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Specimen Geometry Effects on High-Strain-Rate Testing of Graphite/Epoxy Composites

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Numerous papers have been published that include high-strain-rate experimental data obtained from Split Hopkinson Pressure Bar (SHPB) tests. There have been no standardized test specimens with differing dimensions and geometry. For this reason, it can be difficult to compare results of tests performed by other researchers. The SHPB facility was used in this study to determine if specimen geometry has an effect on the results of high-strain-rate compression tests. The material used in all of the tests is a unidirectional IM7/8551-7 graphite/epoxy composite. The experiments discussed herein show the effect of varying the length-to-diameter (*L/D*, or aspect) ratio of the specimen, as well as the effect of changing from the more typical cylindrical to a square/rectangular specimen geometry. The *L/D* study examined 84 cylindrical specimens with *L/D*s from 0.5 to 2.0, with $D = 0.261$ in., and tested in both the 1 and 2 directions. The geometry study used 42 square/rectangular specimens and tested in the 1, 2, and 3 directions. The results of both studies are compared, and no statistically significant effect of either *L/D* or geometry could be found.

Introduction

THE Split Hopkinson Pressure Bar (SHPB) facility is shown in Fig. 1, and the related Lagrangian diagram is shown in Fig. 2. Kolsky introduced a method for determining mechanical properties of materials at high-strain rates using the SHPB in 1949.[1] The method was developed based on wave propagation theory in elastic bars and the interaction between a stress wave and a short specimen. After Kolsky's introduction, the method was expanded to include tensile and shear testing.[2,3]

To begin a test, a specimen is placed between two long, 1.9-cm (3/4 in.) diam Inconel bars, the incident bar and the transmitter bar, which are supported by Teflon® bearings. Each end of the specimen is lubricated. Impact is initiated by releasing nitrogen gas from a pressurized chamber. The gas propels a striker bar (supported by and riding on Teflon rings) through a guiding barrel, at the end of which it strikes the incident bar. The velocity of the striker bar just prior to impact is measured using two infrared beams at the end of the barrel. At impact, the incident bar receives an elastic compressive stress wave with specific wave velocity and a wave shape that is a function of time. When the wave reaches the incident bar/specimen interface, a portion of the incident wave is reflected back into the incident bar as a tensile wave. The remaining portion of the wave is transmitted into the specimen as a compressive wave. The wave transmitted into the specimen travels through the specimen and reaches the specimen/transmitter bar interface, where a portion of the wave is reflected back into the specimen. The rest is transmitted into the transmitter bar as again a compressive wave. The transmitter bar is also displaced along its length axis and comes to rest when it reaches a dashpot.

The initial stress wave in the specimen undergoes numerous internal reflections during the test because the specimen length is short, and therefore, the wave reflections in the specimen are not shown in the Lagrangian diagram of the SHPB. The stress distribution in the specimen is assumed to be uniform because of the numerous reflections. In addition it is assumed that the stress waves undergo minimal dispersion, that the bars remain elastic, and that the ends of both the incident and transmitter bars in contact with the specimen remain flat. The Lagrangian diagram shows that there is a characteristic time window corresponding to the duration of the stress wave. The wave pulse time window of the University of Delaware SHPB is approximately 290 μs. This means that the specimen must fail within 290 μs after the initial portion of the wave reaches the specimen for failure to be accurately characterized. This has not been a problem with the relatively brittle composites tested to date.

Strain gauges are mounted on both bars equidistant from the specimen interfaces and are connected to a Fluke PM3394A recording oscilloscope. The strain gauge mounted on the incident bar also acts as trigger for the oscilloscope. The oscilloscope records the strain gauge's output as a voltage vs time graph. Using these data, along with the speed of the striker bar and the physical dimensions of the bars and specimens, stress vs strain curves can be generated for different strain rates. Zukas has shown that for many metals the mechanical properties vary significantly with strain rate.[4] These new data will add to what is currently available for other materials. Other recent research using the same facility has focused on material systems that include glass/epoxy, glass/polyester, graphite/epoxy, carbon/metal matrix, and carbon/ceramic matrix composites.

Numerous papers have been published that include high-strain-rate experimental data obtained from SHPB tests. There is no standardized test specimen geometry, and different researchers use specimens with differing dimensions and geometry. For this reason, it can be difficult to compare results of tests performed by other researchers. This suggests that experiments be performed to determine if either varying the length-to-diameter (L/D) ratio of the specimen or changing the specimen geometry from circular to square/rectangular affect the material properties determined by the testing.

