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High Strain Rate Properties of Cycom 5920/1583 Cloth Glass/Epoxy Composites

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Polymer matrix composites offer excellent properties such as high specific strength and stiffness, which make them attractive for many naval, aerospace, and automotive applications. Although they are candidate materials for many applications where high strain rate loading is probable, little is known of the material responses to shock loading for most composite materials. Because mechanical properties vary significantly with strain rate, the use of static properties in the analysis and design of structures that undergo dynamic loadings can, on one hand, lead to a very conservative overweight design or, on the other hand, can lead to designs that fail prematurely and unexpectedly. The use of dynamic material properties will ensure the design of composite structures, which are weight efficient and structurally sound when they are subjected to dynamic loads. A split Hopkinson pressure bar is used to obtain compressive mechanical properties of Cycom 5920/1583, an uniaxial cloth, E-glass/rubber toughened epoxy composite being used presently by the Electric Boat Division of General Dynamics for undersea structures. Yield stress, yield strain, ultimate stress, ultimate strain, and modulus of elasticity values are presented and analyzed wherein the strain rates vary from 60 to 1150 s^{-1}.

Introduction

AT present, a program is underway at the University of Delaware that involves three phases: 1) the high strain rate testing in compression and tension of various polymer matrix composite (and other) materials, using the existing split Hopkinson pressure bar facility, and correlation and statistical analysis of the dynamic material properties obtained; 2) examination of the samples tested, using optical and electron microscopy to characterize the deformation and fracture processes; and 3) the evaluation of the suitability of current models, such as Johnson–Cook, Ferilli–Armstrong, Steinberg–Guinan–Lund, and Bodner–Partom, to describe the strength, deformation, and failure of these materials at high strain rates and the modification of these models, or, wherever necessary, the development of new models. This paper concentrates on the first phase for this particular material.

The split Hopkinson pressure bar facility at the University of Delaware is illustrated in Fig. 1.

This new data will add to what is now available for other materials. Zukas[1] shows that for many metals the mechanical properties vary significantly with strain rate. For composite material systems, there is relatively little data available. At Delaware, materials systems tested at high strain rates using the split Hopkinson pressure bar to date include unidirectional E-glass/3501 epoxy, random nonwoven glass/Cycom 4102 polyester, unidirectional T40/ERL 1908 graphite/epoxy, unidirectional AS4/3501 graphite epoxy, quasi-isotropic AS4 cloth/3501 graphite/epoxy, Metton, 6061-T6 aluminum, carbon/aluminum MMC, silicon carbide/aluminum MMC, unidirectional continuous fiber carbon/glass CMC, silicon carbide reinforced 2080 aluminum, IM7/8551-7 graphite epoxy, AS4/3501 graphite epoxy, AS4/K3B graphite polyimide, IM7/K3B graphite polyimide, AS4/PEKK graphite thermoplastic, and K49/3501-6 Kevlar® epoxy. The high strain rate effects are reported in Refs. 2–17.

Test Results

The Cycom 5920/1583 is an uniaxial cloth, E-glass/rubber toughened epoxy composite used in mast fairings, bow domes, propulsor components, turtleback superstructures, and sonar windows. The use of such advanced composites in external ship structures is increasing due to the weight savings they afford over equivalent metallic structures and due to acoustic requirements for components such as sonar windows.

The results of the 27 in-plane compression tests performed to date are given in Table 1. All of the tests were in the 0-deg direction, using the test pieces provided by Electric Boat. At room temperature and dry, the strain rates varied from 59.3 to 1144.2 s^{-1}. The data are grouped according to strain rate, wherein the pressure refers to the nitrogen pressure level in the pressure chamber, which propels the striker bar. The strain rate is calculated for each firing, and it is seen that although the pressure may be the same in various firings the strain rates that result do vary.

