TECHNICAL ARTICLE

Low Strain Rate Testing Based on Drop Weight Impact Tester

G. Li and D. Liu

Department of Mechanical Engineering, Michigan State University, East Lansing, MI

Keywords
Fiber Composite, Strain Rate, Drop Weight Impact

Correspondence
D. Liu,
Department of Mechanical Engineering,
Michigan State University,
East Lansing, MI, USA
Email: liu@msu.edu

Received: July 1, 2012; accepted: August 24, 2012

doi:10.1111/j.1747-1567.2012.00862.x

Abstract

As the use of fiber composites extends to automotive applications, there is a need to characterize the composite properties at low strain rates, such as below 100/s. In performing such low strain rate tests, the commonly used split Hopkinson's pressure bar for high strain rate investigations should become inadequate. A high-speed hydraulic testing machine may be suitable for testing at the low strain rates; however, it is not necessarily available to the general engineers because of its high cost. On the basis of a drop weight impact tester, this study presents an affordable testing technique for characterizing a carbon composite at low strain rates. Both compressive and tensile tests are demonstrated in this study.

Introduction

Owing to their high stiffness and high strength with low density, fiber-reinforced polymer matrix composites are excellent materials for high-performance structures which are commonly exposed to dynamic environments. The behavior of composite materials under high strain rates, however, can be quite different from that under low strain rates. Taking the automotive application as an example, the composite materials and structures may be subject to vibration and dynamic loading with a strain rate up to 100/s. Hence, there is a need to characterize the properties of automotive composites from static to low strain rate of that level.

Among the dynamic testing techniques available, split Hopkinson's pressure bar (SHPB)[1,2] is the most commonly used method for high strain rate characterizations, such as from 10^2/s to 10^4/s. Its usefulness for strain rates lower than 100/s, however, should become very challenging, if not impossible. In order to fill the gap between static loading and high strain rate testing, high-speed hydraulic testing machines, such as Instron's VHS 8800 (Instron, Norwood, MA, USA),[3] should prove to be useful. However, in order to achieve high-speed loading rates, large pneumatic capacity is required for fast response. An efficient feed-back system is also needed to achieve constant loading rates. Accordingly, the high-speed hydraulic testing machine may become very costly and not necessarily available to general engineers. On the basis of a conventional drop weight impact tester (DWIT), this study presents an affordable testing technique suitable for performing dynamic characterizations of fiber composites up to a strain rate of 100/s.

Drop Weight Impact Tester

Force equilibrium

In order to achieve constant strain rates in drop weight impact testing, an existing DWIT was modified to be equipped with a large impacting mass, hence the specimen being tested can deform with a strain rate as constant as possible. Shown in Fig. 1 is a DWIT attached with an impacting mass of 150 kg. As the large mass and impact head drop onto the specimen, a relatively constant speed of deformation can be achieved in the specimen because of the significantly large weight induced by the large impacting mass against the resistance of the specimen.

Besides constant strain rates, or at least nearly constant strain rates, a constant force through the specimen is also required for validating the dynamic testing. As the impact occurs, the impact head will

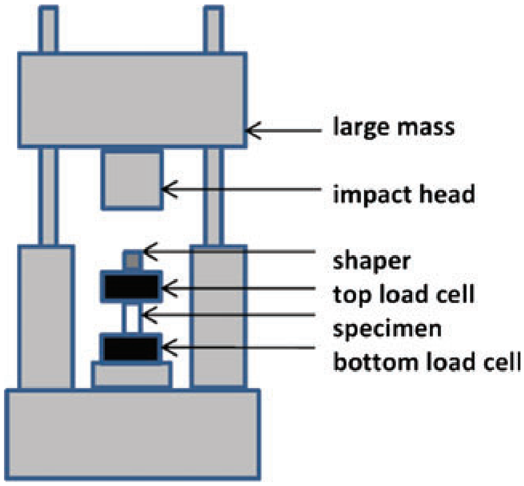

Figure 1 DWIT-based compressive strain rate testing.

first contact with the top surface of the specimen. The impact-induced force will subsequently propagate to the bottom surface of the specimen. Although very short, a period of time is required for the specimen to achieve equilibrated force through the length. Once the force in the specimen reach equilibrium during the impact testing, the testing result can be used for further analysis, otherwise the test is deemed invalid and the testing result should be nullified.

Right after the contact-impact takes place, the top surface of the specimen may experience damage while the rest of the specimen remains intact. This is likely to occur in brittle specimens such as polymer composites. If the premature damage does occur, the impact test should be claimed invalid because the specimen does not reach the equilibrium condition.

