Scaling Effect in Composite Plates Subjected to High-Pressure Waves

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ABSTRACT

Owing to their high stiffness and high strength with low density, fiber-reinforced polymer-matrix composites are excellent candidate materials for high-performance structures. Since polymer materials are sensitive to strain rate, the behavior of polymer composites at high strain rate is of important concern in designing composite structures for dynamic applications. This study looks into the scaling effect of woven composites subjected to high-pressure loading. Three scales, 3, 5 and 10, were used in the study based on composite specimens made of 3, 5 and 10 plies of woven fabrics, respectively. Based on Buckingham's theory, all testing parameters were determined. The dimensions of the specimens also had a scaling ratio of 3:5:10. Three gas pressure nozzles, i.e. blast tubes, were used to introduce scaled pressures to the scaled composite specimens. Their maximum pressure level should be identical but their pressure sizes (diameters) and durations should be in a ratio of 3:5:10. In recording the deformation of the composite specimens, both projection moire and electrical resistant strain gages were used. Results from the two independent measuring techniques seemed to be consistent with each other. Due to the highly dynamic testing environment, structure vibration and wave propagation were found to be significant during the tests. However, an overall scaling of 3:5:10 seemed to exist among the deformation of the three scaled specimens investigated, at least before perforation takes place. In other words, the deformations of the three scaled specimens had a very similar behavior. It seemed to be possible to scale the testing results from small specimens to large specimens, at least for the specimen sizes and strain rates used in the study. More investigations are recommended for larger specimens and post-perforation process. In terms of characterizing the properties of the composite materials, a structural stiffness was identified based on the out-of-plane pressure and associated out-of-plane deformation. Again, there seemed to exist similar proportion among the three specimens when considering experimental variations in the tests.

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INTRODUCTION

Owing to their high stiffness and high strength with low density, fiber-reinforced polymer-matrix composite materials are excellent candidate materials for high-performance structures subjected to dynamic loadings. In developing composite structures, many analyses and experiments must be performed. Although analyses can provide basic understanding of the performance of composite structures under investigation, they need to be validated by experiments. This is especially important for the development of composite structures as they involve many non-conventional properties, such as anisotropy, inhomogeneity, strain rate effect, etc.. Experimental validation may be divided into several levels from simple geometry to small component, and to prototype structure. Quite some studies on scaling effects have been available in the literature, e.g. Ref. [1-7]. It seems the elastic performance of larger composite specimens with simple geometry under static loading and low-velocity impact can be relatively easily predicted from their smaller counterparts.

The motivation behind the current study is to identify the feasibility of predicting the behavior of prototype composite structures in the real-world operations based on the results obtained from laboratory coupon tests. If a relation or even a correlation exists between the prototype and the coupon counterparts, it will significantly ease the effort of composite structure design. However, issues concerning size scaling and loading complexity between coupon specimens and prototype structures must be carefully addressed. This study focuses on characterizing the scaling effect, if there is any, on the behavior of composites under high-pressure loading. No geometrical parameter, both macroscopic and microscopic, is considered. That is, only simple geometry, such as plate, is of interest in the investigation.

SCALING OF SPECIEMNS AND PRESSURES

A glass woven fabric and an epoxy matrix were chosen for this study due to their flexibility in making composite materials with various thicknesses and dimensions for scaling study. The glass fabric was of orthogonal plain weave and the widths of both warp and fill tows were 9.5mm (0.375”). Hence, there was no microscopic scaling due to the use of the fabric, and hence the fixed tow size, for various specimen sizes. An epoxy matrix was chosen based on its suitability for VARTM (vacuum assisted resin transfer molding) manufacturing process. Accordingly, a large range of specimen sizes could be prepared.

Based on Buckingham’s theory, a linear scaling was required for specimen dimensions. Having considered the availability of composite material and the capability of testing facility, a dimensional scaling ratio of 3:5:10 was determined for the current investigation. Since the composite plates were made of plain-weave glass fabrics and an epoxy matrix, their thicknesses should be scaled similarly to that of dimensional scaling ratio of 3:5:10. Accordingly, composite plates consisting of three, five and ten layers of fabrics were determined for the scaling investigation. The in-plane dimensions of the specimens were also chosen to be 75mm, 125mm and 250mm, following the scaling ratio of 3:5:10.