It is seen that for group A, the specimens did not fail and, therefore, the stress and strain values recorded were the maximum values attained in the test; because the material was in the elastic range, the modulus of elasticity is recorded. For group A, that modulus is the highest stress value divided by the highest strain value. The group A specimens never experienced a maximum stress greater than the static ultimate strength. For other groups, where there is yielding, the modulus is defined as the yield stress divided by the yield strain. The yield stress and yield strain here are defined as the stress and strain at which a nonlinearity in the stress–strain curve commences as the stress and strain increase; it is the point at which damage commences. For those specimens in groups G and H that did not yield, the ultimate stress divided by the ultimate strain defines the modulus.

In group B, the specimens did not split into pieces, and the partial fracture surface was at a 45-deg angle to the axis of the specimen. Specimen B3 simply broomed at the incident bar and differed in failure from the other B specimens.

The C specimen statistically belongs in the B group of specimens but fractured into five distinct pieces; hence, it is listed as a separate category. The fracture appeared to be more of a delamination. The D group fractured into three distinct pieces with two parallel 45-deg fracture surfaces.

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Table 1 Experimental data for Cycom 5920/1583

Group	Pressure, kPa	Strain rate, /s	Yield stress, MPa	Ult. stress, MPa	Yield strain, mm/mm	Ult. strain, mm/mm	Modulus, GPa	Notes
A1	52	82.8	——	237.9	——	0.01822	13.0	Specimens did not fail.
A2	55	64.3	——	307.5	——	0.01601	19.2	Ultimate values reported
A3	52	67.6	——	248.2	——	0.01549	16.1	are maximum values
A4	52	59.3	——	258.6	——	0.01322	19.5	for the test
A5	52	76.8	——	239.3	——	0.01682	14.2	
B1	90	135.7	103.4	455.1	0.00524	0.02470	19.8	1 piece, shear
B2	97	125.2	114.5	494.4	0.00480	0.02491	23.9	1 piece, shear
B3	103	131.1	123.4	504.0	0.00557	0.02583	22.2	Broomed at incident end
B4	97	132.9	145.5	450.9	0.00623	0.02511	23.4	1 piece, shear
B5	97	184.9	142.7	442.6	0.00739	0.03439	19.3	1 piece, shear
B6	97	200.2	101.4	399.9	0.00606	0.02762	16.7	1 piece, shear
C1	97	237.1	107.6	312.3	0.00531	0.01992	20.3	5 pieces, delamination
D1	138	335.5	166.9	473.0	0.00725	0.02449	23.0	3 pieces, shear
D2	138	325.5	148.9	477.8	0.00685	0.02539	21.7	3 pieces, shear
E1	241	481.5	200.6	392.3	0.00998	0.02263	20.1	Specimens fragmented
E2	241	433.7	253.7	479.9	0.01012	0.02689	25.0	and all appear to
E3	241	619.5	210.3	425.4	0.01218	0.02974	17.3	have a shear plane
F1	448	693.7	337.8	484.0	0.01286	0.02636	26.3	
F2	448	645.2	384.0	487.5	0.01198	0.02551	32.1	
G1	689	894.8	——	632.3	——	0.01521	41.5	
G2	689	926.1	414.4	495.0	0.01606	0.02778	25.8	
G3	689	1144.2	——	564.0	——	0.01945	28.8	
G4	689	940.9	——	502.6	——	0.01976	25.4	
G5	689	837.3	402.0	470.2	0.01554	0.02512	25.9	
G6	689	918.5	——	377.1	——	0.02480	15.2	
G7	689	847.5	435.8	490.2	0.01658	0.02205	26.3	
H1	827	934.3	——	480.6	——	0.01682	28.5	

