CRASHWORTHINESS OF COMPOSITES – MATERIAL DYNAMIC PROPERTIES

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ABSTRACT

The rate sensitivity of energy absorption devices and composite structures has been investigated experimentally using a building block approach. In the current phase of the program, the effects of load/stroke rate on the crushing responses of laminated corrugated beams and the scaling effects associated with the rate sensitivity of tensile behavior of composite material systems are being studied experimentally. The experimental details and some results are presented in this paper.

1. INTRODUCTION

The crashworthiness of an airframe structure is measured in terms of its ability to maintain a survivable volume for the occupants and alleviate the loads transmitted to the occupants during potentially survivable accident scenarios per FAR requirements. The occupant loads are minimized by dissipating the kinetic energy using an energy absorption device, while the structural integrity is maintained by accounting for the dynamic loads during the sizing of structural elements. The performance of an airframe under crash loads is dictated primarily by its geometry, structural arrangements, materials and energy absorption devices used to dissipate the energy, and the interaction of these variables. The energy dissipation in metallic airframes is primarily due to plastic deformation while in composite airframes is due to synergistic sequence of failure mechanisms[1]. The limited number of dynamic and drop tests performed on fully composite fuselage structures have indicated differences in the crush patterns/failure modes[1], stiffness and other structural properties, compared with the traditional metallic fuselage structures. The test results are useful in the appraisal of the structural performance under crash loading, but do not reveal the various mechanisms that do and do not contribute to the overall performance of the structure. Further, the performances of individual components may be influenced by the overall structural assembly. To investigate the effectiveness of various components, numerical modeling would be more appropriate and less expensive. However, the predictions of the numerical models are dependent on the geometric definition of the structure, the material models, failure criteria, etc. The description of material behavior under dynamic loading is a key aspect of the numerical modeling of the crash scenarios.

In this study, a building block approach illustrated in Figure 1 has been embraced to study the rate effects on the behavior of composite airframe structures. To begin with, the rate effects (i.e., strain rate effects), will be characterized at the fundamental ply level, since for most numerical analysis, the material properties are specified at this level. The material testing at this level includes the characterization along the primary ply directions and off-axis specimen testing. The off-axis specimen tests are intended to simulate a combined stress state in the plies and not to characterize material property. This combined stress state will be used for benchmarking material models in the future. The next level of testing includes cases where *strain* and *strain rate* gradients exist, e.g., open-hole tension, which will serve as benchmark data for the material failure models. Moving up the building blocks, small components and assembly of components will be characterized under dynamic loading, culminating in characterization of scaled aircraft structures, which would be the most expensive. The understanding of rate effects at the ply level will help identify the contributions of geometric effects and material rate sensitivity to the observed rate effects in structural components and their assemblies subjected to dynamic loading.

