ult} (%)	
Glass / Epoxy cross-ply	Z	3168	861	21.97	4.9	Jenq and Sheu (1993)
S2 glass / Vinylester	Z	1260	192.5	6.80	3.16	Haque and Ali (2005)

Table-4 : High strain rate behaviour of woven fabric composites - compressive loading (from literature)

Material	Along	Strain rate (per sec)	High strain rate properties			Reference
			σ^{ult} (MPa)	E (GPa)	ε^{ult} (%)	
Twill weave S2 glass / Vinylester	W	544	218	11.7	2.4	Hosur et.al (2001)

Table-5 : High strain rate compressive properties of glass and carbon composites : range of property change factor (from literature)

Reinforcing material	Fiber Lay-up	Direction	Range of property change factor		
			for strength	for Young's modulus	for ultimate strain
Glass	Unidirectional	Longitudinal	1.27-2.00	1.40-4.26	0.56-2.66
		Transverse	1.94	0.84	0.59-0.84
		Thickness	1.08	2.40	4.12
	Plain weave	Wrap / Fill	1.4-1.92	1.39-3.3	0.61-2.21
		Thickness	1.16-1.35	-	1.36-1.57
Carbon	Unidirectional	Longitudinal	0.87-1.93	1.01-5.8	0.57-1.74
		Transverse	1.14-2.7	1.37-1.58	0.81-1.17
		Thickness	0.81-1.74	1.10	0.46-0.63
	Plain weave	Wrap / Fill	1.80-2.50	4.24-4.90	0.38-1.83
		Thickness	-	-	-
	Satin weave	Warp	1.33-2.40	3.90-4.63	0.27-0.51
		Fill	1.46-2.43	3.90-5.62	0.23-0.54
		Thickness	-	-	-

Compressive Split Hopkinson Pressure Bar Apparatus

The experimental studies were carried out on the SHPB apparatus as presented in Part I of this paper. During testing, the cylindrical specimen was placed sandwiched between the incident and transmitter bars. The entire strain / deformation history within the specimen was obtained by taking measurements along the incident and transmitter bars from the strain gauges mounted on them. From these signals and using one-dimensional wave propagation theory, force verses time, strain rate verses time, strain verses time, stress verses time and stress verses strain history in the specimen was determined.

Experimental Studies

Experimental studies were carried out on high strain rate behavior of unidirectional glass / epoxy under compressive loading using SHPB apparatus along longitudinal, transverse and thickness directions. Unidirectional composites were prepared using resin film infusion technique. The fiber volume fraction is, $V_f = 0.48$. Studies were carried out in the strain rate range of 548 - 2645 per sec on the compressive SHPB apparatus as presented in Part I of this paper [9]. Studies were also carried out at quasi-static loading for comparison. Further, studies were carried out on 10° and 45° off-axis specimens. Strain rates used and compressive properties are given in Tables-6 and 7 and Figs.1-17.

Table-6 : Strain rate effect on compressive properties of unidirectional glass / epoxy, $V_f = 0.48$ (present study)

Along	Strain rate, $\dot{\in}$ (per sec)	Strength, σ^{ult} (MPa)	Ultimate strain, ε^{ult} (%)	Young's modulus, E (GPa)
L	Quasi-static	463 (+23, -14)	3.12	18.4
	548 (+21, -18)	535 (+9, -5)	1.17	24.2
	982 (+24, -29)	544 (+6, -11)	1.97	24.8
	1510 (+30, -20)	548 (+13, -5)	2.10	27.7
T	Quasi-static	147 (+11, -12)	-	-
	848 (+17, -28)	199 (+4, -12)	1,54	11.2
	1268 (+23, -38)	189 (+11, -10)	1.51	12.6
	1946 (+13, -26)	185 (+6, -12)	1.52	12.2
	2645 (+13, -30)	186 (+4, -5)	1.63	11.8
Z	Quasi-static	136 (+4, -5)	-	-
	842 (+35, -17)	175 (+16, -16)	1.70	9.6
	1432 (+31, -32)	182 (+15, -10)	1.97	10.2
	1720 (+17, -21)	178 (+8, -11)	1.90	10.0
	2535 (+41, -45)	179 (+21, -10)	2.30	9.8

L = Longitudinal, T = Transverse and Z = Thickness

Table-7 : Strain rate effect on compressive properties of off-axis unidirectional and in-plane shear strength of unidirectional glass / epoxy, $V_f = 0.48$ (present study)

Off-axis angle*	Strain rate, $\dot{\in}$ (per sec)	Strength, σ_{ult} (MPa)	Ultimate strain, ε_{ult} (%)	Inplane shear strength, τ_{ult} (MPa)
0	Quasi-static	463 (+23, -14)	3.12	-
	548 (+21, -18)	535 (+9, -5)	1.17	-
	982 (+24, -29)	544 (+6, -11)	1.97	-
	1510 (+30, -20)	548 (+13, -5)	2.10	-
10	Quasi-static	218 (+1, -5)	3.95	37.3
	1112(+38, -19)	286 (+24, -12)	2.03	48.9
	1445 (+34, -25)	1270 (+18, -22)	2.10	46.2
	1813 (+33, -36)	254 (+19, -16)	2.23	43.4
45	Quasi-static	129 (+4, -3)	6.80	-
	1482 (+21, -25)	166 (+1, -4)	4.15	-
	1859 (+31, -38)	172 (+7, -5)	4.23	-
	2252 (+26, -22)	175 (+4, -7)	4.27	-