All previous research performed by the authors used right circular cylinders with an L/D ratio of around 1.5. Cylindrical specimens were used because that has been the traditional geometry and because the facilities and materials used combined to make production of circular samples straightforward. The purpose of this study, using IM7/8551-7 graphite/epoxy composite, is to examine the effect of both varying L/D ratios from 0.5 to 2.0, with $D = 0.261$ in., and using a square/rectangular specimen geometry in place of the more traditional cylindrical one. This study has been instrumental in performing tests on other material systems.[5]

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Sample Preparation

The IM7/8551-7 carbon/epoxy specimens were fabricated at the University of Delaware from continuous fiber unidirectional prepeg tape. The tape was 40.6 cm (16 in.) wide and was cut into 122-cm (48-in.) strips. A 75-ply unidirectional laminate was fabricated by hand lay-up to achieve the desired thickness after processing. The laminate was cured in a Thermal Equipment Corporation computer-controlled autoclave. The finished laminate was then sectioned using a water-cooled masonry saw equipped with a diamond grit blade. This saw produced no delamination or rough surfaces with this material. Cylindrical specimens that were core drilled out of the sectioned pieces were used to study the effect of varying the L/D ratio.

The L/D study included 84 specimens with an L/D ratio ranging from one-half to two, in increments of one-quarter. The diameter of the specimens remained fixed at 0.663 cm (0.261 in.), set by the diameter of the core drill, while the length varied from 0.323 cm (0.127 in.) to 1.3 cm (0.5121 in.). The tests were conducted only in the longitudinal direction (fiber or 1 direction) and the transverse direction (2 direction). Tests were not performed in the thickness direction (3 direction), as the length of the specimen could not be varied over the desired range. In addition, a previous study of the same IM7/8551-7 graphite epoxy composite shows that the 2 and 3 directions have similar properties, and therefore 2 direction testing would give adequate insight into the material properties in the 3 direction.

The square/rectangular specimens of IM7/8551-7 graphite epoxy composite were fabricated out of the flat panels by using a computer-controlled, water-cooled surface grinder equipped with a thin-kerf diamond grit saw blade. This was to compare the results for these square/rectangular specimens both with data obtained from previous research and with the results for the cylindrical samples of the L/D study. A total of 42 square/rectangular specimens were produced, and the tests were performed in all three directions. The samples were approximately 0.635 cm (0.25 in.) square and 0.953 cm (0.375 in.) in length.

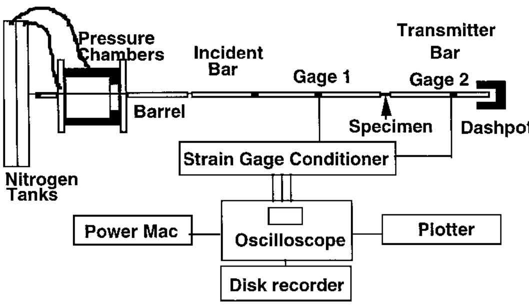

Fig. 1 SHPB apparatus at the University of Delaware.

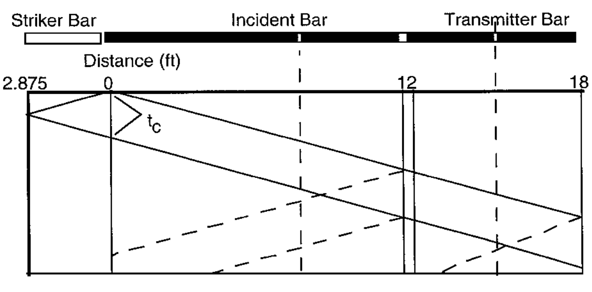

Fig. 2 Lagrangian diagram.

Results and Discussion

The test results for the L/D study are shown in Figs. 3–6. The SHPB chamber pressure varied from 0.2 to 0.68 MPa (30 to 100 psi), which resulted in strain rates of 300 to 1400/s. The results show that for these L/D ratios there are no significant variations in material properties for the range of strain rates achieved in this investigation. A significant variation is defined herein as when the mean value of a property for one group of test results falls outside of the mean value, ± 3 standard deviations, for the same property in another group of tests. The specimens tested fracture, and there is no way of telling whether barreling occurred, but because of the limited ductility and the examination of the fracture surfaces, barreling probably could not occur.