The specimen dimensions and thicknesses are summarized in Table I. It should be pointed out that the true scaling ratio for the thicknesses from manufacturing is not exactly the same as that based on the layer number. Besides, there was no scaling in the fiber microstructure, including fiber diameter, tow size and cell size, because all composite materials were made of identical glass fabrics.

Table I: SCALING PARAMETERS.

Scaling Factor	(3)	(5)	(10)
Specimen Diameter (mm)	75	125	250
Specimen Thickness (layer number / mm) Scaling Factor	3 / 2.01 (3)	5 / 3.12 (4.66)	10 / 6.07 (9.06)
Blast Tube Diameter (mm)	3.75	6.25	12.5
Blast Duration (ms) Scaling Factory	6.3 (3)	11.7 (5.57)	23.3 (11.10)

In producing high-pressure waves, the radii of the blast tubes should also follow the same ratio as the designated dimensional scaling ratio. Besides, all three cases should have identical pressure peak but scaled pressure durations in the ratio of 3:5:10. However, the scaling ratio of loading durations was not exactly the same as designated due to the complexity involved in adjusting the testing facility. Figure 1 shows the three pressure histories based on a one-dimensional computational fluid dynamic (CFD) simulation for the high-pressure wave generator, the so-call laboratory blast simulator (LBS), shown in Figure 2. All three curves have similar peak pressure but scaled durations in a ratio of 3.00:5.57:11.10.

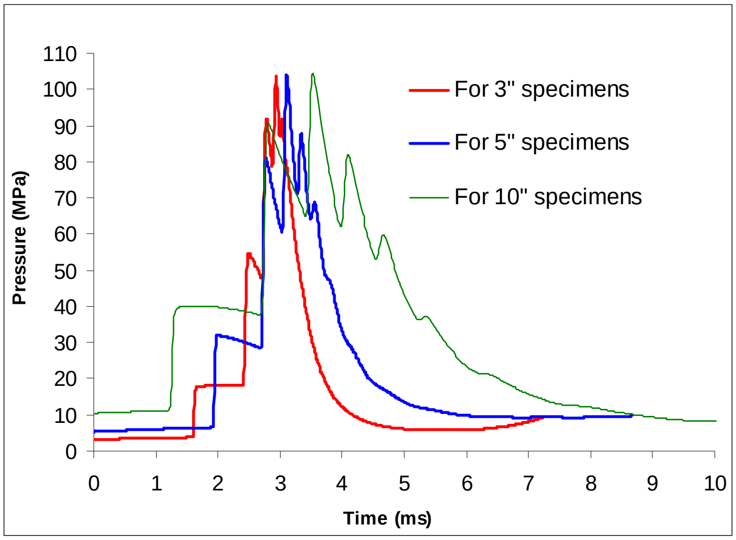


Figure 1 – Scaled pressure waves based on CFD analysis.

EXPERIMETNAL METHODS

Laboratory Blast Simulator (LBS)

For high pressure testing, the Laboratory Blast Simulator (LBS) [8,9] was used. As shown in Figure 2, the LBS is based on a piston-assisted shock tube due to its capability of producing pressure waves with a high pressure of 210 MPa, a high temperature around 1,000 ^{o}C and a high speed about 5 Mach. In order to achieve a blunt wave front, i.e. a shock wave, as those occurred in real blasts, a second set of diaphragm was installed right before the blast tube to convert the 80 mm-diameter pressure waves generated in the shock tube into smaller pressure waves, such as 3.75 mm-diameter, 6.25 mm-diameter and 12.5 mm-diameter used for the scaling studies.