* with respect to wrap

Along Longitudinal Direction

Strain gauge signals obtained on oscilloscope during testing along longitudinal direction are presented in Fig.1a. The durations of incident and reflected signals are represented by a_1a_2 and a_3a_4 respectively. Further, P represents a point on the signal at the end of rise time. In the present case, a_1a_2 = 155 μ sec. It may be noted that the durations of incident and reflected signals are nearly the same. Force verses time plots are obtained from the strain gauge signals and are presented in Fig. lb. Force history on the incident bar is plotted based on strain gauge signals I+R, whereas force history on the transmitter bar is plotted based on strain gauge signal T. The force history obtained based on signals I+R is referred to as F_1 and the force history obtained based on signal T is referred to as F_2 for further discussion. Force F_1 would be acting on the interface between the incident bar and the specimen whereas force F_2 would be acting on the interface between the transmitter bar and the specimen.

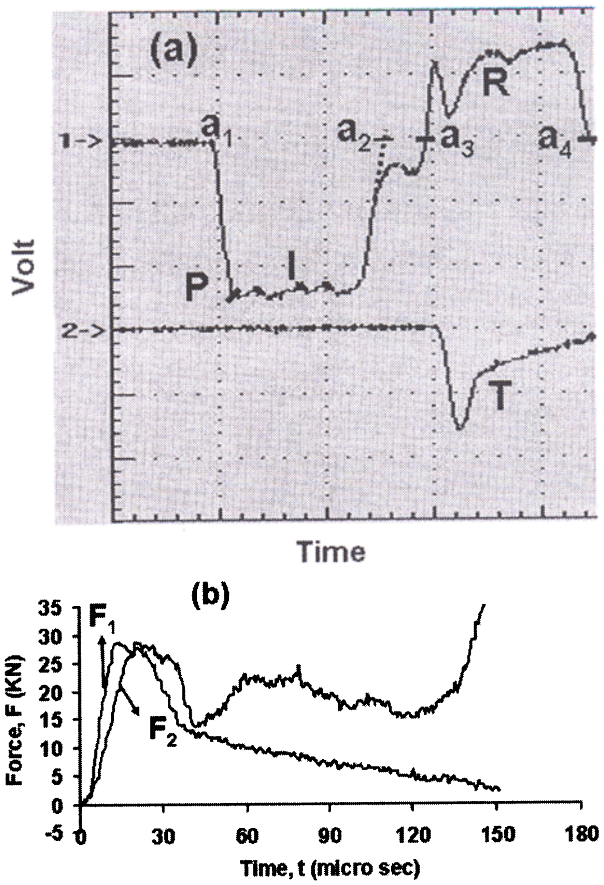

Fig.1 Compressive SHPB test results for unidirectional glass/ epoxy-along longitudinal direction : (a) strain gauge signals on oscilloscope, (b) comparison of force verses time behaviour, derived from strain gauge signals

Force verses time plots can be subdivided into two regions: one, until the peak force is reached; two, after the peak force is reached. The region two indicates behavior after the specimen has failed. Obviously, in this region, F_1 and F_2 would be different. The peak forces F_1 and F_2 are nearly the same. It may be noted that the peak force is attained at time duration of 20 μ sec. During this period 16 numbers of transits take place. One transit equals to time required for a pulse to travel from one end of the specimen to another end during testing.

Time verses strain rate, strain and stress plots along longitudinal direction are given in Fig. 2. These plots are obtained based on strain gauge signals and the theory presented in Part I of this paper [9]. As indicated earlier, Point P indicates the end of the rise time. Point A indicates first peak strain rate whereas Point B indicates peak stress. Point C indicates overall peak strain rate. It may be noted

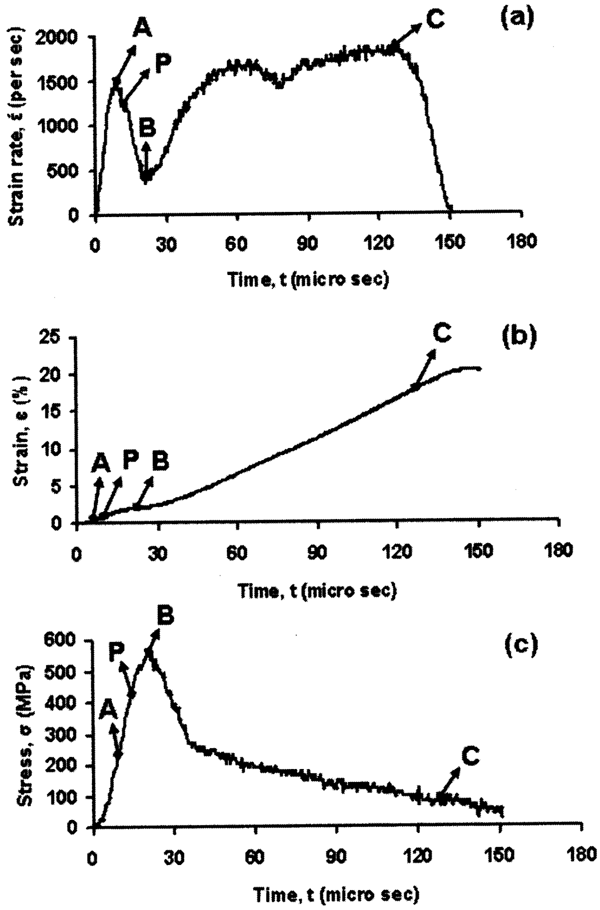

Fig.2 High strain rate compressive test results for unidirectional glass/epoxy-along longitudinal direction : (a) time verses strain rate plot, (b) time verses strain plot, (c) time verses stress plot