Most specimens tested fracture into indiscernible small pieces, and there is no way to tell if barreling occurs. However, because of the brittleness of IM7/8551-7 graphite epoxy composite and the examination of the fractured surfaces of some of the specimens, there seems to be no barreling during the high strain rate loading of these specimens. Further investigation of the tested specimens using a scanning electron microscope revealed that the modes of failure seem to be similar. For a specimen tested in the 1 direction it was observed that the major mode of failure was longitudinal splitting, with very little fiber buckling, kinking, or fiber breakage.

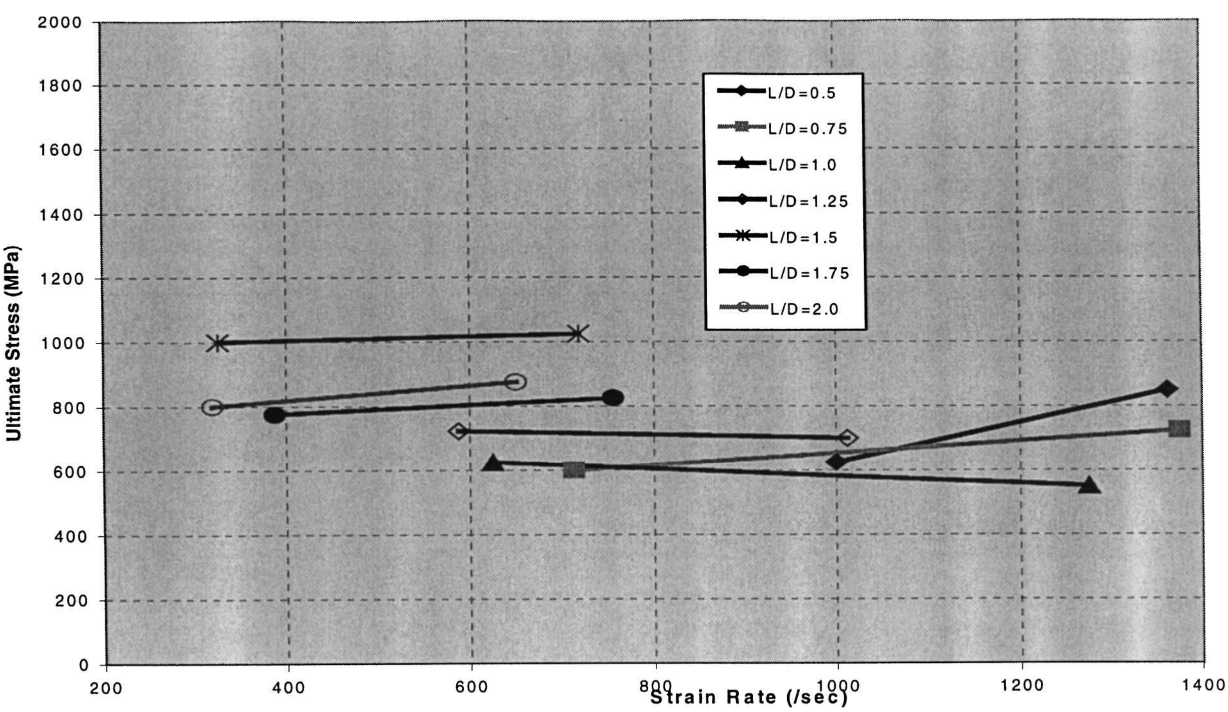

Fig. 3 Ultimate stress vs strain rate for various L/D ratios in the 1 direction.

