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Through-Thickness Stitching Effects on Graphite/Epoxy High-Strain-Rate Compressive Properties

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A split Hopkinson pressure bar is used to obtain high-strain-rate, compressive mechanical properties of a uniweave AS4/3501-6 composite laminate with and without reinforcement stitching in the through thickness. For both in-plane and out-of-plane directions, the compressive mechanical properties of yield stress, yield strain, ultimate strength, ultimate strain, and modulus of elasticity are determined for strain rates varying from 234 to 1216 s^{-1}.

Introduction

THE split Hopkinson pressure bar (SHPB) facility at the University of Delaware is described Ref. 1 and will not be repeated herein. To date, the following materials have been examined on this SHPB: unidirectional E-glass/3501 epoxy; random, nonwoven glass/Cycom 4201 polyester; unidirectional T40 graphite/ERL 1908 epoxy; quasi-isotropic AS4 graphite cloth/3501 epoxy; Metton; 6060-T6 aluminum; carbon/aluminum metal matrix composite; silicon carbide/aluminum; unidirectional, continuous fiber carbon/glass ceramic matrix composite; silicon carbide-reinforced 2080 aluminum; Cycom 5920/1583; IM7 graphite/8551-7 epoxy; AS4 graphite/3501 epoxy; AS4 graphite/K3B polymide; IM7 graphite/K3B; AS4 graphite/PEKK thermoplastic; unidirectional and cross-ply K49 Kevlar®/3501-6 epoxy; IM7 graphite/E7T1-2 epoxy; unidirectional glass/3M Scotchply 1003 epoxy; Kevlar 29/polyethelene; IM7/977-3 graphite epoxy; various Seeman composite resin infusion molding process (SCRIMP) composites; and various resin transfer molding (RTM) composites. These are discussed in Refs. 1–12. However, this is the first time that the effects of through-the-thickness stitching have been investigated on this SHPB.

Material Description

The resin transfer molded, stitched laminate was provided by Sankar. It is an AS4 uniweave graphite fabric, with a layup of [(45/0/ −45)s]4s and 3501-6 epoxy. The stitched material is a 5952 denier glass bobbin yarn with a breaking strength of 436 N. The needle yarn is 400 denier Kevlar-29 yarn with a breaking strength of 53 N.

The top and bottom plies of the laminate are covered with one layer of plain weave fiberglass cloth to act as a retainer cloth for the stitches. The bobbin yarn goes through the entire thickness of the laminate, whereas the needle yarn is only on one of the surfaces holding the bobbin yarn. The stitching is in one direction (0 deg) and has a density of 16 stitches/in.^{2} (4 stitches/in. with a 0.25-in. distance between adjacent stitch rows).

The graphite/epoxy composite was heated to 225°F and held at that temperature under 75 psi for 1 h. Then it was cured at 350°F for 6 h at 100 psi. The heating and cooling rates were 5°F/min.

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Reinforcement, through-thickness stitching of a laminate is a technique to improve laminate out-of-plane properties. Although fiber-reinforced/polymer matrix composite materials can offer exceptional in-plane properties, interply delaminations caused by relatively weak out-of-plane loading or impact can severely damage a composite structure. Low-velocity studies have shown that reinforcement stitching can greatly improve interlaminar fracture toughness and the compression strength after impact.[13] However, stitching is also known to add stress concentrations to the laminate and damage to the fibers local to the reinforcement stitching.

Specimen Preparation

A total of 72 compression specimens in the shape of right circular cylinders: 0.2 in. in diameter and 0.3 in. in length (Fig. 1) were machined from the laminate and prepared for testing. Two principal directions of the laminate are studied: the two direction (90 deg, in-plane) and three direction (through thickness). Of the 72 specimens, 40 specimens in the one direction and three direction contain a single through-thickness stitch. The three-direction specimens with stitching have a single stitch centered and along the axis of the specimen, and the two-direction specimens with stitching have a single stitch centered along its length and perpendicular to its axis, as shown in Fig. 1. The other 32 specimens have no reinforcement stitch within them.

With the material provided, the pitch of the stitching resulted in there only being one stitch per specimen. The right circular cylindrical specimens were also limited by the thickness of the panel from which the specimens were fabricated. However, the 0.2-in.-diam and 0.3-in.-length specimen is in the same order of size as all other tests conducted on the 3/4-in.-diam SHPB facility used in this study. The length to diameter ratio of 1.5 is the baseline value used by the authors.

Test Results

For completeness, all of the data from the 72 tests are presented in Tables 1 and 2. In Tables 1 and 2, the data are grouped according to the nitrogen pressure used to initiate a test. Hence, all of the test pieces in a particular lettered group are replicates. The results are presented succinctly in tabular form. Because the initial portions of stress–strain curves in high-strain-rate tests are erroneous while the specimens reach a uniform state of stress, stress–strain curves are not presented. These data are then presented statistically in Tables 3 and 4, which provide mean values and standard deviations. Quasi-static-strength tests were performed on an Instron universal machine at a strain rate of 0.05 in./min. Quasi-static-test data for the shell material is provided in Table 5. These data will allow other researchers to study and analyze the tests independently.