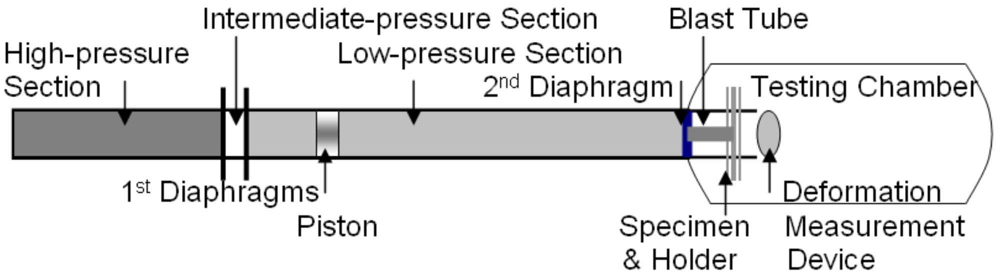
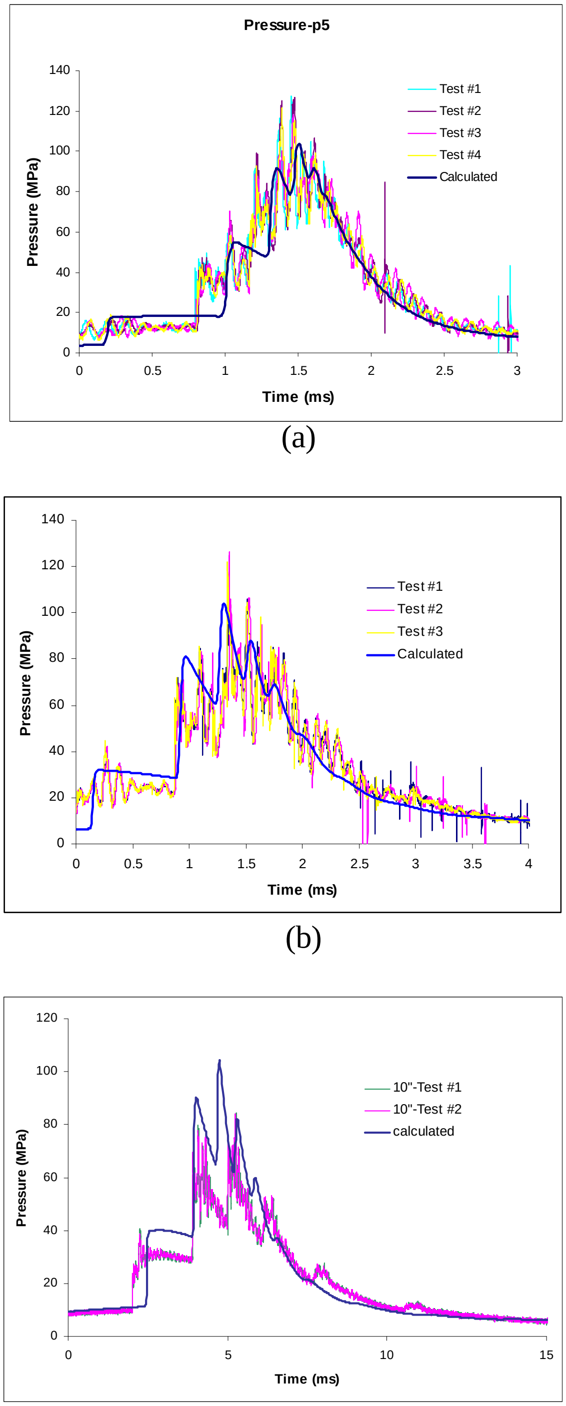


Figure 2 - Laboratory Blast Simulator (LBS).

In preparing the shock wave for high-pressure testing, a one-dimensional computational fluid dynamic (CFD) program was used for identifying the input parameters, i.e. high pressure, intermediate pressure, low pressure and piston mass. Figure 1 shows the calculated pressure histories for all three scales while Figures 3(a), 3(b) and 3(c) show the comparisons between calculated and measured pressure histories at the end of the shock tube. The discrepancy between the calculated and the measured seemed to increase moderately as the blast tube increases from 3.75mm to 6.25mm and to 12.5mm for scaling factor of 3, 5 and 10, respectively. It was believed that the discrepancy was caused by the negligence of friction and viscosity in the calculations. Besides, the measurements were performed at the end of low-pressure chamber, i.e. right before the second diaphragm. Limited pressure measurements at the end of the blast tube, i.e. right before the specimen, were also performed. However, pressure sensors were easily damaged due to the high pressure.

Deformation Measurement Techniques

Measuring material response was as important as measuring loading pressure. Both electrical resistant strain rosettes and projection moire were used in this study. The strain rosettes had three arms arranged in 0-, 45- and 90-degree directions. They were mounted with their apex close to the center of the specimen with the 0-degree and 90-degree legs aligned along either fill or warp directions of the glass fabrics. Besides strain history, strain rate could also be identified from the measurements.



(a)

(b)

(c)

Figure 3 – Comparison of pressure histories between calculated and measured for (a) scaling 3, (b) scaling 5 and (c) scaling 10 cases.