that, at this time interval, the specimen has already failed. Strain rate effects on the compressive properties of unidirectional glass / epoxy are presented in Table-6. The strain rates indicated in this table are with respect to Point A. This strain rate is taken as reference strain rate.

A typical stress-strain plot along longitudinal direction is presented in Fig.3. The stress-strain plot can be subdivided into two regions. Region one represents the behavior of the material until the compressive strength is reached. Region two represents post-failure behavior of the material. Compressive properties at different strain rates are given in Table-6. The results presented are with respect to region one, i.e. up to the peak stress is reached.

For comparison properties at quasi-static loading were also determined experimentally and are presented in Table-6. The property enhancement factor for compressive strength varies from 1.15 to 1.18 corresponding to strain rate varying from 548 to 1510 per sec.

Figures 1a and 2 show rise time of 14 μs. During this period, which is the initial stage of loading, the strain rate is not constant. Hence, the Young's modulus obtained based on the strain gauge data during this period would not be exact. It can be seen, from Fig.1a, that the strain signal is nearly constant beyond the rise time. The stress-strain behavior obtained beyond the rise time of the pulse can be taken as the actual behavior of the material. The end of rise time is represented by Point P. As a first approximation, by joining Point P to the origin, Young's modulus can be determined. This would indicate the lower bound of Young's modulus. Young's modulus can also be found by extrapolating the stress-strain curve in region I from Point P to the origin by a smooth curve.

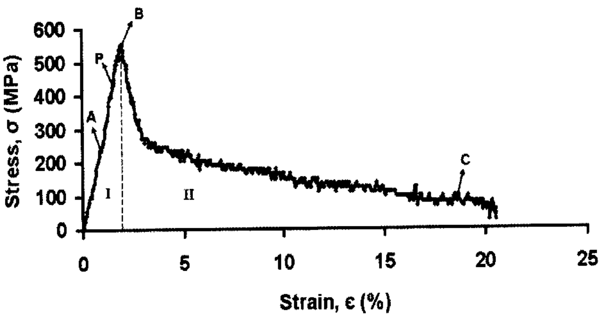

Fig.3 Stress verses strain plot from high strain rate compressive test on SHPB for unidirectional glass/ epoxy-along longitudinal direction

From Table-6 and Fig.10, it can be observed that the compressive strength is enhanced at high strain rate loading compared with that at quasi-static loading. Further, it is observed that it is increased with increasing strain rate. But the rate of increase in compressive strength with the increasing strain rate is not significant. Also, it can be observed that compressive modulus is enhanced at high strain rate loading compared with that at quasi-static loading. The ultimate compressive strain decreases at high strain rate loading compared with that at quasi-static loading.

The compressive strength increases at high strain rate loading compared with that at quasi-static loading. This can be explained as follows: At lower strain rates, damage propagates slowly utilizing most of the applied energy.

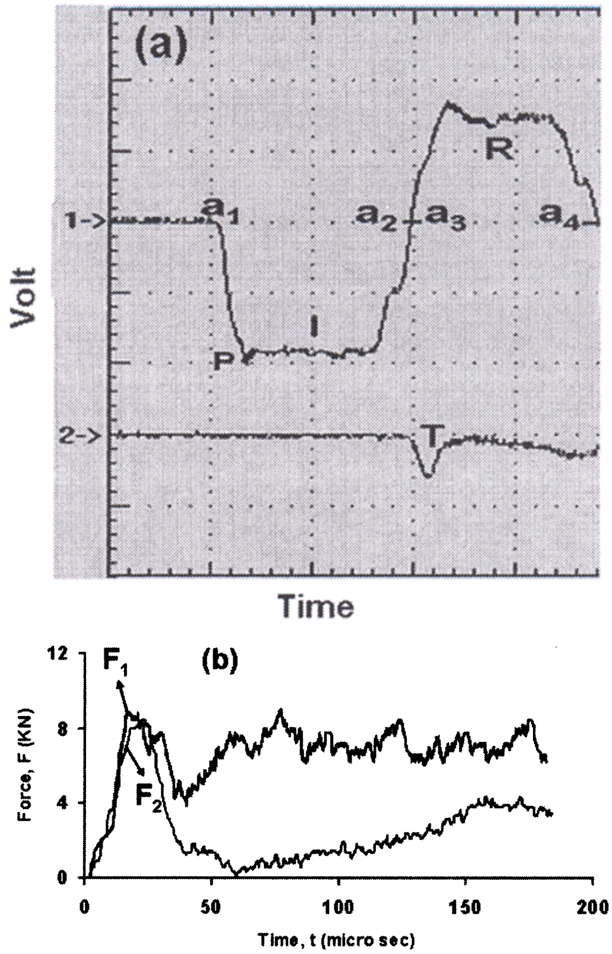

Fig.4 Compressive SHPB test results for unidirectional glass/ epoxy-along transverse direction :(a) strain gauge signals on oscilloscope, (b) comparison of force verses time behaviour, derived from strain gauge signals