Table 1 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: two-direction tests

Group	Pressure, psi	Strain rate, /s	Yield strength, MPa	Yield strain	Ultimate strength, MPa	Ultimate strain	Modulus, MPa
			Without stitch				
A1	20	208	264.58	0.0056	374.39	0.0116	56,571
A2	20	227	230.95	0.0055	376.26	0.0133	60,448
A3	20	244	277.66	0.0068	359.68	0.0113	77,120
B1	40	574	——	——	366.00	0.0128	42,087
B2	40	583	——	——	375.43	0.0132	34,392
B3	40	556	——	——	416.09	0.0116	47,742
C1	60	690	——	——	381.82	0.0174	29,765
C2	60	691	——	——	396.50	0.0173	28,834
D1	80	753	——	——	347.07	0.0209	21,753
D2	80	827	——	——	350.99	0.0176	23,107
D3	80	1006	——	——	368.08	0.0175	25,389
E1	100	1043	——	——	357.82	0.0211	17,098
E2	100	881	——	——	384.80	0.0205	23,804
E3	100	918	——	——	348.88	0.0213	18,647
			With stitch				
A1s	20	527	——	——	318.09	0.0143	30,475
A2s	20	605	——	——	345.79	0.0150	29,660
A3s	20	499	——	——	344.10	0.0158	28,094
A4s	20	453	——	——	347.78	0.0151	29,464
B1s	40	636	——	——	314.40	0.0145	22,499
B2s	40	583	——	——	344.35	0.0158	27,268
B3s	40	682	——	——	325.08	0.0185	22,235
B4s	40	572	——	——	337.59	0.0166	25,099
C1s	60	728	——	——	334.81	0.0154	27,569
C2s	60	428	——	——	305.24	0.0155	21,986
C3s	60	565	——	——	336.06	0.0150	25,191
C4s	60	594	——	——	339.11	0.0197	20,581
D1s	80	834	——	——	336.44	0.0247	20,416
D2s	80	955	——	——	332.77	0.0243	16,419
D3s	80	751	——	——	338.05	0.0199	19,107
D4s	80	714	——	——	364.86	0.0200	26,000
E1s	100	720	——	——	372.43	0.0229	21,767
E2s	100	870	——	——	357.24	0.0260	17,756
E3s	100	844	——	——	359.77	0.0218	19,685
E4s	100	940	——	——	391.26	0.0263	20,228

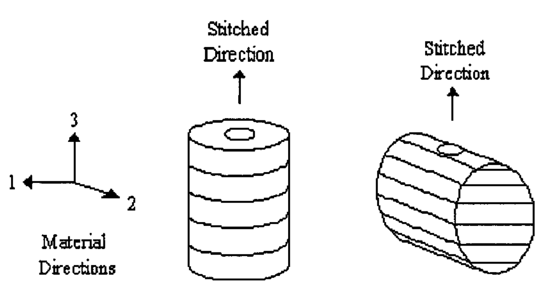

Fig. 1 Three-direction specimen with through-thickness stitch (left) and two-direction specimen with through-thickness stitch (right).

Statistical Analysis

With the complexities of these high-strain-rate tests and the small sample sizes, note how small the coefficient of variance (COV) (i.e. the ratio of standard deviation to mean value, given as a percentage) is for the various mechanical properties as shown in Table 6. The highest COV on a mechanical property value is 19.7% (on a modulus of elasticity), whereas the lowest COV is 0.6% (on an ultimate strain). This is probably because stresses and strains are determined directly from the strain gauge data, whereas the modulus of elasticity is the calculated ratio of these quantities.

To analyze trends from Tables 3 and 4, it is important to define significant differences. For the present purpose, a quantity P is said to be significantly different from Q if the mean value of P falls outside the region of the mean ± 3 standard deviations of Q.

From the first part of Table 3 (without stitch statistics), it is seen that there are significant differences in the range of strain rates for the two-direction, nonstitched specimens. The group A strain rate is significantly different from the other groups. Groups B, C, and E are significantly different from the other groups with the exception of group D. Group D is significantly different from the other groups with the exception of group E. Yielding, or permanent damage, that is, a deviation from a linear stress–strain relation, was not found in the two-direction specimen except at the low strain rate. Therefore, in the strain-rate range between 234.3 and 575.3 s^{-1}, a transition from ductile to brittle behavior must occur. This trend from ductile behavior to brittle behavior has been noticed in other polymer matrix composite materials. Failure of the specimens was achieved at each strain rate. As concerns ultimate strength, it is seen that these values exhibit little strain-rate sensitivity. Whereas ultimate strength values from groups B and C are only significantly different from group D, and group D is only significantly different from only group E, groups A and E are not significantly different from any groups. Ultimate strain values show strain-rate dependence with groups A and B significantly different from all other groups. Ultimate strain values of groups D and E show significant difference from the other groups with the exception of group B, and group C shows significant difference from the other groups with the exception of group D. Modulus of elasticity values show dependence on strain rate. The modulus of elasticity of group A is significantly different from all other groups whereas the remaining groups show some significant difference from other groups.