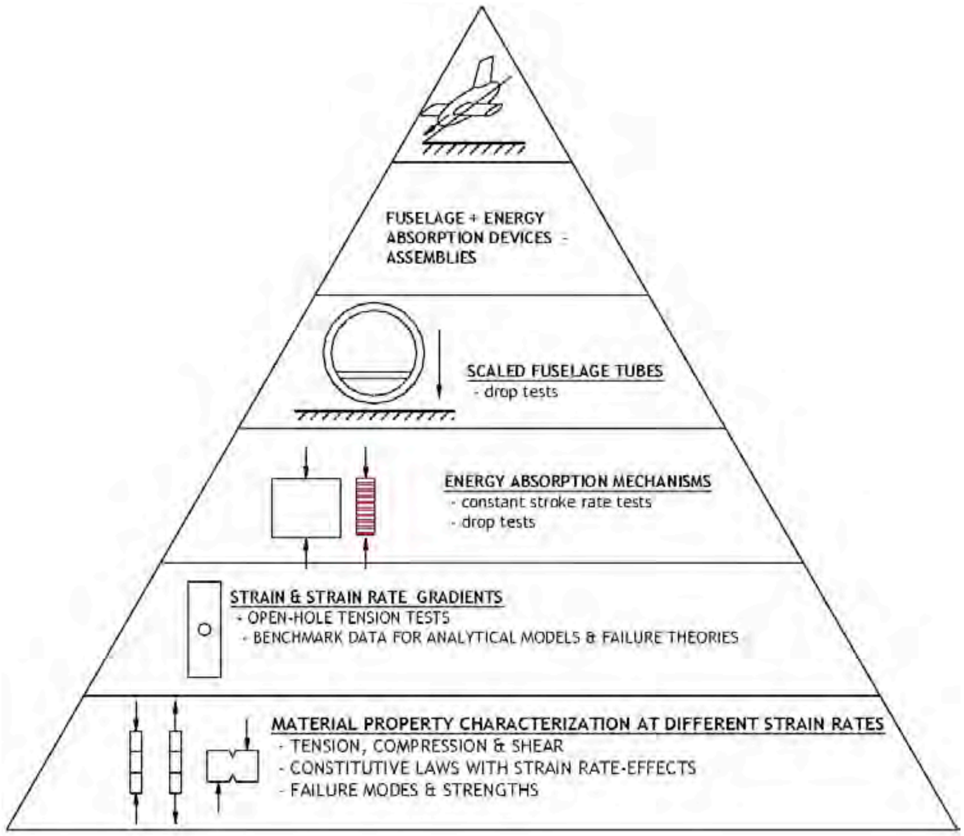

Figure 1. Building block approach for characterizing rate effects on composite airframe structures.

In the initial phase of this study, the effects of strain rate on the in-plane tension, compression and shear properties of selected composite material systems were characterized experimentally. A limited number of off-axis and open-hole tension tests were conducted to investigate the rate effects under combined stress states and in the presence of strain and strain rate gradients. A considerable effort was focused on researching the appropriate methods for high rate tests and the design, fabrication and assembly of apparatus for the experimental program. Subsequently, the rate effects on the mode-I interlaminar fracture toughness was studied using double cantilever beam specimens. While the in-plane strength properties exhibited an increasing trend, the fracture toughness reduced with the crack tip opening displacement rate. The variation of tensile strength and mode-I interlaminar fracture toughness for Newport NB321/7781 fiberglass material is shown in Figure 1. The in-plane tensile strength of the material was observed to increase with strain rate, with the amount of increase being insensitive to the off-axis angle of the fibers. However, the fracture toughness exhibited a decreasing trend with the crack tip opening rate. Further, the rate dependency of material strength and toughness was observed to be dependent on the material system and the specific property.

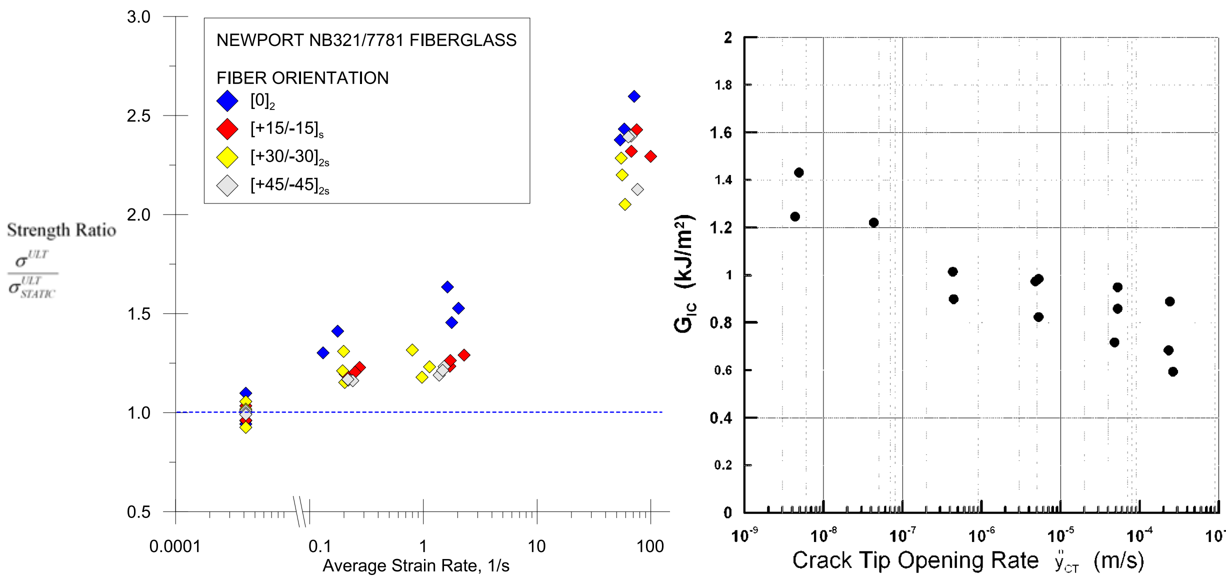

Figure 2. Effects of rate on the in-plane strength and interlaminar fracture toughness of Newport NB321/7781 fiberglass material