Shaper

In order to achieve uniform force through the specimen and to avoid any premature damage to the specimen, a material softer than the specimen, so-called shaper, may be added between the impact head and the top load cell as shown in Fig. 1. Identifying the right type of material and associated thickness as the shaper involves trial and error. Soft materials such as copper and rubbers are often used by composite engineers as shaper materials. It should also be pointed out that the strain rate is usually reduced when a softer shaper is added to the impact system. Hence, it is a challenging task to achieve force equilibrium in the specimen with a softer shaper without significantly reducing the strain rate.

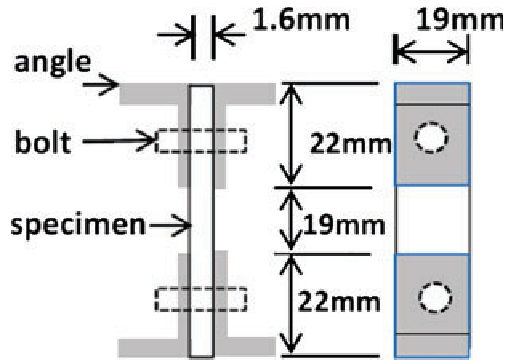

Figure 2 Thin specimen with bolted angles.

Compressive Testing Procedures and Data Analysis

Specimens

Thin specimen for compressive and tensile testing

As an example, a laminated carbon composite with a thickness of 1.6 mm was investigated in this study. All composite specimens were machined to have dimensions of 63 mm × 19 mm. Each of them was then bolted with steel angles from both sides and at both ends as shown in Fig. 2, resulting in a 19 mm × 19 mm × 1.6 mm testing zone. Each specimen-angle set was then bolted to the load cells on both ends, as shown in Fig. 1, for impact testing. This specimen configuration is suitable for both compressive and tensile strain rate testing.

Thick specimen for compressive testing

Owing to the concern of specimen buckling and premature damage during compressive loading, thick specimens with dimensions of 12.7 mm × 12.7 mm × 6.4 mm without the clamping angles mentioned earlier were also used for studying the composite response. The thick specimens were obtained by bonding four 1.6-mm specimens together with an adhesive. Because of the high bonding strength of the adhesive, a specimen may split between individual composite plies rather than along the bonding interfaces when subjected to compressive loading. Besides, a layer of grease was applied to the surfaces between the specimen and the load cells to warrant free transverse expansion during compression. The thick specimen should work better than the thin specimen in compressive strain rate testing because of to its simplicity (without the joining angles) and higher resistance to buckling. However, cautions must be exercised in selecting the dropping height, hence no hard-to-hard impact, such as between the impact head and the top load cell and between the two load cells, would occur.

Effect of shaper

Shaper material

The task to identify a suitable shaper material with an adequate thickness for the carbon composite material under investigation was essentially based on trial and error. Four tests based on different shapers, from hard to soft, are given in Fig. 3. The hard material was of a carbon epoxy with dimensions of 40 mm × 20 mm × 3 mm. The hard rubber stands for polyurethane with dimensions of 20 mm × 20 mm × 13 mm. The medium soft rubber is Buna-N rubber with dimensions of 25 mm × 25 mm × 13 mm. The soft rubber is of latex rubber with dimensions of 25 mm × 25 mm × 20 mm. The force measured by the top load cell is much more significantly affected by the hardness/softness of the shaper than that measured by the bottom load cell. Figure 3(a) shows a large difference of measurements from the two load cells when a hard material was used as the shaper. Figure 3(b and 3c) shows significant improvements in the equilibrium of the two forces measured by the top and the bottom load cells when a hard rubber and a medium soft rubber were used as shapers, respectively. Using a soft rubber as a shaper, a good agreement up to 4 ms between the two measurements was obtained and is shown in Fig. 3(d). It demonstrates the equilibrium of the dynamic force through the length of the specimen. The result from Fig. 3(d) can then be used for further analysis.

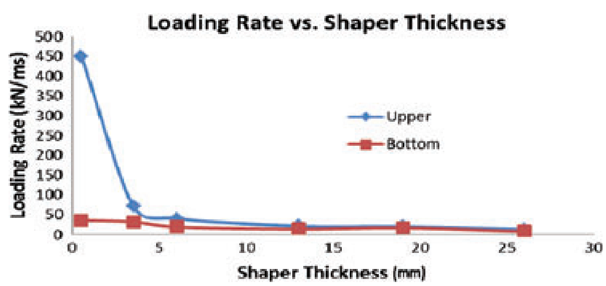

Figure 4 Decrease of loading rate due to the increase of shaper thickness.