From the second part of Table 3, strain rates of the two-direction, stitched specimens show little significant difference. Groups Bs and Cs show no significant difference from other groups. Group As is only significantly different from group Es, and groups Ds and Es are only significantly different from groups As and Bs. Failure of the specimens was achieved at each strain rate. Ultimate strength values show no significant dependence on strain rate. Ultimate strain values show some strain-rate dependence with groups As, Bs, and Cs being significantly different from group Es, group Ds being significantly different from groups As and Bs, and group Es being significantly different from groups As, Bs, and Cs. Modulus

Table 2 AS4 universal graphite fabric/3501-6 epoxy stitched laminate: three-direction tests

Group	Pressure, psi	Strain rate, /s	Yield strength, MPa	Yield strain	Ultimate strength, MPa	Ultimate strain	Modulus, MPa
			Without stitch				
F1	20	562	——	——	741.98	0.0555	13,897
F2	20	615	——	——	709.93	0.0523	14,336
F3	20	575	——	——	719.47	0.0564	12,582
G1	40	705	——	——	706.43	0.0521	13,558
G2	40	792	——	——	638.54	0.0460	12,428
G3	40	780	——	——	664.46	0.0507	14,364
G4	40	793	——	——	647.35	0.0485	15,565
H1	60	914	——	——	695.24	0.0563	14,259
H2	60	992	——	——	701.43	0.0552	14,027
H3	60	870	——	——	616.72	0.0484	14,683
I1	80	873	——	——	686.62	0.0518	18,399
I2	80	1107	——	——	754.97	0.0602	15,690
I3	80	1081	——	——	688.81	0.0546	15,318
I4	80	1049	——	——	784.55	0.0614	15,629
J1	100	1143	542.55	0.0440	652.49	0.0499	20,339
J2	100	1137	——	——	724.32	0.0580	15,398
J3	100	1217	——	——	665.61	0.0548	15,548
J4	100	1197	——	——	697.72	0.0534	16,891
			With stitch				
F1s	20	630	——	——	571.92	0.0487	13,274
F2s	20	594	——	——	596.44	0.0392	15,323
F3s	20	583	——	——	642.83	0.0434	16,740
F4s	20	581	——	——	555.09	0.0409	14,460
G1s	40	794	——	——	647.91	0.0474	14,817
G2s	40	761	——	——	620.13	0.0436	15,122
G3s	40	790	——	——	566.77	0.0437	13,669
G4s	40	684	——	——	592.54	0.0406	15,671
H1s	60	1025	——	——	638.71	0.0453	15,500
H2s	60	958	——	——	579.13	0.0394	17,894
H3s	60	917	——	——	591.06	0.0425	15,360
H4s	60	972	——	——	586.39	0.0487	13,990
I1s	80	1130	——	——	554.96	0.0419	14,888
I2s	80	826	——	——	643.33	0.0369	17,597
I3s	80	917	——	——	635.50	0.0458	16,467
I4s	80	1119	——	——	604.64	0.0479	15,611
J1s	100	1201	495.74	0.0331	594.32	0.0494	17,966
J2s	100	1173	480.85	0.0299	597.18	0.0468	20,225
J3s	100	1190	——	——	582.11	0.0468	18,638
J4s	100	1301	——	——	579.35	0.0508	16,226

of elasticity values show little strain-rate dependence with groups Bs, Cs, Ds, and Es being only significantly different from group As, and group As only being significantly different from group Es.

From the first part of Table 4, strain rates of the three-direction, nonstitched specimens show significant differences. Groups F and I show significant difference from all other groups whereas the remaining groups exhibit some significant differences to other groups. Yielding was not found in the three-direction specimen except at the high strain rate. Therefore, in the strain-rate range between 1027.3 and 1173.4 s^{-1}, a transition from brittle to ductile behavior must occur. Failure of the specimens was achieved at each strain rate. Ultimate strength values show very little significant dependence on strain rate. Ultimate strength values of groups F, I, and J are statistically equivalent to all groups, whereas groups G and H are only significantly different from group F. Ultimate strain values show no strain-rate dependence. Modulus of elasticity values show very little strain-rate dependence with groups F, G, and H being statistically equivalent to all groups, group I being significantly different from group J, and group J being only significantly different from groups F and H.

From the second part of Table 4, strain rates of the three-direction, stitched specimens show significant differences. Groups Fs, Gs, Hs, and Js show significant difference from all other groups with the exception of group Is, whereas group Is shows significant difference from all other groups with the exception of group Hs. Yielding was not found in the three-direction specimen except at the high strain rate. Therefore, in the strain-rate range between 1027.3 and 1216.2 s^{-1}, a transition from brittle to ductile behavior must occur. Failure of the specimens was achieved at each strain rate. Ultimate strength and strain values show no significant dependence on strain rate. Modulus of elasticity values show very little strain-rate dependence with only group Js showing a significant difference from group Gs.

Discussion

For the two-direction, nonstitched specimens, ultimate strength values show little significant difference with strain rate, whereas ultimate strain and modulus of elasticity values show some significant strain-rate sensitivity. Ultimate strain values show an increasing trend with strain rate, increasing 74% over the tested strain rates. Modulus of elasticity values show a decreasing trend with strain rate, decreasing 70% over the tested strain rates. Yielding was not found in the two-direction specimen except at the low strain rate, indicating a transition from ductile to brittle behavior in the strain-rate range between 234.3 and 575.3 s^{-1}.

The two-direction, stitched specimens for the most part displayed little or no strain-rate dependence. Ultimate strength did not vary with strain rate. Ultimate strain showed some strain-rate dependence, and modulus of elasticity displayed very little strain-rate dependence. Ultimate strain values show an increasing trend with strain rate, increasing 61% over the tested strain rates. Modulus of elasticity values show a decreasing trend with strain rate, decreasing 33% over the tested strain rates. Yielding was not found in the two-direction specimen except at the low strain rate, indicating a transition from ductile to brittle behavior in the strain-rate range between 234.3 and 575.3 s^{-1}.