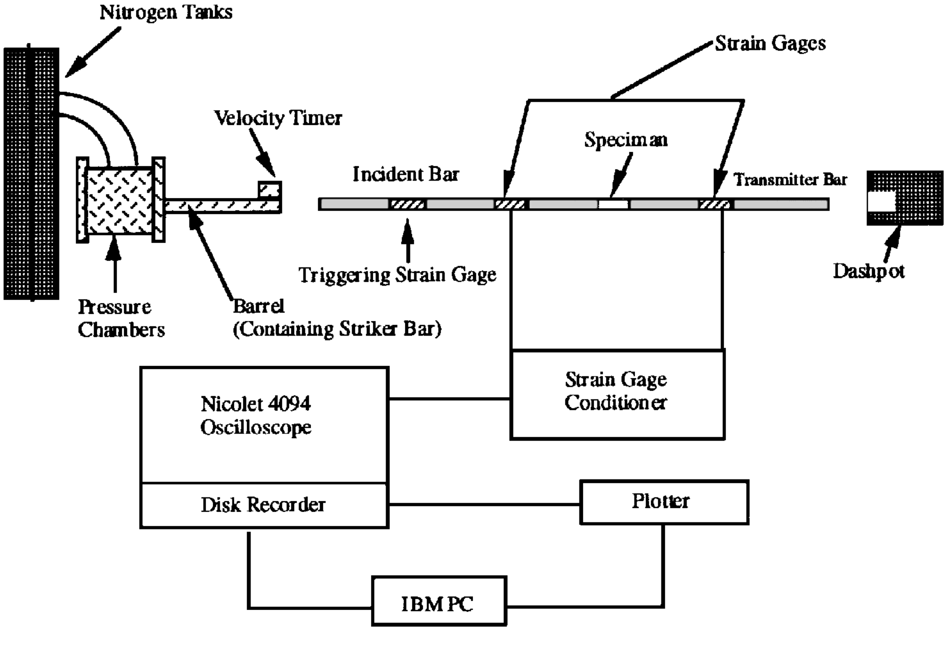

Fig. 1 University of Delaware split Hopkinson pressure bar equipment.

Groups E–H test pieces all fractured into numerous pieces, with many 45-deg fracture surfaces visible. The size of the debris decreased with increasing strain rate.

The data of Table 1 are statistically analyzed and presented in Table 2. Where possible, mean values and standard deviations were obtained. It is interesting to note that for yield stress values, the coefficients of variation vary between 8.5 and 12.7%. For ultimate strength, they vary between 0.4 and 15.6%; for yield strains, they vary between 3.2 and 11.4%; for ultimate strains, they vary between 2.3 and 19.3%; and the moduli vary between 4.0 and 28.6%. With additional testing, perhaps the larger sample sizes will reduce the standard deviations.

For purposes here, one can define the difference between measured quantities to be significant if the mean value of one quantity falls outside the mean ± 3 standard deviations of another quantity. Using this definition, some conclusions can be drawn as follows.

The strain rate of C is not significantly different from that of B. However, the strain rates of B, D, and E are significantly different from each other. The E strain rate is significantly lower than F, and the G strain rate is significantly higher than F.

Concerning yield stress, again C is not significantly different from B. In all other replicate groups, there is a significantly different increase in yield stress (Fig. 2).

With regard to ultimate strength, there is no significant difference between any of the ultimate strength values measured. However, the static strength of the Cycom 5920/1583 material is 344.7 MPa; hence, Table 3 shows that there is a considerable increase in the static ultimate strength and that of high strain rate behavior (Fig. 2). It has

Table 2 Statistical analysis for Cycom 5920/1583

Group		Strain rate, /s	Yield stress, MPa	Ult. stress, MPa	Yield strain, mm/mm	Ult. strain, mm/mm	Modulus, GPa
A	Average	70.2	——	258.6	——	0.01595	16.1
	Standard deviation	9.5	——	28.8	——	0.00184	3.1
B	Average	151.7	113.8	484.7	0.00520	0.02515	21.9
	Standard deviation	32.2	10.0	25.9	0.00039	0.00060	2.1
D	Average	330.5	157.9	475.7	0.00705	0.02494	22.3
	Standard deviation	7.1	12.7	3.4	0.00028	0.00064	0.9
E	Average	511.6	221.3	432.3	0.01076	0.02642	20.8
	Standard deviation	96.5	28.3	44.2	0.00123	0.00358	3.9
F	Average	669.5	361.3	486.1	0.01242	0.02594	29.2
	Standard Deviation	34.3	32.7	2.4	0.00062	0.00060	4.1
G[a]	Average	935.8	417.1	483.2	0.01606	0.02316	24.6
	Standard Deviation	110.8	17.1	60.8	0.00052	0.00330	4.7

[a] Average values for yield stress and strain only include samples G2, G5, and G7. Average values for strain rate, ultimate stress, ultimate strain, and modulus include samples G1–G7.