The material characterization conducted in the previous phases used sub-scale specimens to facilitate high speed tests on a load frame with reduced load capacity. In addition, the gage length was reduced to achieve higher strain rates for a given stroke rate. The specimen size scale has been reported to influence strength and failure mode of composite materials. Jackson et al[2] report that the strength and failure modes of AS4/3501 laminates tested under tension and flexure were dependent on specimen size and stacking sequence. Carillo and Cantwell[3] investigated the scaling effects on the tensile properties of fiber-metal laminates. The tensile strength was observed to decrease with increase in size for 1D (thickness) and 3D (thickness and areal) scaling which was attributed to the severity of the edge delamination in larger specimens. An opposite effect was however observed for the 2D (areal) scaling which was also attributed to the edge delamination effects. The specimen sizes used in the previous phase of the ongoing program were subscale and thus the magnitude of observed rate effects could have been affected by the specimen scale. To utilize the rate sensitive strength data for simulation purposes, scaling issues have to be addressed.

Following the material characterization, per the building block approach, the rate sensitivity of energy absorption devices has been addressed. The energy absorption behavior of corrugated/sine wave beams and tubes have been widely reported in literature[5-9]. Due to their inherent stability, and ease of fabrication, corrugated beams were chosen for the study. The objective of the experimental program was to study the rate sensitivity of corrugated beams fabricated using material systems with known rate sensitivity.

In the ongoing phase of the program, (1) the effects of rate on the crush response of laminated corrugated beams and (2) the specimen scaling effects on the observed rate sensitivity are being investigated experimentally. The details of the experiments and some results are summarized in this paper.

2. EXPERIMENTAL DETAILS

2.1 Crush Behavior of corrugated beams

2.1.1 Material System and Specimen details

The corrugated laminates were fabricated using Newport NB321/7781 E-glass fabric prepreg and Toray T700G-12K-50C/3900-2 Plain Weave Carbon Fabric. Stacking sequences of $[0]_n$ and $[\pm 45]_n$, where n=4,8 and 12 have been used. The corrugated specimen geometry is illustrated in

Figure 2. The half wave geometry for the 8 ply and 12 ply laminates was used to limit the initiation and crush loads to within the machine capability. Corrugated laminates were fabricated using a closed mold process where the prepreg assembly was cured between two matching molds made of aluminum shown in Figure 3. Three sets of molds were used to accommodate the different thicknesses of the laminates (4, 8 and 12 ply). The prepreg assemblies were cured in the matched molds in an oven. The match molds were encapsulated in a vacuum bag and subjected to vacuum pressure during the curing cycle. Corrugated laminates of length of 350mm were obtained using the molds, from which specimens with a height of 50.8mm were cut. One edge of the specimen was chamfered at 45° using a grinding wheel. The chamfering was done to initiate failure along this edge and reduce the peak loads under compression.