In the comparison of the mechanical properties of the two-direction specimen with and without stitching, Fig. 2 shows ultimate

Table 3 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: two-direction tests

Group	Yield	Strain rate, /s	Yield strength, MPa	Yield strain, in./in.	Ultimate strength, MPa	Ultimate strain	Modulus, MPa
			Without stitch statistics				
A	Average	234.3	257.73	0.0060	370.11	0.0121	64,713.0
	Standard deviation	13.6	24.10	0.0007	9.08	0.0011	10,918.2
B	Average	575.3	—	—	386.11	0.0125	41,407.0
	Standard deviation	23.7	—	—	26.32	0.0008	6,700.9
C	Average	705.5	—	—	389.16	0.0174	29,299.5
	Standard deviation	3.5	—	—	10.38	0.0001	658.3
D	Average	849.3	—	—	355.38	0.0187	23,416.0
	Standard deviation	152.5	—	—	11.17	0.0019	1,838.0
E	Average	925.3	—	—	363.83	0.0210	19,850.0
	Standard deviation	72.4	—	—	18.70	0.0004	3,511.0
			With stitch statistics				
As	Average	520.9	—	—	338.94	0.0151	29,423.0
	Standard deviation	63.9	—	—	13.98	0.0006	988.0
Bs	Average	618.1	—	—	330.36	0.0164	24,275.0
	Standard deviation	54.9	—	—	13.30	0.0017	2,377.0
Cs	Average	578.4	—	—	328.81	0.0164	23,832.0
	Standard deviation	123.0	—	—	15.81	0.0022	3,151.0
Ds	Average	813.1	—	—	350.53	0.0222	20,486.0
	Standard deviation	106.8	—	—	17.60	0.0026	4,035.0
Es	Average	843.1	—	—	370.18	0.0243	19,859.0
	Standard deviation	91.5	—	—	15.55	0.0022	1,656.0

Table 4 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: three-direction tests

Group	Yield	Strain rate, /s	Yield strength MPa	Yield strain, in./in.	Ultimate strength, MPa	Ultimate strain	Modulus, MPa
			Without stitch statistics				
F	Average	583.8	—	—	723.79	0.0547	13,605.0
	Standard deviation	27.3	—	—	16.46	0.0022	912.7
G	Average	767.0	—	—	664.95	0.0493	13,978.8
	Standard deviation	42.1	—	—	31.55	0.0027	1,322.4
H	Average	925.0	—	—	671.13	0.0533	14,323.0
	Standard deviation	61.7	—	—	47.22	0.0043	332.7
I	Average	1027.3	—	—	728.74	0.0570	16,259.0
	Standard deviation	105.6	—	—	48.89	0.0046	1,435.9
J	Average	1173.4	542.55	0.0440	685.04	0.0540	17,044.0
	Standard deviation	39.8	—	—	32.36	0.0034	2,296.9
			With stitch statistics				
Fs	Average	596.6	—	—	591.57	0.0431	14,949.3
	Standard deviation	23.0	—	—	38.16	0.0041	1,459.7
Gs	Average	756.9	—	—	606.84	0.0438	14,819.8
	Standard deviation	51.0	—	—	34.99	0.0028	844.6
Hs	Average	968.0	—	—	598.82	0.0440	15,686.0
	Standard deviation	44.6	—	—	27.04	0.0040	1,622.0
Is	Average	997.9	—	—	609.61	0.0431	16,140.8
	Standard deviation	151.0	—	—	40.08	0.0048	1,165.8
Js	Average	1216.2	488.30[a]	0.0315[a]	588.24	0.0485	18,263.8
	Standard deviation	57.7	10.53[a]	0.0023[a]	8.82	0.0020	1,656.1

[a] Average and standard deviation calculated from J1s and J2s of Table 2.

Table 5 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: quasi-static strength tests

Direction	Number	Stitched specimen?	Ultimate strength, MPa	Average ultimate strength, MPa
2	1	No	227.02	
2	2	No	254.05	241.80
2	3	No	244.32	
2	1	Yes	227.02	
2	2	Yes	270.26	241.43
2	3	Yes	227.02	
3	1	No	704.59	
3	2	No	645.43	718.93
3	3	No	806.78	
3	1	Yes	591.64	
3	2	Yes	580.89	598.81
3	3	Yes	623.91	

strength of the nonstitched specimens being approximately 17% stronger than the stitched specimens at the 600-s^{-1} strain rate. This strength gap decreases with increasing strain rate until the strengths become equivalent near the 840-s^{-1} strain rate. Figure 3 shows the ultimate strain in the stitched specimens being initially lower than the nonstitched specimens. However, for strain rates above 690 s^{-1}, the ultimate strain of the stitched specimens becomes greater than the nonstitched specimens. Modulus of elasticity values of the nonstitched specimens are greater than the stitched samples over the test strain rates (Fig. 4), being about 71% greater than the stitched specimen modulus near the 575-s^{-1} strain rate and about 18% greater near the 850-s^{-1} strain rate.