But at higher strain rates, not enough time is available for the damage to initiate and propagate. Under such condition, there is need for more work to be carried out for the deformation of the specimen, leading to enhanced compressive strength at high strain rate loading. Visco- elastic nature of the polymer matrix composites is also responsible for the increase in compressive strength at high strain rate loading.

Along Transverse Direction

Strain gauge signals obtained on oscilloscope during testing along transverse direction are presented in Fig. 4a. In this case, a_1a_2 = 182 μ sec. The durations of incident and reflected signals are nearly the same. Force verses time plots are presented in Fig. 4b. In this case the peak force is attained at a time duration of 18 μ sec. During this period eight numbers of transits take place. The peak forces F_1 and F_2 are nearly the same.

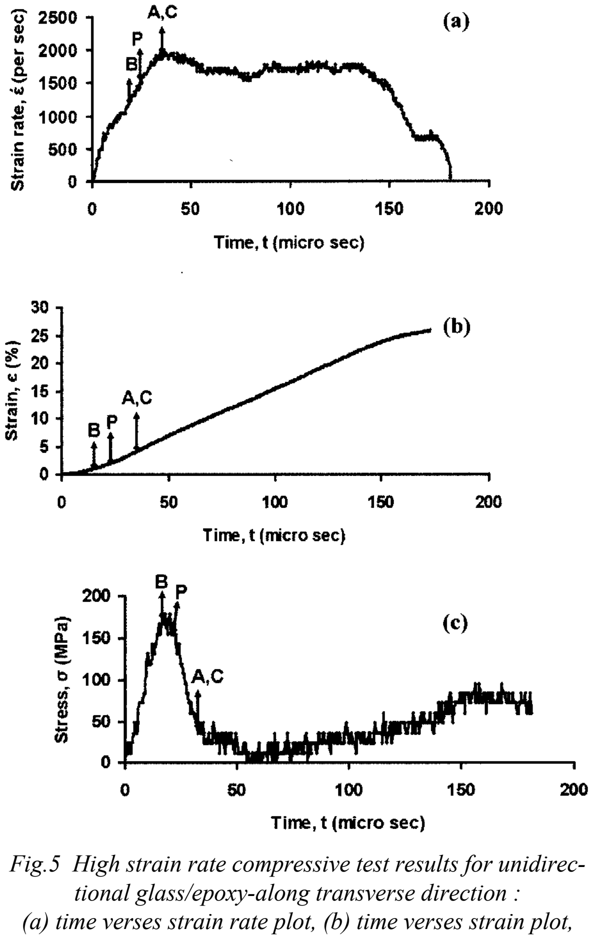

Fig.5 High strain rate compressive test results for unidirectional glass/epoxy-along transverse direction : (a) time verses strain rate plot, (b) time verses strain plot, (c) time verses stress plot

Time verses strain rate, strain and stress plots along transverse direction are given in Fig. 5. A typical stress-strain plot along transverse direction is presented in Fig.6. Strain rate effects on the compressive properties of unidirectional glass / epoxy along transverse direction are presented in Table-6. The strain rates indicated in this table are with respect to point A. This strain rate is taken as the reference strain rate. The property enhancement factor for compressive strength varies from 1.35 to 1.26 corresponding to strain rate varying from 848 to 2645 per sec.

From Table-6 and Fig.10, it can be observed that the compressive strength is enhanced at high strain rate loading compared with that at quasi-static loading. But at different high strain rates, the compressive strength is nearly the same.

Along Thickness Direction

The experimental results for the case of loading along thickness direction are presented in Figs. 7-10 and Table-6. The behavior with respect to loading along thickness direction is nearly the same as that for loading along transverse direction.

Compressive Behavior of Off-Axis Unidirectional Composites

Compressive behavior of off-axis unidirectional glass / epoxy composite was studied. The results are presented in Figs.11-17 and Table-7. Strain gauge signals and force verses time plots are presented in Fig.11 for 10° off-axis case and in Fig.14 for 45° off-axis case. It may be noted that the peak force F_2 is significantly less than the peak force F_1. This is explained based on stress wave attenuation studies (Appendix-A). Since F_1 and F_2 are not equal, the specimen would not be under uniform stress state

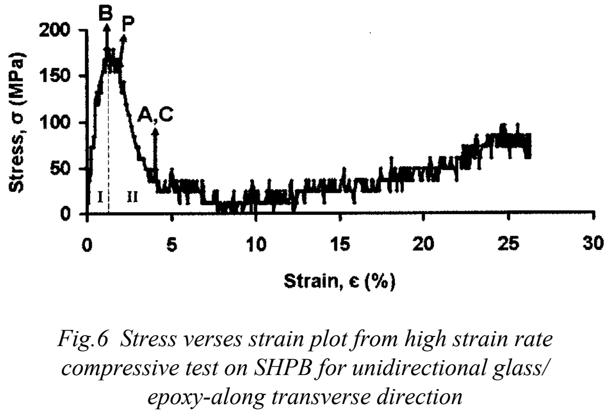

Fig.6 Stress verses strain plot from high strain rate compressive test on SHPB for unidirectional glass/ epoxy-along transverse direction