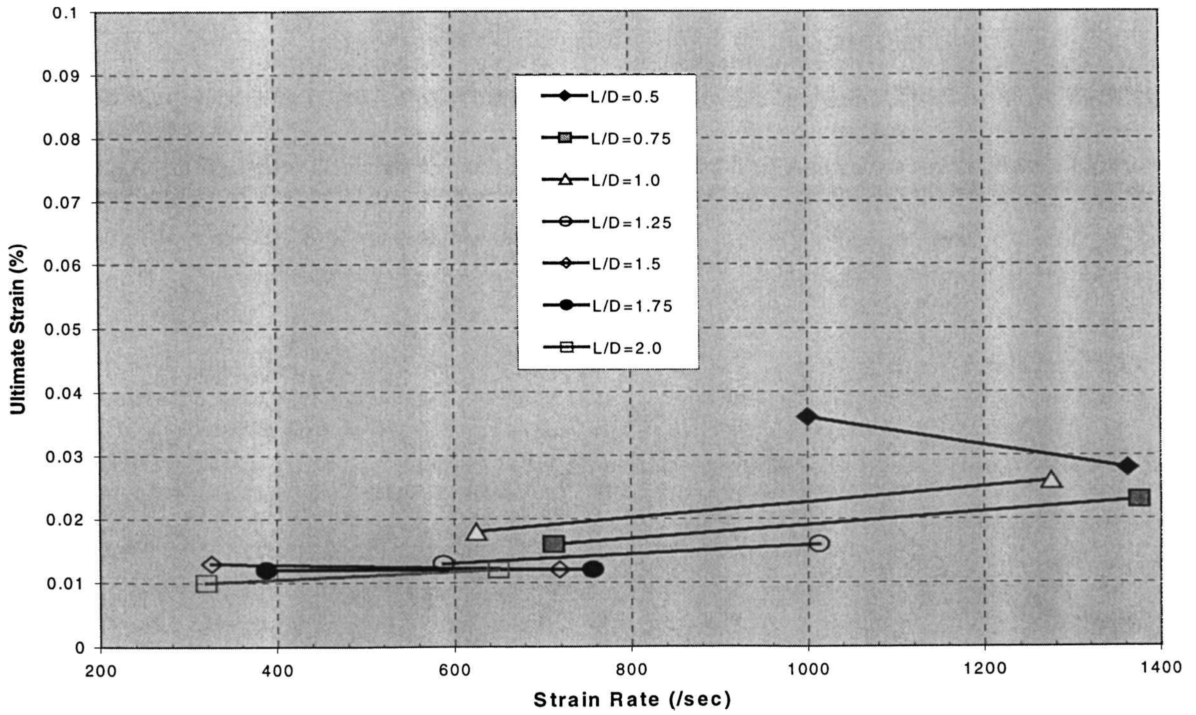

Fig. 4 Ultimate strain vs strain rate for various *L/D* ratios in the 1 direction.

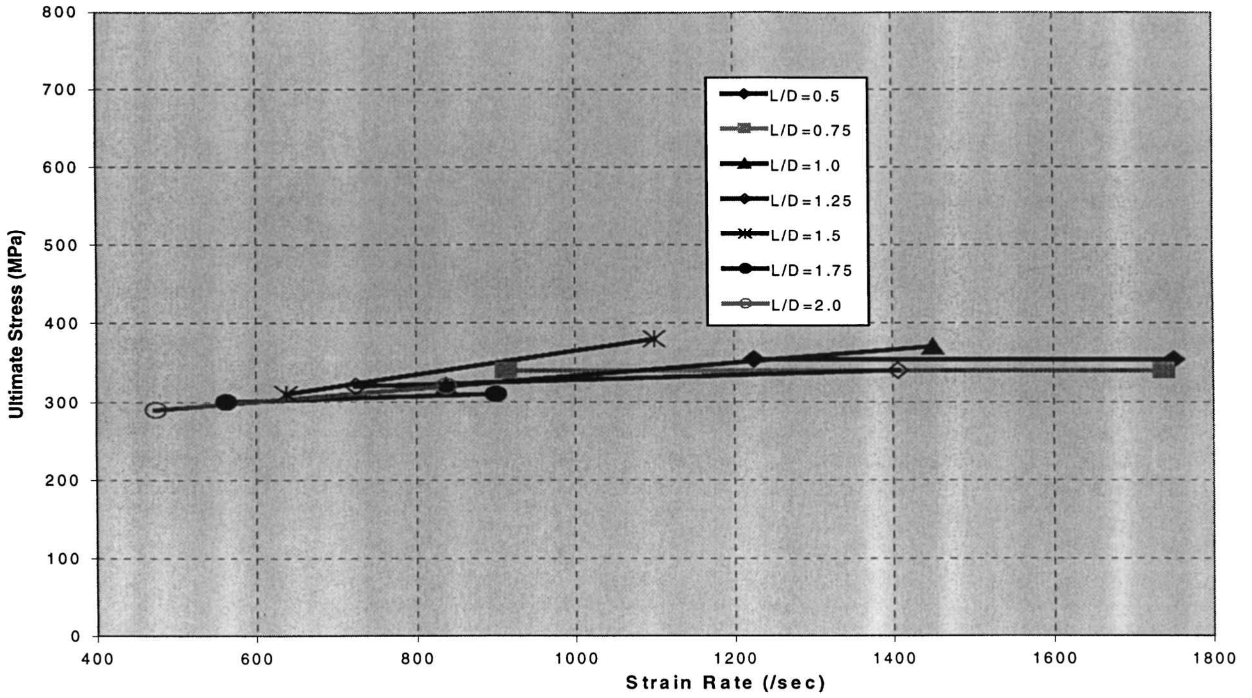

Fig. 5 Ultimate stress vs strain rate for various *L/D* ratios in the 2 direction.