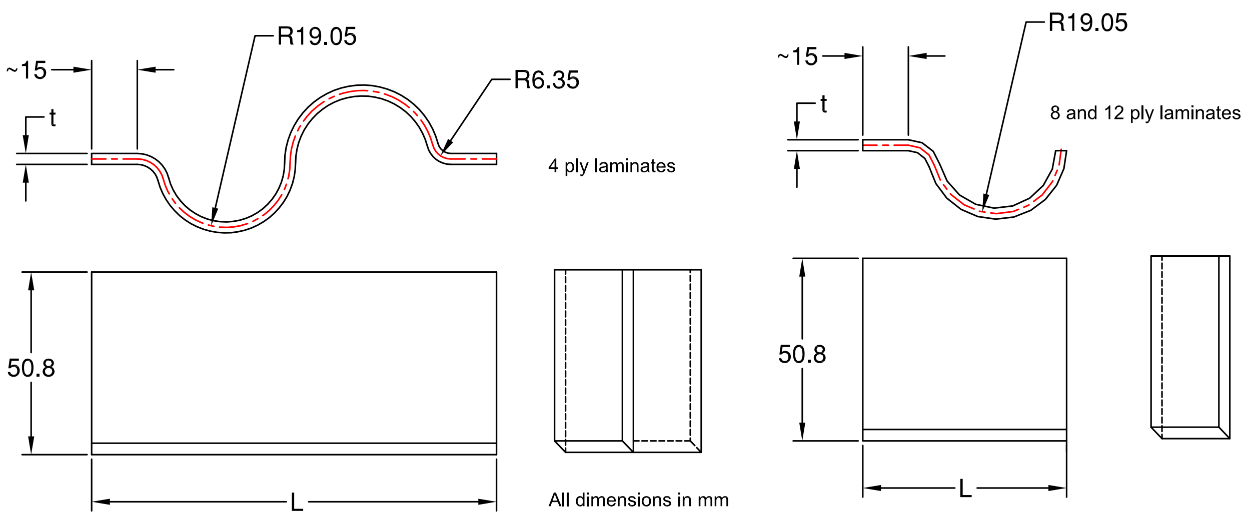

Figure 2. Test specimen geometry

Figure 3. Matching molds and cured corrugated spceimen[10].

2.1.2 *Crush Testing*[10]

The typical test arrangement used for the compression tests is illustrated in Figure 4. The test specimens were clamped in a test platen which was in-turn fastened to the actuator of the testing machine. Different sets of clamping plates were used to clamp corrugated beams of different thicknesses. The top edge of the corrugated beam specimen (chamfered edge) was crushed against another platen which was fastened to the load cell as shown in the figure.

The quasi-static tests were conducted using a 98kN capacity MTS electromechanical testing machine. The dynamic tests were conducted using a 24kN capacity MTS high rate servo hydraulic testing machine. The specimens were crushed to a nominal length of 25.4mm. The load measurement at quasi-static rates was done using a strain gage based load cell, while the dynamic load measurements were made using a piezoelectric load cell (PCB Piezotronics model M06). The piezoelectric load cell had a capacity of 44kN and was used with a PCB model 443B102 amplifier. The data acquisition rate used at quasi-static test speed was 2Hz, while at higher test speeds, data acquisition rates up to 1MHz (at 2540 m/s) were used. The actuator displacement and load were recorded during each test.

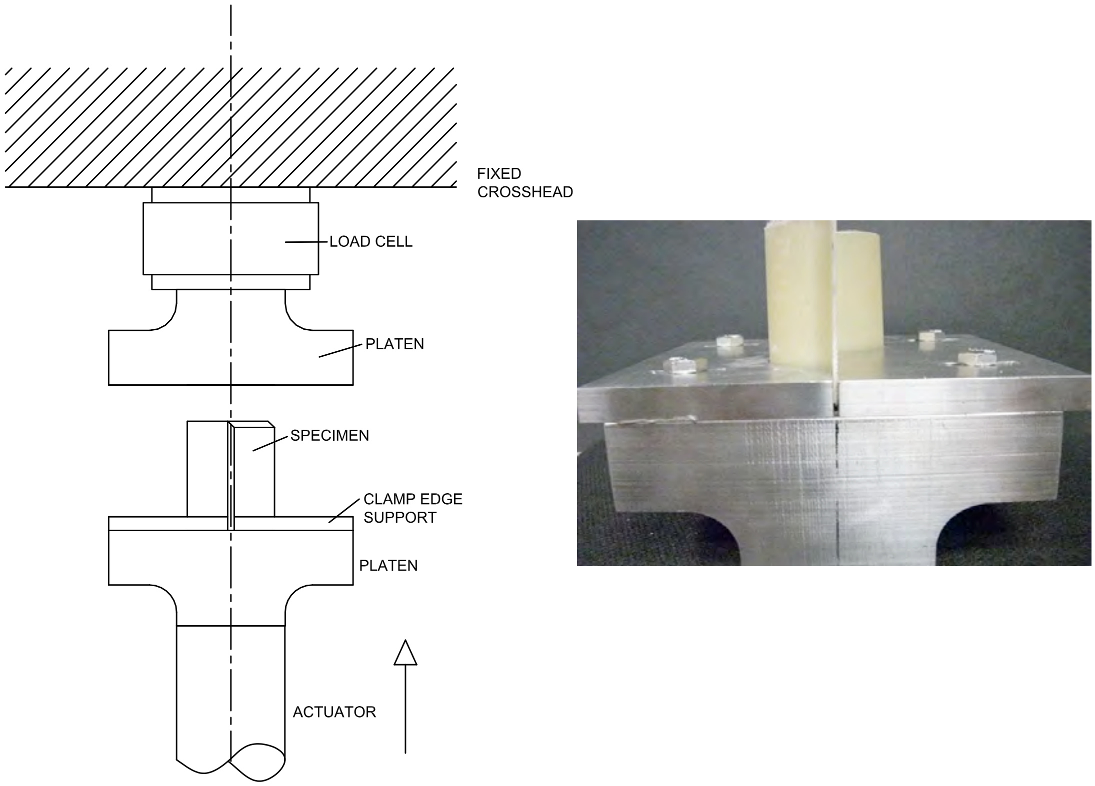

Figure 4. Schematic of test set-up and picture of specimen clamped in the fixture[10].