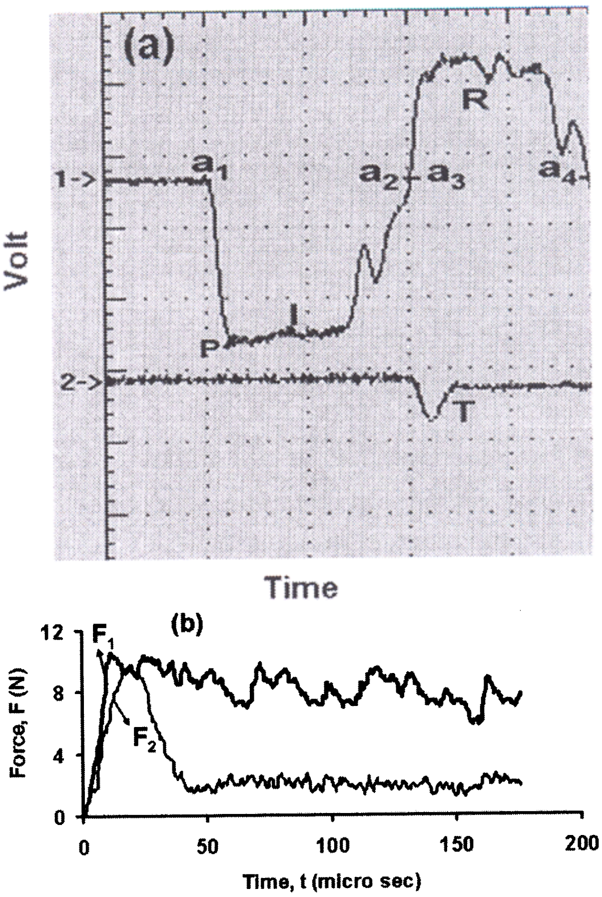

Fig.7 Compressive SHPB test results for unidirectional glass/ epoxy-along thickness direction :(a) strain gauge signals on oscilloscope, (b) comparison of force verses time behaviour, derived from strain gauge signals

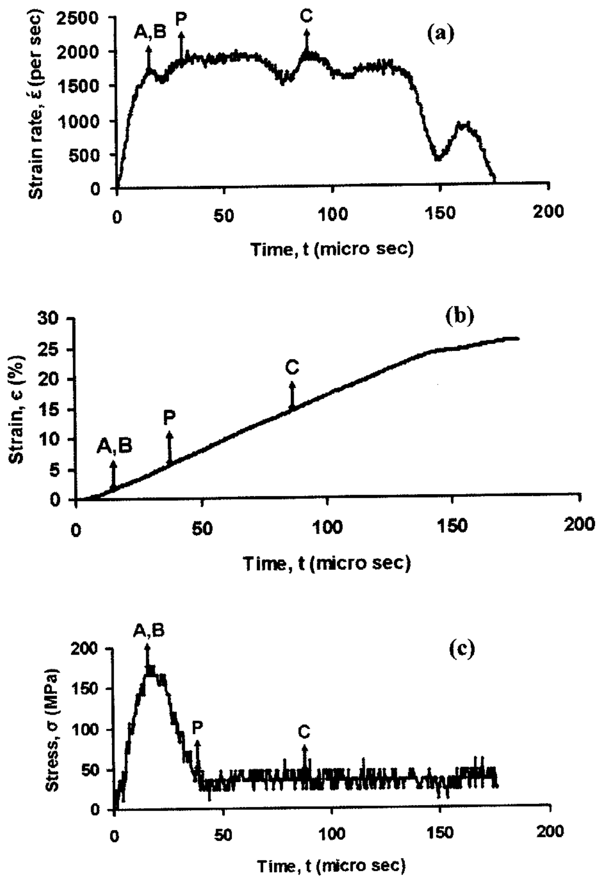

Fig.8 High strain rate compressive test results for unidirectional glass/epoxy-along thickness direction : (a) time verses strain rate plot, (b) time verses strain plot, (c) time verses stress plot

during the failure process. The compressive properties reported further are based on F_2. This is to obtain conservative estimates of compressive properties.

Time verses strain rate, strain and stress plots are given in Fig.12 for 10° off axis case and in Fig.15 for 45° off-axis case. Strain rate effects on the compressive properties are presented in Table-7 and Fig. 17. The strain rates indicated here are with respect to Point A.

Typical stress-strain plots are presented in Fig. 13 for 10° off-axis case and in Fig.16 for 45° off-axis case. For comparison properties at quasi-static loading were also determined experimentally and are presented in Table-7.