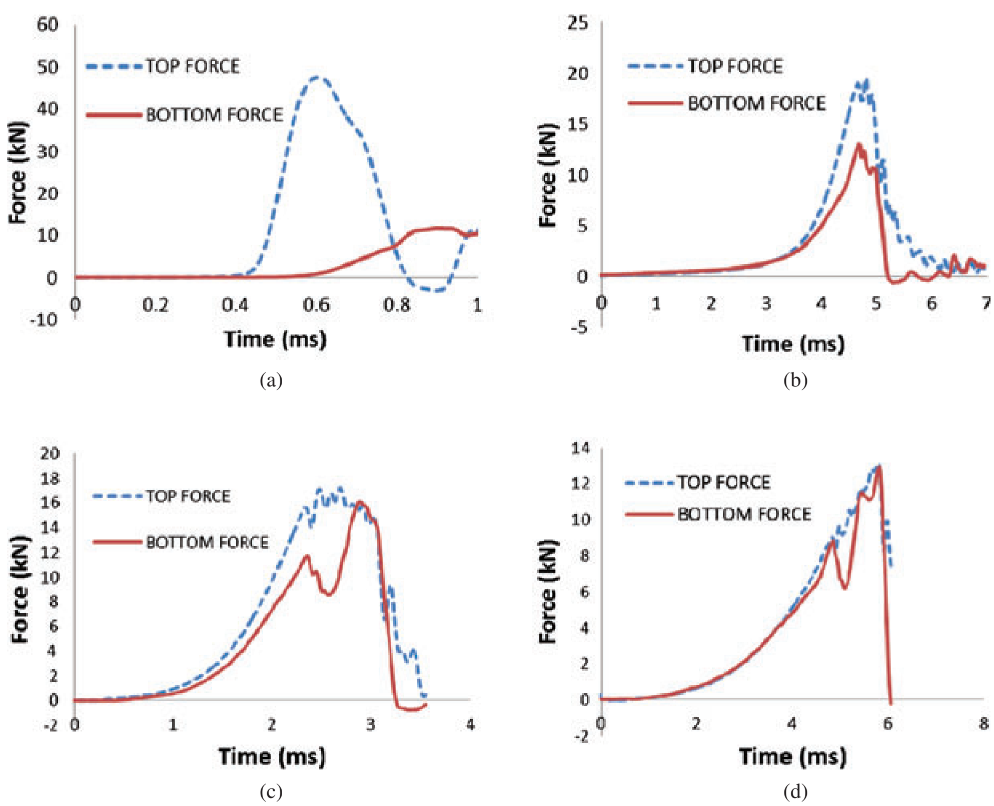

Figure 3 Effect of shaper softness on the balance of top and bottom forces. (a) Hard material, (b) hard rubber, (c) medium soft rubber, and (d) soft rubber.

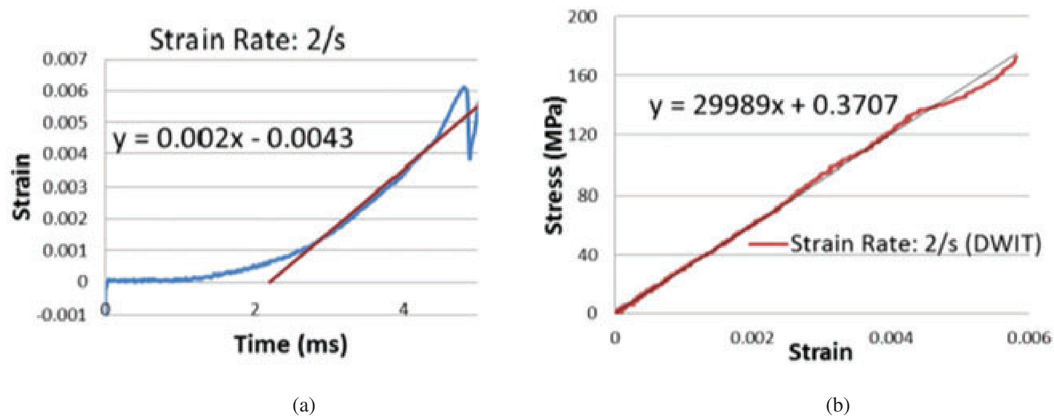

Figure 5 DWIT-based compressive testing results. (a) Strain history and strain rate and (b) stress–strain relation.