2.1.3 Test Matrix

The corrugated beam specimens were tested at test speeds ranging between 0.0254 to 2540mm/s. Three replicates of each specimen were tested at these speeds. The test specimens were inspected for failure modes post test. A limited number of specimens were bonded with strain gages to obtain a measure of the strain rates achieved ahead of the crush front.

2.2 Scaling Studies

In the current phase of the program, the specimen geometry scaling effects on the rate sensitivity of tensile properties has been investigated experimentally. In the current phase a limited experimental investigation on the scaling effects using two material systems – Newport NB321/7781 fiberglass/epoxy and Toray T800S/3900-2B unitape has been conducted. The 2D (width and gage length) scaling effects on the tensile behavior of $[0]_4$ and $[+45/-45]_S$ specimens has been studied at five stroke rates ranging from 0.02mm/s to 254mm/s. The stroke rate will be varied with specimen gage length to achieve constant strain rates (nominal) for the different gage lengths. The schematic of the specimen geometry is illustrated in Figure 5. The combinations of widths and gage lengths used are summarized in Table 1.

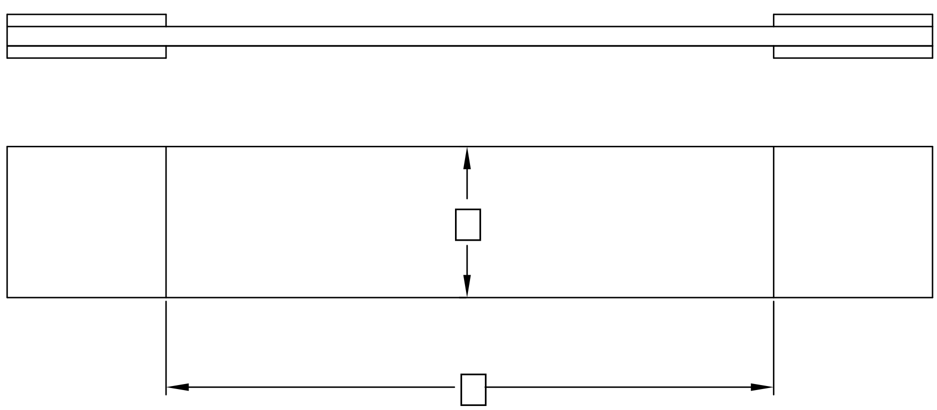

Figure 5. Tension specimen geometry for scaling studies

Table 1. Test matrix for scaling studies on tensile properties

MATERIAL	STACKING SEQUENCE	SCALE λ	L (mm)	W (mm)
NB321/7781 fiberglass,	$[0]_4$ $[+45/-45]_S$	1/4*	50.8	12.7
		1/2	101.6	25.4
		1	203.2	50.8
Toray T800S/3900-2B unitape	$[0]_4$	1/4*	50.8	12.7
		1/2	101.6	12.7
		1	203.2	12.7
	$[+45/-45]_S$	1/4*	50.8	12.7
		1/2	101.6	25.4
		1	203.2	25.4

*Specimen size used in phase-I

3. RESULTS & DISCUSSION

3.1 Corrugated beams

3.1.1 Load-Displacement Responses

The behavior of corrugated specimens has been characterized in terms of their load-displacement behavior and the specific energy absorption (SEA). The specific energy absorption is defined as the energy absorbed per unit crushed volume of the specimen. The typical load-displacement behavior of the $[0]_4$ fiberglass corrugated beams are illustrated in Figure 6. The plots compare the behavior at two different test speeds. At the quasi-static rate, a smooth transition from the initial load-displacement behavior to the sustained crushing load was observed. The use of chamfered edges facilitated in such a behavior by triggering failure. However, with increasing speed, the peak load was observed to increase, while the sustained crushing load was either higher or lower than the quasi-static case depending on the stacking sequence and laminate thickness. The peak loads (average of 3 replicates at each speed) recorded for the different material types and stacking sequences are summarized in figures 7 and 8. The rate sensitivity of peak loads were found to be dominant with increasing laminate thickness.