From Table-7 and Fig. 17, it can be observed that the compressive strength is enhanced at high strain rate loading compared with that at quasi-static loading. But it

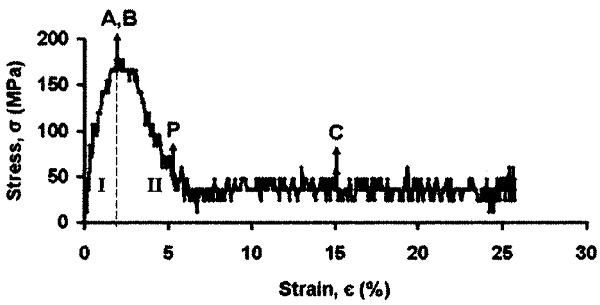

Fig.9 Stress verses strain plot from high strain rate compressive test on SHPB - along thickness direction, unidirectional glass/epoxy

remains nearly constant with increasing strain rate at high strain rates. As expected, the compressive strength decreases as the off-axis angle increases. The ultimate compressive strain decreases at high strain rate loading compared with that at quasi-static loading. But it remains

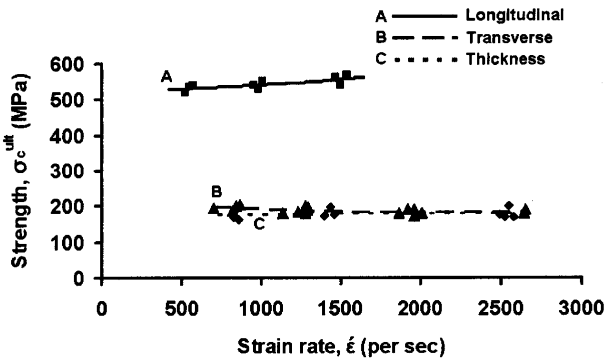

Fig.10 Strain rate verses compressive strength plots : longitudinal, transverse and thickness directions, unidirectional glass/epoxy

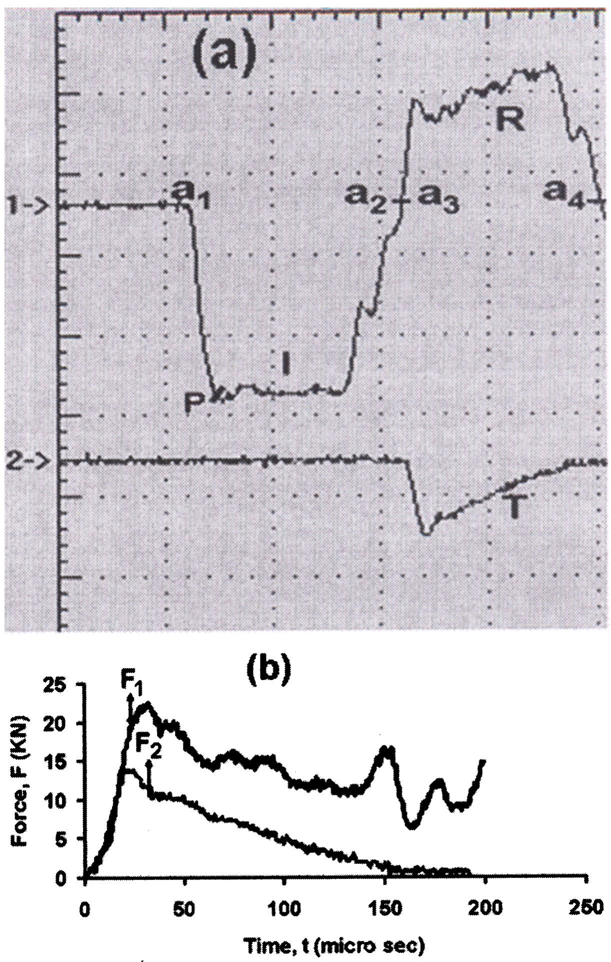

Fig.11 Compressive SHPB test results for unidirectional glass / epoxy - off-axis 10° : (a) strain gauge signals on oscilloscope, (b) comparison of force verses time behaviour, derived from strain gauge signals

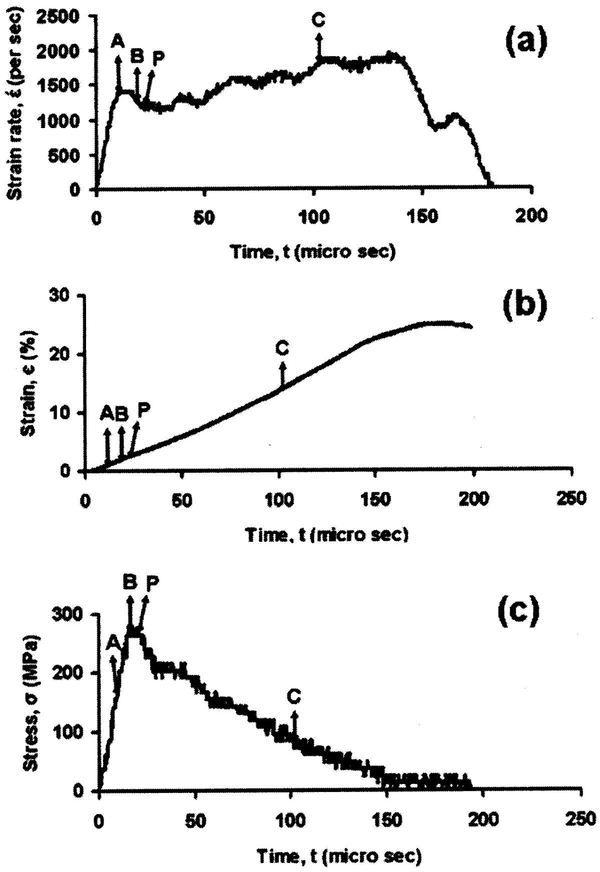

Fig.12 High strain rate compressive test results for unidirectional glass/epoxy - off-axis 10° : (a) time verses strain rate plot, (b) time verses strain plot, (c) time verses stress plot