A strain rosette was only able to measure strains at a point. A whole-field measurement should prove to be more informative. Among the optical methods, projection moire was found to be able to record the whole-field, out-of-plane deformation of composite materials subjected low-velocity drop-weight impacts [10]. It was implemented in this study for measuring whole-filed, out-of-plane deformation of composite plates loaded with high-pressure waves. Figure 4 shows a schematic of the setup of the projection moire. A light source projects a grating approximately 4 lines/cm on the back surface (free of loading) of specimen. The grating lines were distorted due to specimen deformation caused by the pressure wave. The distorted images were then recorded by a high-speed camera with a frame rate of 20 frames per millisecond. Roughly fifteen frames of deformed specimens were obtained for deformation analysis. The maximum deformation can then be found for further analysis.

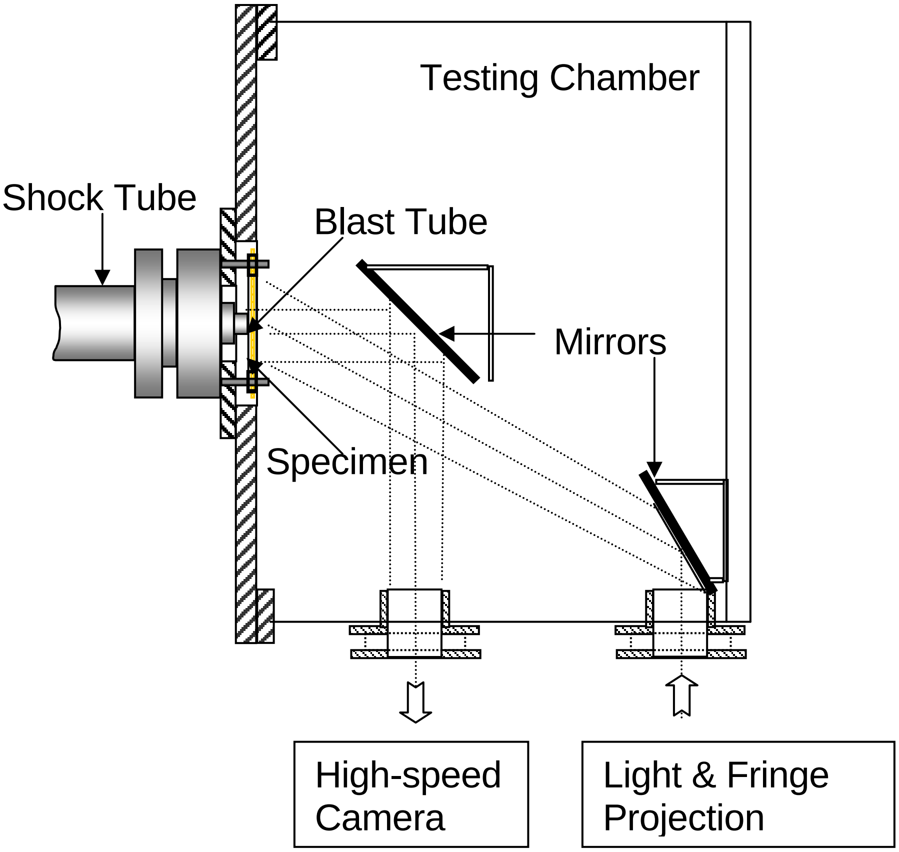


Figure 4 – Setup for projection moire.