Table 1 Young's modulus and yielding stress at various compressive strain rates

Compressive Strain rate (1/s)	Static	2	3	8	18	30	63	125
Young's modulus (GPa)	28	30	30	34	31	29	30	31
Yielding stress (MPa)	160	165	185	250	275	160	270	150

Shaper thickness

From Fig. 3, it is clearly seen that the peak force measured by the top load cell decreases as the two forces measured from the two load cells become closer. The peak force measured by the bottom load cell, however, remains relatively constant. This clearly indicates the function of the shaper in reducing the top force and achieving the balance of the two forces. Figure 4 shows that the loading rate (and the strain rate) decreases as the thickness of the shaper increases (becomes softer). This is especially significant in the top load cell although the bottom load cell also experiences reduction of loading rate.

Identification of strain rates

The strain history of Fig. 3(d) is given in Fig. 5(a). It was obtained from a strain gage mounted on the specimen. The nearly constant strain rate can be identified as 2/s by taking the derivative of the largely linear portion of the strain history as shown in Fig. 5(a). The corresponding stress–strain relation for the nearly constant strain rate of 2/s is given in Fig. 5(b). The Young's modulus and the yielding stress can then be identified as 30 GPa and 165 MPa, respectively. Tests for strain rates higher than 8/s were also performed, and the resulting Young's moduli and yielding stresses at several strain rates are summarized in Table 1.

Higher strain rates

As far as the concern of force balance, thin specimens held with metallic angles were useful for strain rate testing up to 8/s. For higher strain rates, thick specimens made from bonding four thin specimens together are required. Figure 6(a) shows the result

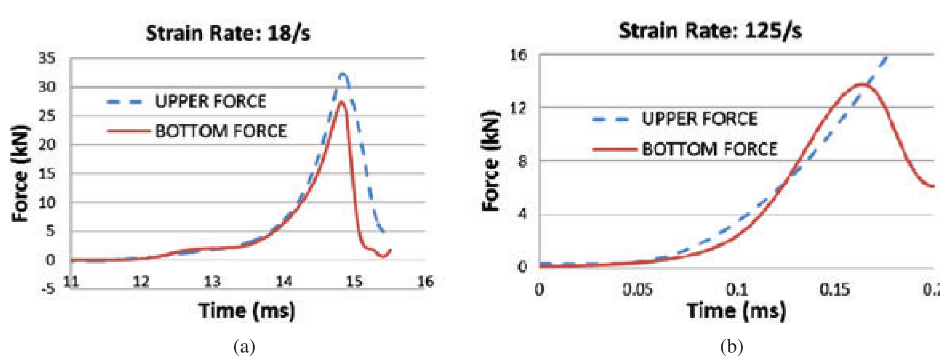

Figure 6 Force histories measured by load cells at compressive strain rate (a) 18/s and (b) 125/s.

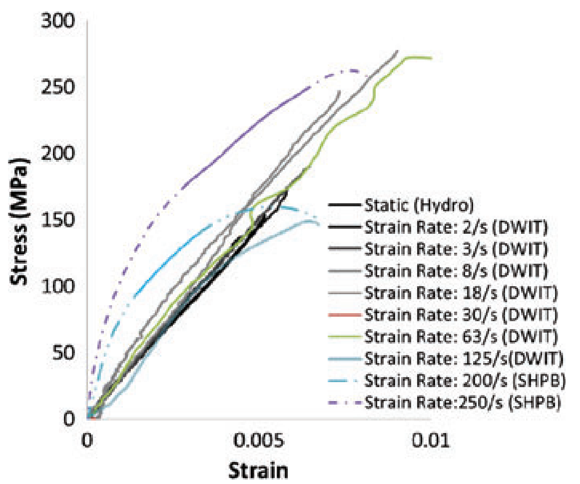

Figure 7 Collection of stress–strain curves under various strain rates.