For the three-direction, nonstitched specimens, ultimate strength values and modulus of elasticity values show little significant difference with strain rate. Ultimate strength and strain values are basically flat over the strain rates tested. Modulus of elasticity values show an increasing trend with strain rate, increasing 25% over the tested strain rates. Yielding was found in the three-direction specimen in

Table 6 COV of the dynamic mechanical properties

Property	Two-direction without stitch, %	Two-direction with stitch, %	Three-direction without stitch, %	Three-direction with stitch, %
Strain rate	0.5–18.0	8.9–21.3	3.4–10.3	3.9–15.1
Yield strength	9.40	N/A	N/A	2.2
Yield strain	11.70	N/A	N/A	7.2
Ultimate strength	2.5–6.8	4.0–5.0	2.3–7.0	1.5–6.6
Ultimate strain	0.6–10.2	4.0–13.4	3.9–8.0	4.1–11.2
Modulus	2.2–17.7	3.4–19.7	2.3–13.5	5.7–10.3

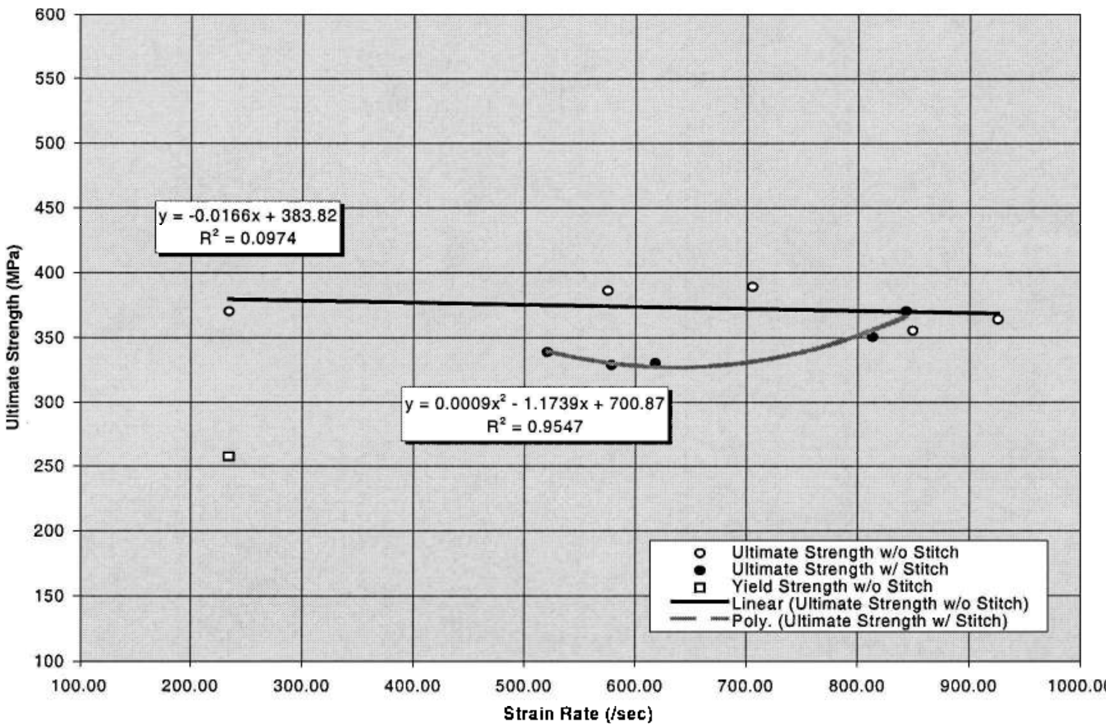

Fig. 2 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: two-direction ultimate and yield strength as a function of strain rate.

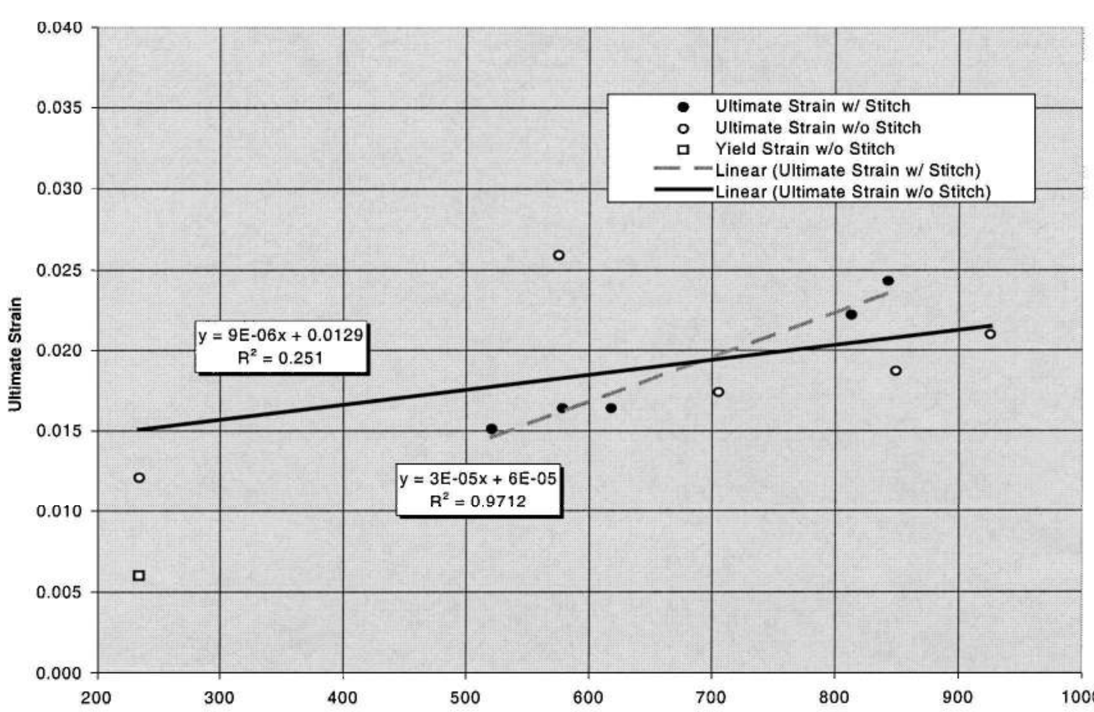

Fig. 3 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: two-direction ultimate and yield strain as a function of strain rate.