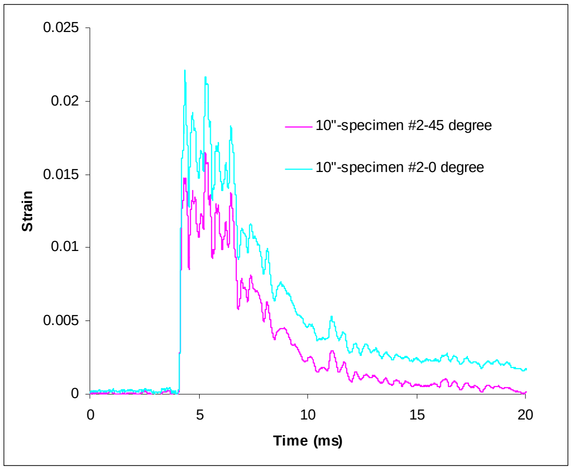
TESTING RESULTS

Strain and Deformation

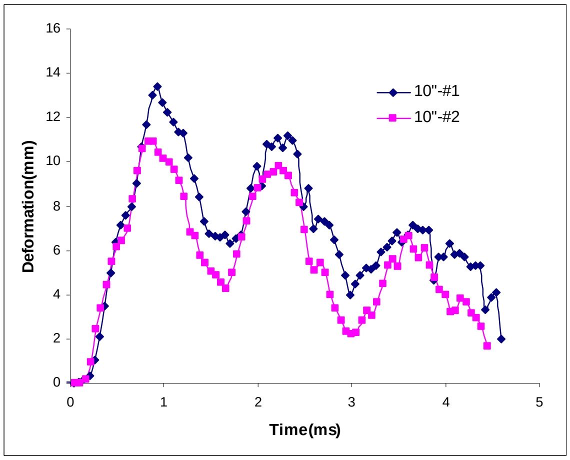
Figure 5(a) shows the strain histories (based on electrical resistance strain rosette attached close to the center of 10-layer specimens) while Figure 5(b) shows the deformation histories (based on projection moiré) at the center of 10-layer specimens. The deformation results seem to be more consistent among different tests than the stain results. This may be due to the fact that strain gage is of a point technique and the associated results can be strongly affected by the local fiber structure while the projection moiré is of a global technique and the associated results are less sensitive to the local fluctuation. Both results seem to also reveal strong vibration and wave propagation during the high-pressure loading.

Figure 5(c) presents strain and deformation histories on the same diagram for comparison for a 10-layer specimen. Justifications were made in the drawing to enhance the qualitative comparison. It is interesting to see that the similarity of trend between strain history and deformation history for the 10-layer specimen.

The comparison among the results seems to also indicate the strong effect of the wave front. A shock wave front in the 10-layer specimens (250mm in diameter), produces steep strain increase while a gradually increasing pressure wave front yields mild strain increase in the beginning of strain history. The strain rates for all three cases investigated can also be found from the strain histories. They are 230/s, 210/s and 180/s for 3-layer, 5-layer and 10-layer specimens, respectively. They are of medium strain ranges even the pressure wave is as high as 105 MPa.



(a)



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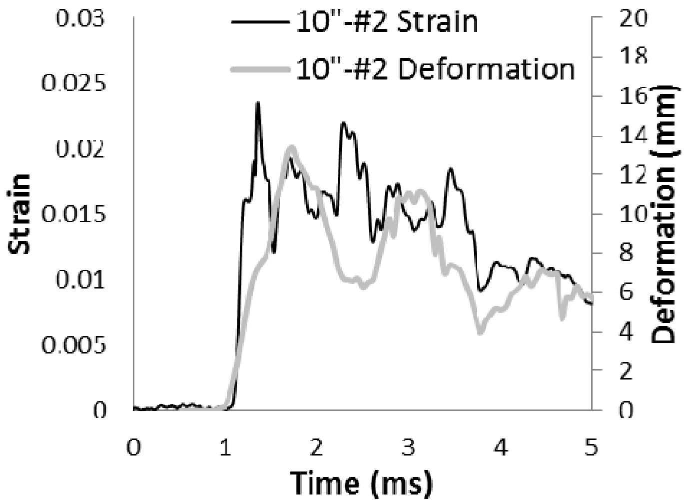

(c)

Figure 5 – (a) Strain histories based on strain gage, (b) deformation histories based on projection moire and (c) comparison between strain and deformation histories.

Deformation Scaling

The deformation histories of the three cases, 3-layer, 5-layer and 10-layer, are presented together in Figure 6(a). The scaled deformation histories, after being multiplied by 10/3 for the 3-layer case and 10/5 for the 5-layer case, are presented in Figure 6(b). There is some similarity among the three cases when considering the experimental variations including wave propagation and vibration effects.

Figure 6(c) gives the comparison of the scaled strain histories. Although the three cases are not completely random, they are not as much in agreement as the deformation results. The argument used earlier that strain results are more prone to the local effect as opposed to the deformation results may be used in the understanding of the larger discrepancy among the strain histories.

Pressure and Deformation Relation

Figures 7 show the relations between pressure history and deformation history for all three scaling cases. There is a strong correlation between the two histories especially in the beginning stage up to the peak pressure. A correlation factor, which may be considered as pressurizing stiffness, can be identified. They are 323 kN/m, 554kN/m and 993 kN/m for 3-layer, 5-layer and 10-layer cases, respectively. The scaling ratio of them may be expressed as 3.00:5.14:9.22 which is not too far from the expected 3:5:10.