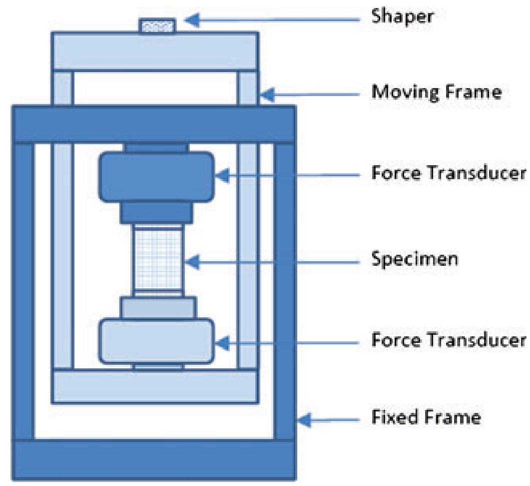

Figure 8 Loading fixture for DWIT-based tensile strain rate testing.

obtained from a thick specimen at a strain rate of 18/s. It was also found that thick specimen was useful for strain rates up to 63/s. As shown in Fig. 6(b), however, the top force and the bottom force deviate when the strain rate reaches 125/s. A softer shaper will be required to achieve the balance of the forces between the two load cells although it is also recognized that the strain rate will decrease as the softer shaper is employed. Figure 7 shows a collection of stress–strain curves under various strain rates. Possible Young's modulus and yielding stress based on Fig. 6(b) are also presented in Table 1. The low yielding stresses for 30/s and 125/s may be due to material nonuniformity.

Tensile Testing

In characterizing the carbon composite at low tensile strain rates, a loading fixture, shown in Figure 8, was constructed to convert the compressive loading generated from DWIT into tensile loading in the specimen. Two force transducers, one above and the other below the specimen, were installed to record the force histories. With a suitable shaper, Figure 9(a) shows the achievement of balance of forces, at least in the beginning of the loading history. It then is eligible for further analysis. Figure 9(b) shows the constant strain rate of 18/s and the stress–strain relation with a Young's modulus of 56.7 GPa. This value is higher than those obtained from compressive testing.

Summary

The large impacting mass used in this study is adequate for achieving nearly constant compressive strain rates close to 125/s. The tensile testing for strain rates up to 18/s has also been demonstrated. In selecting the specimen dimensions, the microstructure of fiber composite must be considered. The thick specimen based on bonding four thin specimens together seems to work better than the thin specimen

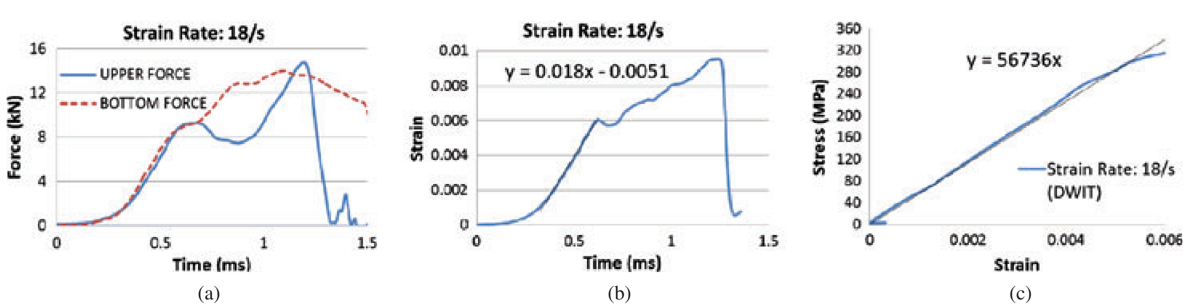

Figure 9 DWIT-based tensile testing results. (a) Forces recorded in the force transducers, (b) strain history and strain rate, and (c) stress–strain relation.

for higher compressive strain rates. The thin specimen held with steel angles has also worked adequately for tensile testing. Trial and error has been involved in the identification of a suitable shaper material with an adequate thickness for achieving force balance. As the shaper becomes softer, the forces at the two ends of specimen become closer while the strain rate becomes lower. The compressive Young's moduli fluctuate between 29 and 34 GPa for the compressive strain rates between 2/s and 125/s, while the associated yielding stresses fluctuate between 150 and 275 MPa. The tensile Young's modulus has been found to change from 43 to 57 GPa when the strain rate changes from 3/s to 18/s. Both values are higher than the compressive counterparts. The microstructure of the carbon composite such as voids and fiber waviness may play a significant role in the discrepancy. Multiple tests are required for obtaining more reliable testing results.

Acknowledgments

This research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-11-2-0017. The authors wish to express their sincere appreciation for the financial support.

References

1. Chen, W., and Song, B., *Split Hopkinson (Kolsky) Bar, Design, Testing and Applications*, Springer, New York, New York (2011).
2. Li, G., *Construction, Calibration and Application of a Split Hopkinson's Pressure Bar*, M.S. Thesis, Michigan State University (2002).
3. http://www.instron.us/wa/product/VHS-8800-High-Strain-Rate-Systems.aspx? [accessed on 13 September 2012].