Longitudinal splitting results from failure at the fiber/matrix interface at a specific location, which then propagates through the entire length of the interface. Longitudinal splitting will presumably be active whenever the interfacial strength is below a certain threshold, and it can result from transverse tensile stresses that develop because of Poisson's ratio differences between matrix and fiber.[6] In examining a specimen tested in the 2 direction, the primary surface feature was where the matrix and fibers were pulled down and broken. This failure mode is commonly seen in an angled failure plain. It is most likely caused by fibers bridging the fracture, which were subsequently sheared downward and broken.

Furthermore, these tests show that it is possible to vary the applied strain rate by varying the length of the specimen. Thus one can obtain comparable strain rate values by either changing the chamber pressure or the specimen length. However, there are certain limitations that must be considered. The SHPB results are usually taken to be valid if there are at least four or five reflections of the stress wave within the specimen prior to failure, which directly relates to the assumption of a uniform stress field that was mentioned earlier.

If c_s represents the wave speed in the specimen and L_s represents the specimen length, then the transit time t_s that is needed for the incident wave to travel through the specimen once is given by

$$t_s = L_s / c_s \qquad (1)$$

The time to failure t_f should then be greater than the time required to obtain a uniform state of stress within the specimen:

$$t_f \geq \gamma t_s = \gamma (L_s / c_s) \tag{2}$$

where γ represents the number of times the pulse is reflected back and forth. Therefore, the specimen length can be varied as long as Eq. (2) is valid, which was the case in this study. Using a value of 4 for γ, the minimum time to failure for the shortest and longest longitudinal and transverse specimens are given in Table 1, and it

Table 1 Time to failure for IM7/8551-7 graphite epoxy composite for different lengths in the *L/D* study

Direction	Length, in.	Transient time t_s, μs	γt_s, μs	Time to failure (shortest time), μs
Longitudinal	0.125	0.32	1.28	19
Transverse	0.125	1.33	5.32	24
Longitudinal	0.5	1.28	5.12	17
Transverse	0.5	5.32	21.28	39