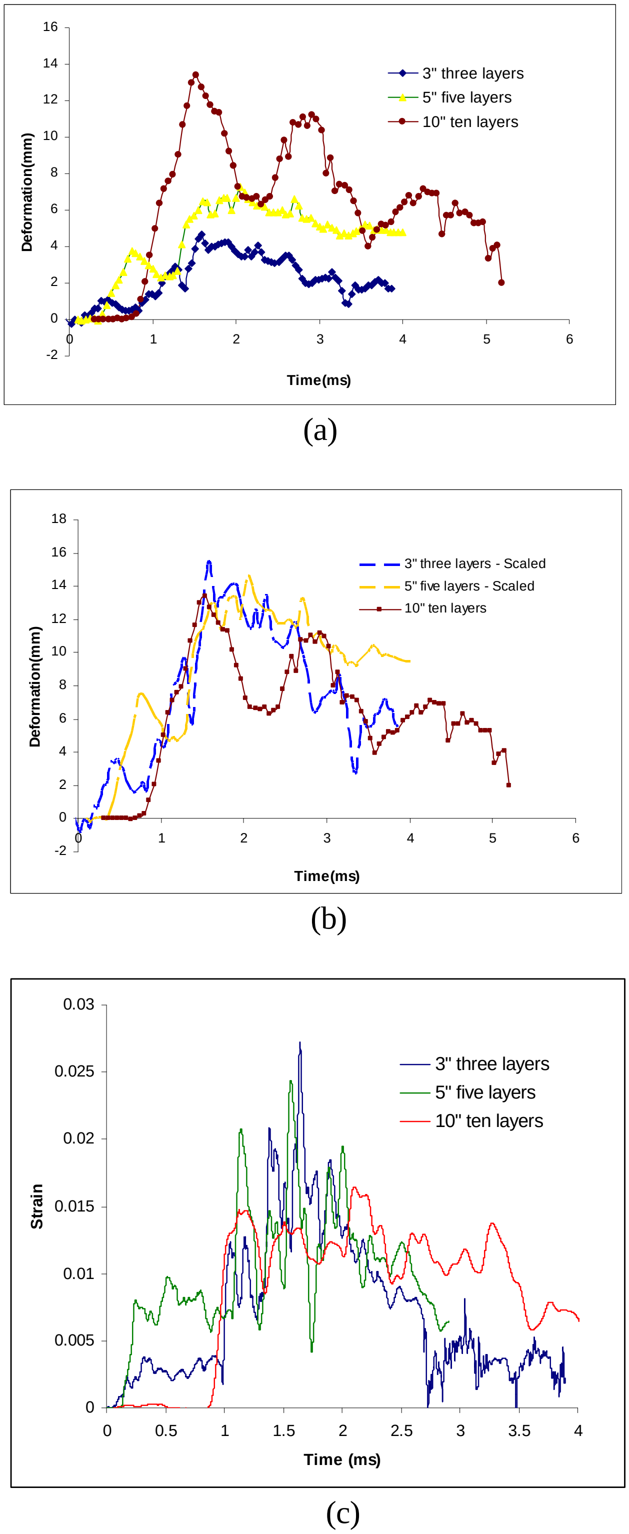

Figure 6 – (a) Deformation histories, (b) Scaled deformation histories and (c) scaled strain histories.