Table 3 Comparison of static and dynamic values for Cycom 5920/1583

Rate, /s	Ult. stress, MPa
Static	344.7
152	484.7
331	475.7
512	432.3
670	486.1
936	483.2

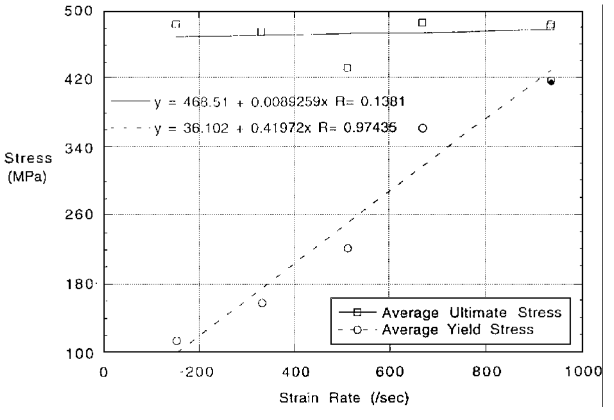

Fig. 2 Yield and ultimate stress vs strain rate for Cycom 5920/1583.

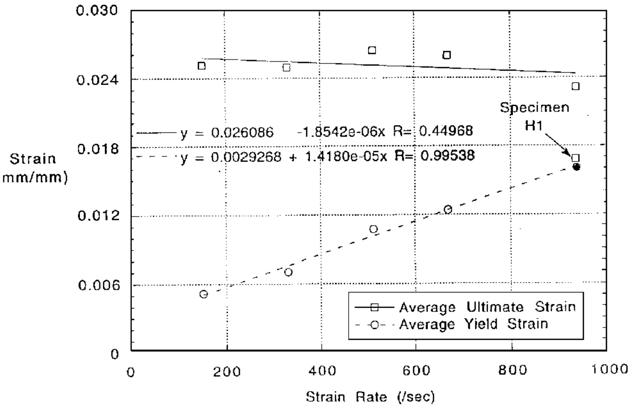

Fig. 3 Yield and ultimate strain vs strain rate for Cycom 5920/1583.

been suggested that in some materials the major changes in properties between static dynamic values occur between static loading and strain rates of 100 s^{-1}. This may be one of those materials.

Concerning yield strains, again C falls within the range of B, whereas B, D, and E are significantly different. F is not significantly different from E, but G is. Therefore, yield strains, like yield stresses, do increase significantly with strain rate (Fig. 3).

With regard to ultimate strains, again C does not differ significantly with B, and there are no significant differences among B, D, E, F, and G, similar to the ultimate stresses (Fig. 3).

Finally, looking at the moduli of elasticity, there is no significant difference among any of the groupings for the high strain rate tests, with one exception. If one assumes specimens G2–G7 only to be of the same population and asks whether specimen G1 falls into this group, the answer is yes, except for the modulus value. In the group of G2–G7, the mean modulus value is 24.6 GPa and the standard deviation is 4.72 GPa. Therefore, the G1 modulus of 41.5 GPa falls above the mean plus three standard deviation value of 38.3 GPa.

To the authors' knowledge this material has never been tested at these high strain rates, and so no comparisons with other sources are possible.

Conclusions

For the Cycom 5920/1583 composite material in compression and dry, the following conclusions can be made.

1) The ultimate strength does not significantly vary between strain rates of 125 and 1144 s^{-1}, but these values exceed the static values by at least 25%. Thus, the high strain rate effect on ultimate compressive strength takes place at strain rates below 125 s^{-1}.

2) The yield strength increases significantly with strain rate by more than a factor of 3.6 between strain rates of 152 and 926 s^{-1}, and the material may be transitioning in the higher strain rate region from ductile to brittle behavior.

3) Regarding yield strains, over the range of strain rates from 152 to 930 s^{-1}, there is an increase by a factor of 3.09.

4) There is no significant difference in strain to failure or modulus of elasticity over the range of strain rates tested.

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