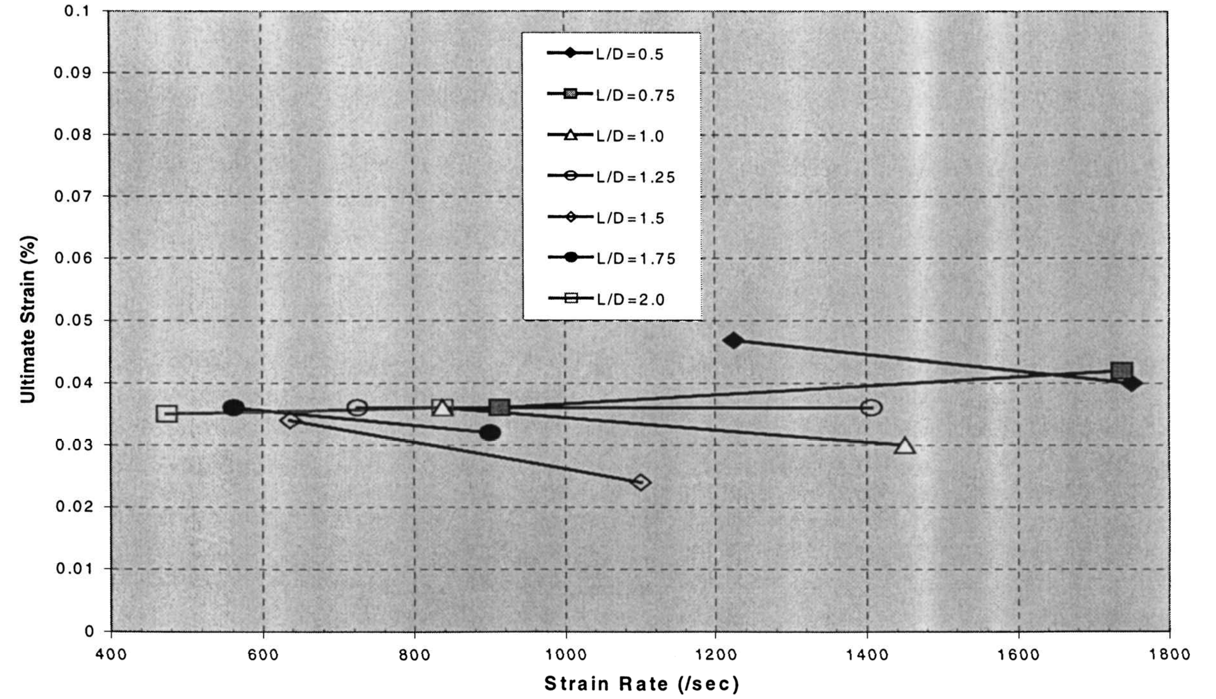

Fig. 6 Ultimate strain vs strain rate for various *L/D* ratios in the 2 direction.

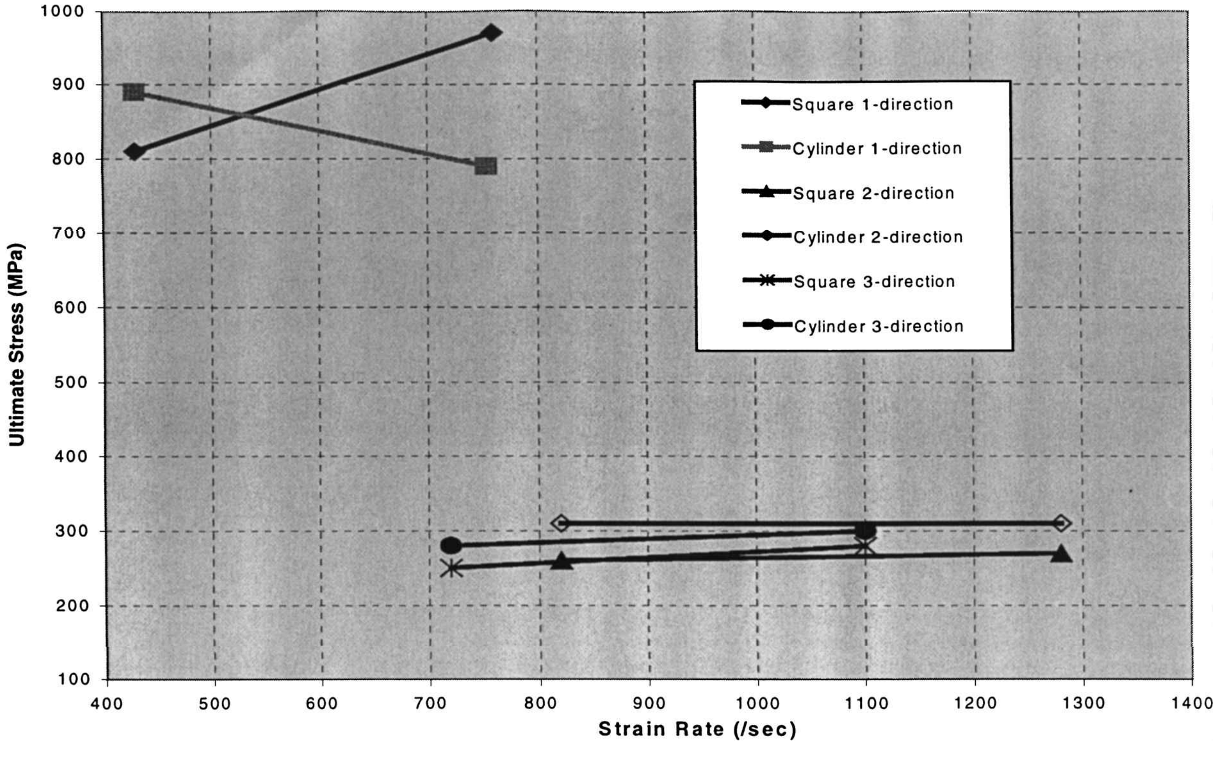

Fig. 7 Comparison of ultimate stress vs strain rate for cylindrical and square/rectangular specimens.