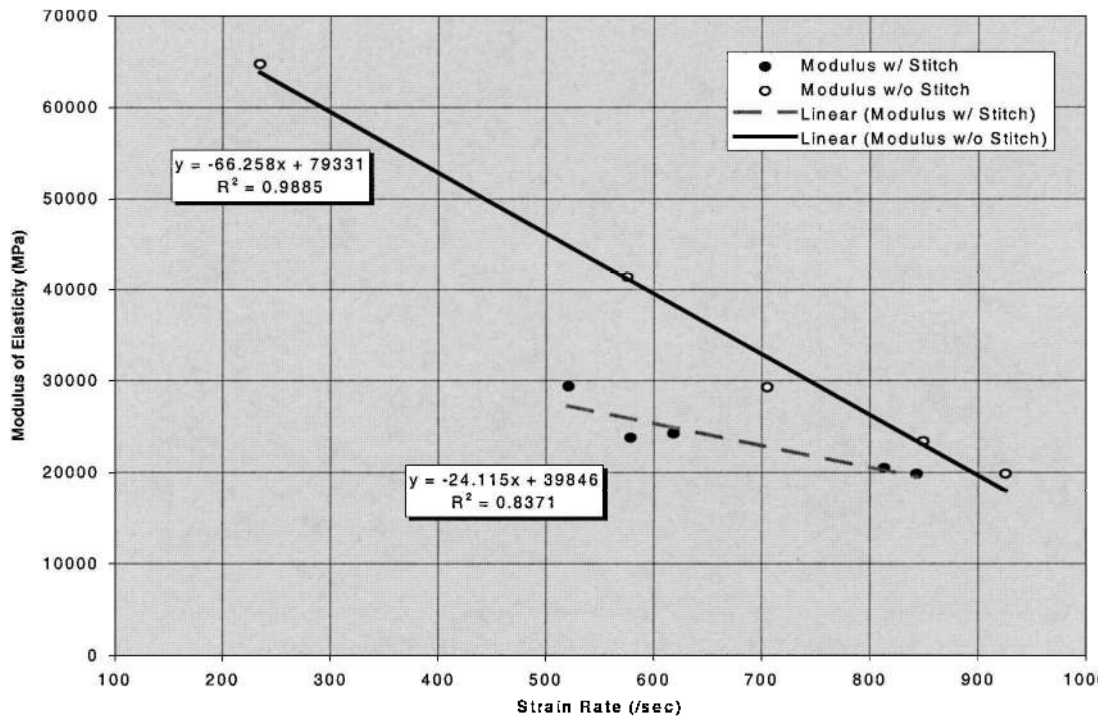

Fig. 4 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: two-direction modulus of elasticity as a function of strain rate.

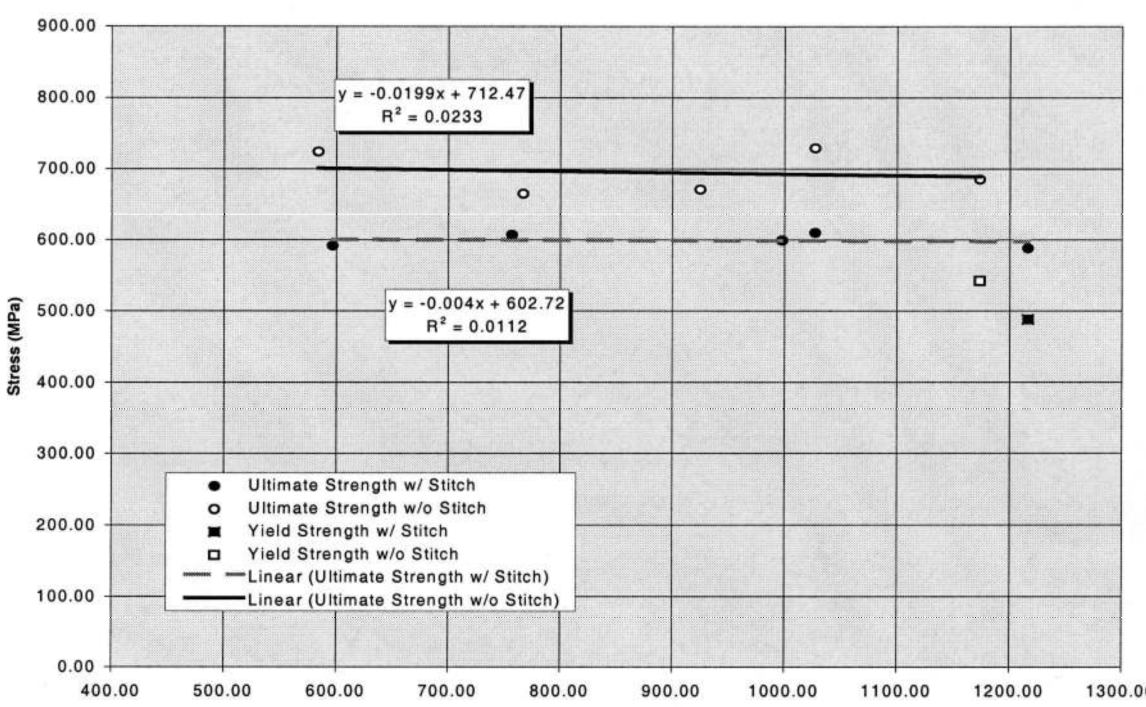

Fig. 5 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: three-direction ultimate and yield strength as a function of strain rate.

only one of four specimens in group J. Therefore, a transition from ductile to brittle behavior in the strain-rate range between 1027.3 and 1173.4 s^{-1} may occur.