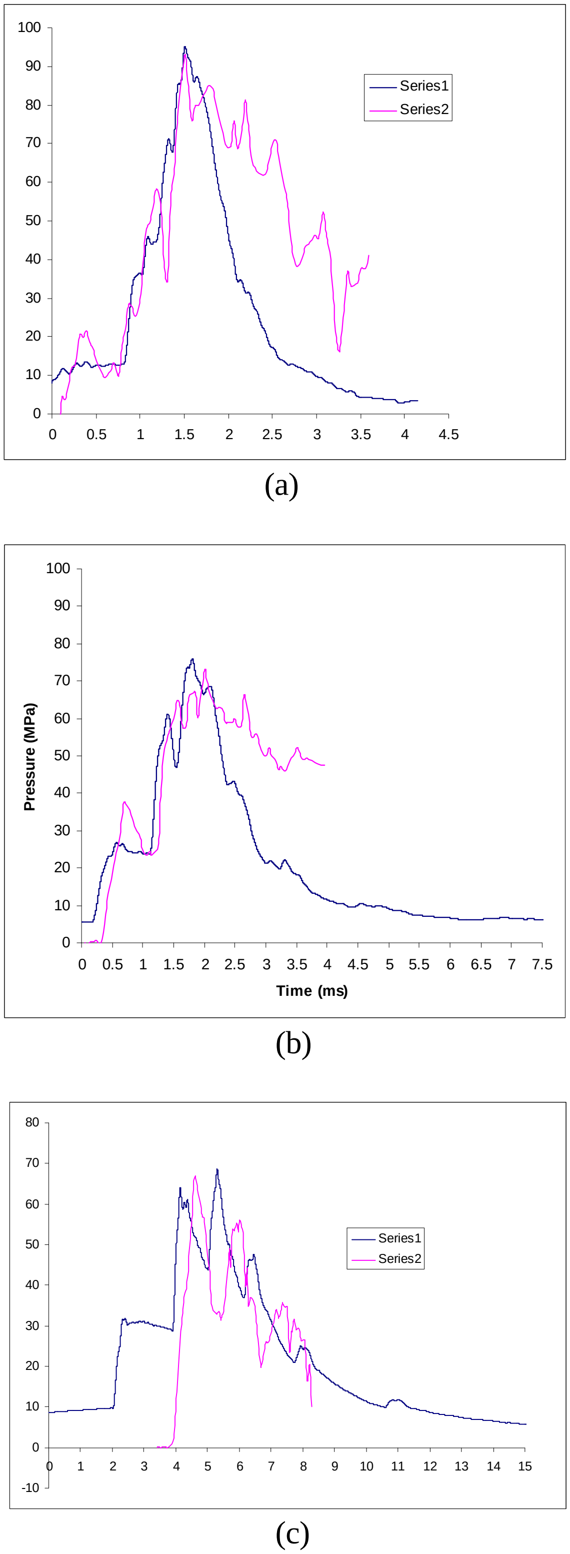

Figure 7 – Pressure (dark line) and deformation (light line) histories for (a) 3-layer, (b) 5-layer and (c) 10-layer specimens.

CONCLUSIONS

The high-pressure testing presented in this study is a unique technique for characterizing the stiffness of composite materials, so-called pressurizing stiffness. Three scaling cases in a ratio of 3:5:10 have been investigated. The strain rates of the cases studied were around 200/s. Considering experimental variations, the experimental results show clear similarity among the deformation histories of the three cases after they are scaled by the respective dimensional ratios, indicating that there is no significant effect due to scaling among the three scales studies. The stiffness scaling ratio of the three scaling cases is 3.00:5.14:9.22, similar to that of dimensional scaling ratio, further confirming the similarity among the three scaling cases.

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REFERENCES

1. Morton, J., “Scaling of impact-loaded carbon-fiber composites,” AIAA Journal, 26(8), 989-994, 1988.
2. Qian, Y. and Swanson, S.R., “An experimental study of scaling rules for impact damage in fiber composites,” J. Composite Materials, 24, 559-570, 1990.
3. Jackson, K.E., editor, Workshop on scaling effects in composite materials and structures, NASA Conference Publication 3271, 1993.
4. Swanson, S.R., “Scaling of impact damage in fiber composites from laboratory specimens to structures,” Composite Structures, 25, 249-255, 1993.
5. Greneche, R., Ravalard, Y. and Coutellier, D., “A method for crash tests on laminated composite scaled-down models,” Applied Composite Materials, 12, 355-379, 2005.
6. Sutherland, L.S. and Soares, C.G., “Scaling of impact on low fiber-volume glass-polyester laminates,” Composites: Part A, 38, 207-317, 2007.
7. McKown, S., Cantwell, W.J. and Jones, N., “Investigation of scaling effects in fiber-metal laminates,” J. Composite Materials, 42(9), 865-888, 2008.
8. Li, Q., Liu, D., Templeton, D.W. and Raju, B.B., “A Shock Tube-Based Impact Testing Facility,” Experimental Techniques, 31(4), 25-28, 2007.
9. Li, G., Li, Q., Liu, D., Raju, B.B. and Templeton, D.W., “Designing Composite Vehicles against Blast Attack,” SAE 2007 World Congress, Detroit, MI, April 16-19, 2007, Paper 2007-01-0137.
10. Gulker, B.G., Techniques for Enhancing Impact Testing, M.S. Thesis, Michigan State University, Dec. 2009.