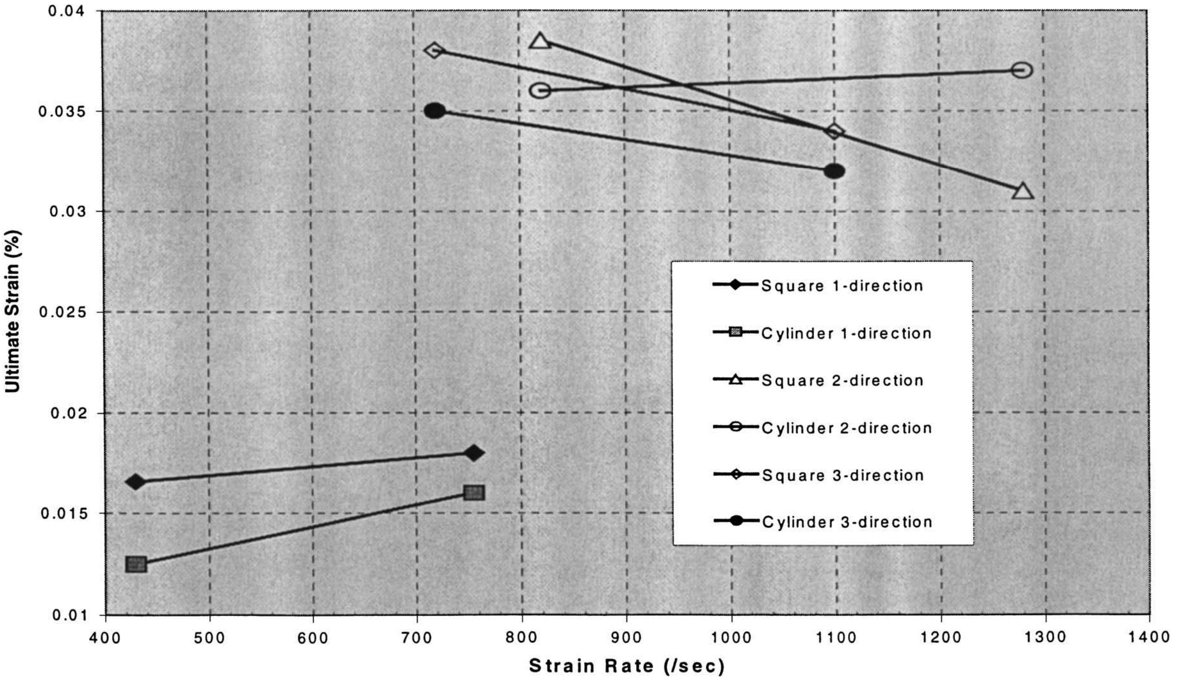

Fig. 8 Comparison of ultimate strain vs strain rate for cylindrical and square/rectangular specimens.

shows that all of the tests specimen lengths are valid because all of the calculated values are less than the experimental values that are the shortest times from all of the tests. The value of 4 for γ has been determined to show that there is a stress equilibrium after 4 wave reflections in the specimen.

The test results of the portion of the study involving the comparison of the square/rectangular specimen geometry with the cylindrical geometry are shown in Figs. 7 and 8. Previous research performed with this SHPB facility used all cylindrical samples because that was the traditional geometry and the facilities to produce cylindrical samples were available. The strain rates in this study varied between 400 and 1300/s. The results are compared with various studies of cylindrical IM7/8551-7 graphite epoxy composite samples, and Figs. 7 and 8 show that both shapes result in similar high-strain-rate properties. This result is important because it leads to easier sample preparation and also facilitates the comparison of data from different sources.

Conclusions

The study of aspect ratio variation shows that it is possible to vary the L/D ratio from 0.5 to 2.0, with $D = 0.261$ in., for IM7/8551-7 graphite epoxy composite and obtain similar results. The square/rectangular vs cylindrical geometry study clearly indicates the possibility of varying the shape of an IM7/8551-7 graphite epoxy composite sample while still obtaining the same material properties. These results are important for several reasons. First, it is possible to compare results from different sources. Second, sample preparation can be greatly simplified. Third, it provides the researcher another way of varying the strain rate.

Although these studies have been conducted for one unidirectional graphite/epoxy composite material system, it is felt that the results can be generalized to other materials and other stacking sequences. In any case, only limited additional testing would be needed to confirm these conclusions for other materials and architectures.

Acknowledgments

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