The three-direction, stitched specimens for the most part displayed little or no strain-rate dependence. Ultimate strength and strain did not vary significantly with strain rate, and modulus of elasticity values displayed little significant strain-rate dependence. Ultimate strength values are basically flat over the strain rates tested whereas ultimate strain values increased 12.5% over the tested strain rates. Modulus of elasticity values show an increasing trend with strain rate, increasing 22% over the tested strain rates. Yielding was found in the three-direction specimen among two of four specimens in group Js. A transition from ductile to brittle behavior in the strain-rate range between 1027.3 and 1216.2 s^{-1} may occur.

In the comparison of the mechanical properties of the three-direction specimen with and without stitching, Fig. 5 shows the ultimate strength of the nonstitched specimens being approximately 16.7% stronger than the stitched specimens throughout the tested strain rates. Figure 6 shows ultimate strain values of the nonstitched

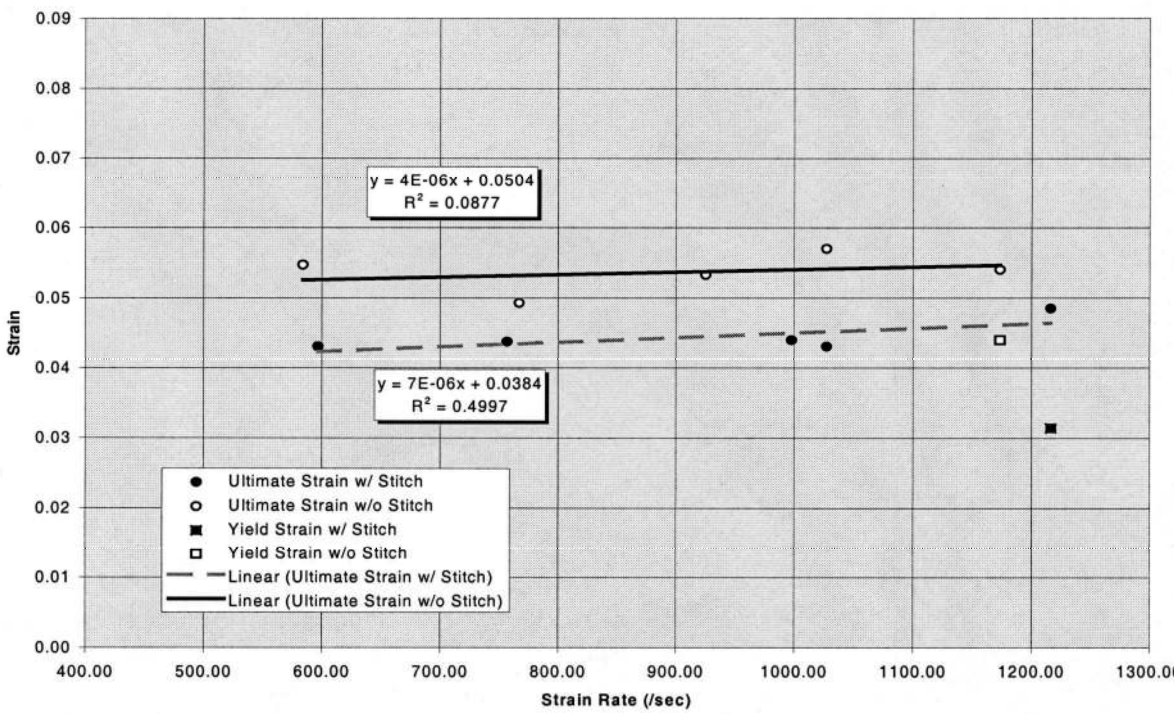

Fig. 6 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: three-direction ultimate and yield strain as a function of strain rate.