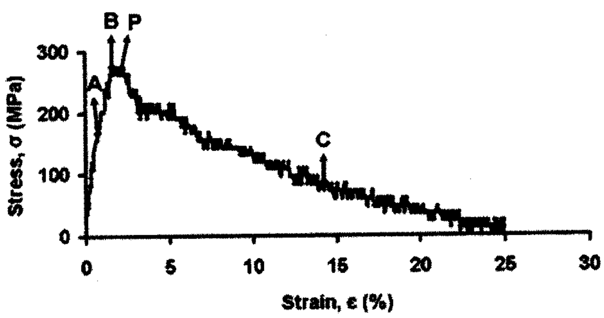

Fig.13 Stress verses strain plot from high strain rate compressive test on SHPB - unidirectional glass/epoxy- off-axis 10°

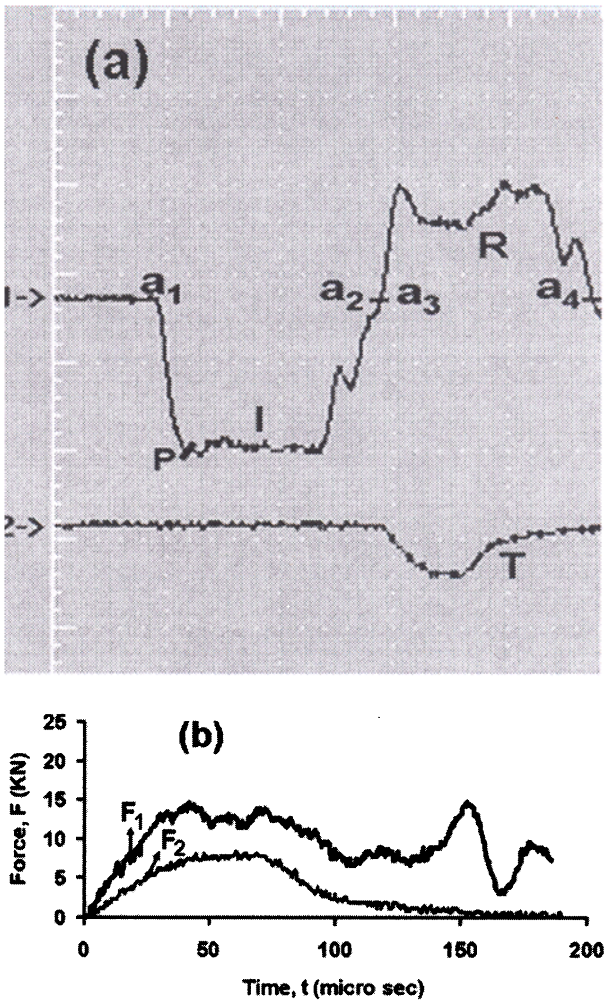

Fig.14 Compressive SHPB test results for unidirectional glass / epoxy - off-axis 45° : (a) strain gauge signals on oscilloscope, (b) comparison of force verses time behaviour, derived from strain gauge signals

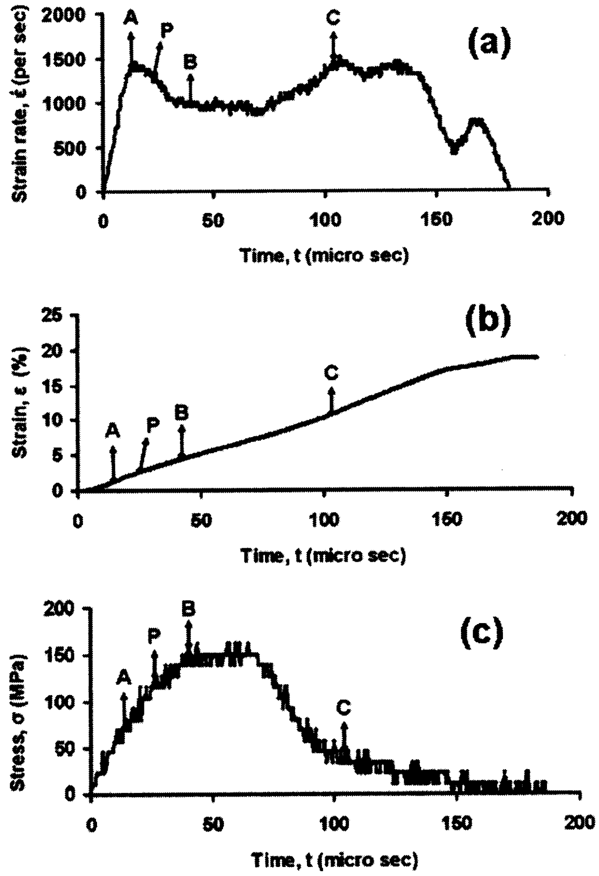

Fig.15 High strain rate compressive test results for unidirectional glass/epoxy - off-axis 45° : (a) time verses strain rate plot, (b) time verses strain plot, (c) time verses stress plot