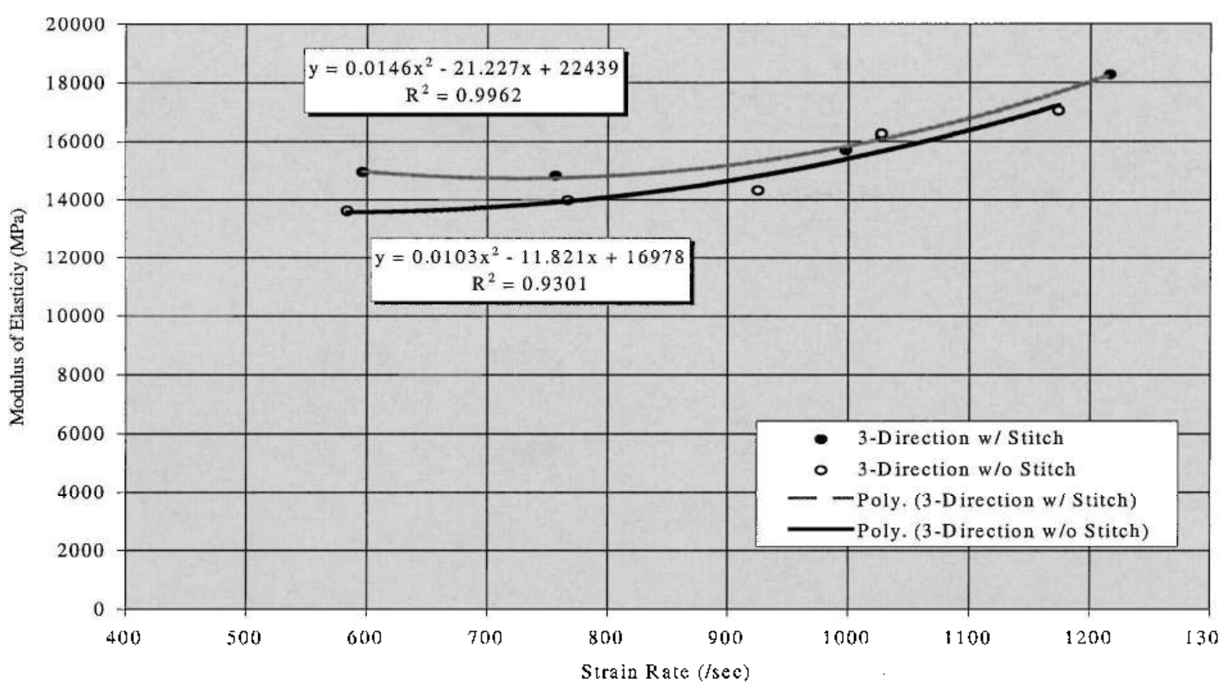

Fig. 7 AS4 uniweave graphite fabric/3501-6 epoxy stitched laminate: three-direction modulus of elasticity as a function of strain rate.

specimens being about 27% greater than the stitched specimens over the tested strain rates. Modulus of elasticity values of the stitched specimens are slightly greater than nonstitched samples over the test strain rates (Fig. 7), being about 10% greater than the nonstitched specimen modulus near the 590-s^{-1} strain rate and about 7% greater near the 1200 s^{-1} strain rate.

Answers as to why the ultimate strength of the nonstitched specimens are generally greater than the stitched ones may be found by observing the failed specimens. The two-direction, nonstitched, failed specimens showed visible interply delamination, with the surviving plies becoming smaller in size with increasing strain rate. The two-direction, stitched specimens also showed visible interply delamination. However, the majority of the surviving plies were fractured midway across the plies, where the stitching had intersected it, suggesting that the reinforcement stitch may have acted as a stress concentration. The three-direction, nonstitched, failed specimens predominately fractured parallel to the loading direction into smaller disks, with the surviving fragments decreasing in size with increasing strain rate. The three-direction, stitched specimens also showed visible fracture predominately parallel to the loading direction. However, the majority of the surviving fragments were smaller than the nonstitched samples and showed fracture from the axis where the stitching had intersected it, suggesting that the reinforcement stitch may have acted as a stress concentration.

When quasi-static-strength results are examined, no difference in strength is observed between stitched and nonstitched specimens in the two directions. However, in the three directions, stitched specimens are 16.7% weaker than nonstitched specimens. Comparing quasi-static-strength test results to dynamic-strength values, significant differences exist between two-direction static values and dynamic values. The two-direction, nonstitched specimen average static strength is 38% lower than the highest average dynamic value, and the two-direction, stitched specimen average static strength is 35% lower than the highest average dynamic value. In the three directions, static strength values for both stitched and nonstitched specimens are in line with dynamic results and show no significant differences.

Conclusions

Some of the conclusions expressed in the Discussion section are repeated herein, for the strain-rate ranges tested.

Two Direction

In the nonstitched material, the following results are noted:

1) The ultimate strain increased 74%.

2) Compressive modulus of elasticity decreased 70%.

3) Yielding (or the start of significant damage) was not found before failure except at lower strain rates; hence, a transformation to brittle behavior occurs between strain rates of 234 and 575 s^{-1}.

In the stitched material, the following results are noted:

1) Ultimate compressive strength did not vary with strain rate.

2) Ultimate strain increased 61%.

3) Compressive modulus of elasticity decreased 33%.

4) See point 3 of the nonstitched material results.

When stitched and nonstitched materials are compared, the following results are noted:

1) Nonstitched specimens are up to 17% stronger than the stitched material (at 600 s^{-1}).

2) The materials are equally strong at 840 s^{-1}.

3) Ultimate strain of the stitched material is lower than the nonstitched specimens up to 690 s^{-1}, then the reverse is true.

4) Compressive modulus of elasticity is greater by 18–71% in the nonstitched material than the stitched material.

When dynamic properties are compared with quasi-static properties, the following results are noted:

1) Quasistatically, there is no difference in compressive strengths between stitched and nonstitched materials.

2) Significant differences exist between dynamic and static property values.

3) In nonstitched material, the highest dynamic compressive strength is 61% higher than the static value.

4) In the stitched material, the highest value for dynamic compressive strength is 54% higher than the static value.

Three Direction

In the nonstitched material, the following results are noted:

1) Compressive ultimate strength values are constant over the strain rates measured.

2) Compressive modulus of elasticity increases 25% over the various strain rates.

3) Stress and strain are linear over the entire range of strain rates tested.

In the stitched material, the following results are noted:

1) Compressive ultimate strength did not vary with strain rate.

2) Ultimate strain values increase 12.5% over the strain rates tested.

3) Compressive modulus values increased 22%.

When stitched and nonstitched materials are compared, the following results are noted:

1) Over the strain rates tested, the compressive ultimate strength of the nonstitched material is 16.7% higher.

2) Ultimate strain values of the nonstitched material are 27% greater than the stitched material.

3) Modulus of elasticity values for the nonstitched material varies between 7 and 10% greater than that of the stitched material.

When dynamic properties are compared to quasi-static properties, there are no significant variations between static and dynamic values.

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