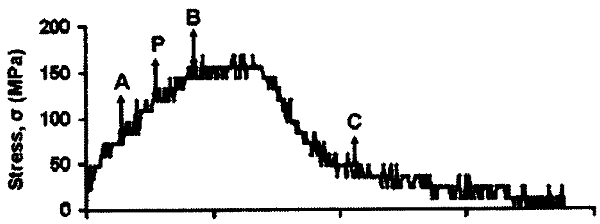

Fig.16 Stress verses strain plot from high strain rate compressive test on SHPB - unidirectional glass/epoxy - off-axis 45°

nearly constant with increasing strain rate at high strain rate loading. As expected, the ultimate compressive strain increases as the off-axis angle increases.

In-plane Shear Behavior of Unidirectional Composites

Off-axis tension test is one of the test techniques used for the determination of in-plane shear strength of unidirectional composites [37]. Off-axis tension tests produce combined state of stresses due to shear coupling effect of unidirectional composites. Such tests do not develop pure shear conditions at the test section. The relative magnitudes of the longitudinal, transverse and shear stress components vary as a function of off-axis angle between the material coordinate system and loading direction. The fraction of shear stress contribution to the failure of specimen under off-axis loading condition determines the suitability of a particular specimen configuration for the evaluation of in-plane shear strength. 10° off-axis speci-

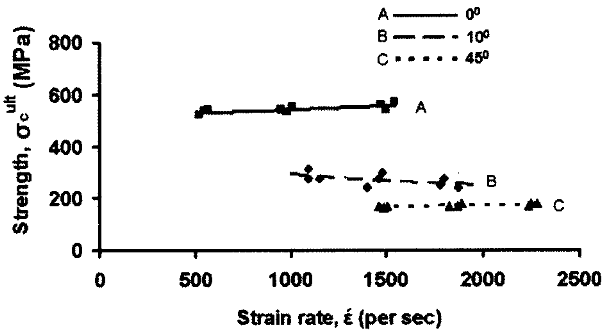

Fig.17 Strain rate verses compressive strength plots, unidirectional glass/epoxy : on-axis and off-axis loading

mens are widely used for the determination of in-plane shear strength of unidirectional composites. With 10° off-axis specimens, shear contribution to the ultimate failure of specimens is 92% for a typical glass / epoxy composite [37].

In-plane shear strengths are determined based on 10° off-axis test results and are presented in Table-7. The in-plane shear strength is increased at high strain rate loading compared with that at quasi-static loading. But it remains nearly constant with increasing strain rate at high strain rates.

Conclusions

The compressive properties of a typical unidirectional glass / epoxy are presented at high strain rate loading. Quasi-static properties are also presented for comparison. The properties are presented with respect to the principal directions, i.e., along longitudinal, transverse and thickness directions. Further, studies are also presented on compressive behavior of off-axis unidirectional glass / epoxy and in-plane shear strength using 10° off-axis specimens. The overall conclusions are

- There is compressive strength enhancement at high strain rate loading compared with those at quasi-static loading for all the cases considered.
- The compressive strength and modulus increase with increasing strain rate along longitudinal direction at high strain rates. But they remain nearly constant with increasing strain rate at high strain rates along transverse and thickness directions.
- The in-plane shear strength is increased at high strain rate loading compared with that at quasi-static loading. But it remains nearly constant with increasing strain rate at high strain rates.

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Appendix-A

Stress wave attenuation in off-axis unidirectional composites

When the striker bar hits the incident bar, an elastic stress wave pulse is generated. It travels through the incident bar, specimen and the transmitter bar. In the case of on-axis unidirectional composites, the stress wave would be propagating without encountering any boundary / discontinuity along the length of the specimen. The stress-strain behavior would be generally linear. This indicates that the micro cracks are not formed during the initial stage of loading. In such cases, force history F_1 and F_2 would be identical, at least until the failure of the specimen takes place. The peak forces F_1 and F_2 would be nearly the same (Fig. 1b).

In the case of off-axis unidirectional composites, the stress wave, while it is propagating further, would be encountering fibers at an angle. This would lead to reflection and transmission of the incident stress wave within the specimen. This would lead to attenuation of the stress wave. Further, the stress-strain behavior would be generally non-linear for the off-axis composites. The non-linearity would be associated with possible plastic deformation and micro crack formation. This would also add to stress wave attenuation. In such cases, peak force F_2 would be less than peak force F_1 (Figs.11b and 14b).

In the case of loading along transverse and thickness directions, peak forces F_1 and F_2 are nearly identical (Figs.4b and 7b). Even though, the stress wave would be encountering the fibers while it is propagating further, the stress wave attenuation is not observed in this case. This may be because the stress-strain behavior is linear, indicating that the micro cracks are not formed during the initial stage of loading.