The average sustained crush loads however did not exhibit consistent trends relative to rate sensitivity . While the crush loads were more or less constant for the $[0]_N$ specimens, the thicker (N=8,12) $[\pm45]_N$ specimens (for both materials) exhibited slightly increasing crush loads with test speed as shown in figures 9 and 10. Thus, the SEA, which is the area under the load-displacement curve, will also exhibit the same rate dependency as the crush load.

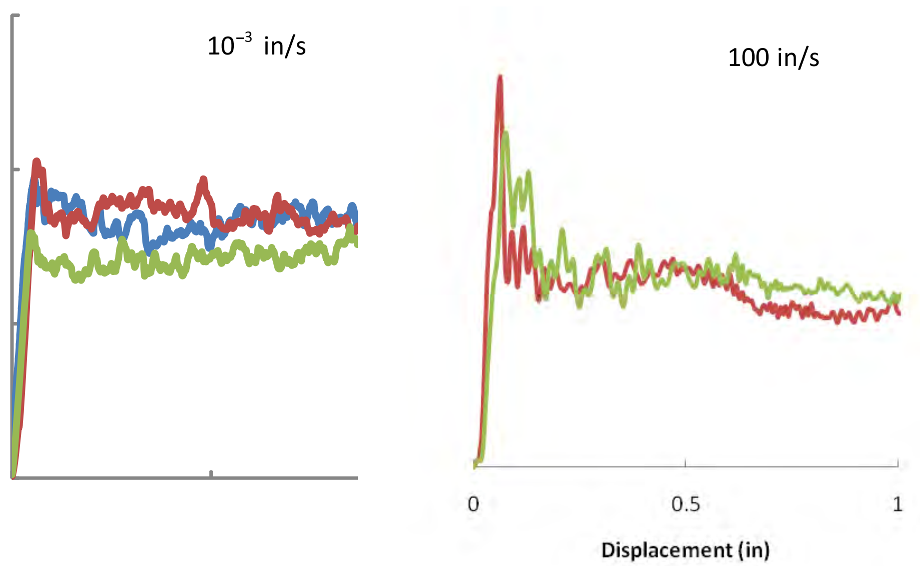

Figure 6. Comparison of load displacement curves for $[0]_4$ fiberglass beams at two test speeds.

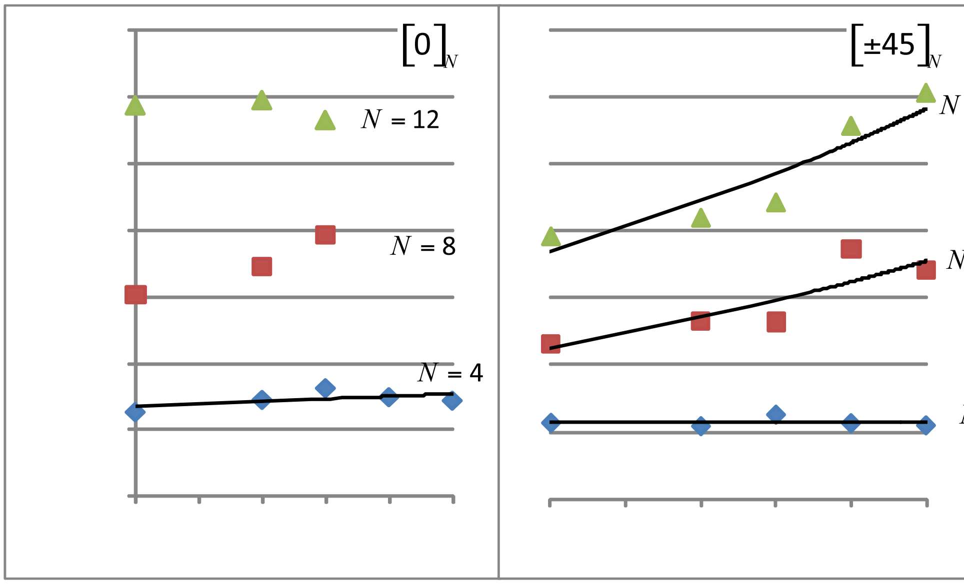

Figure 7. Effects of rate on the peak loads for $[0]_N$ and $[\pm45]_N$ fiberglass corrugated beams

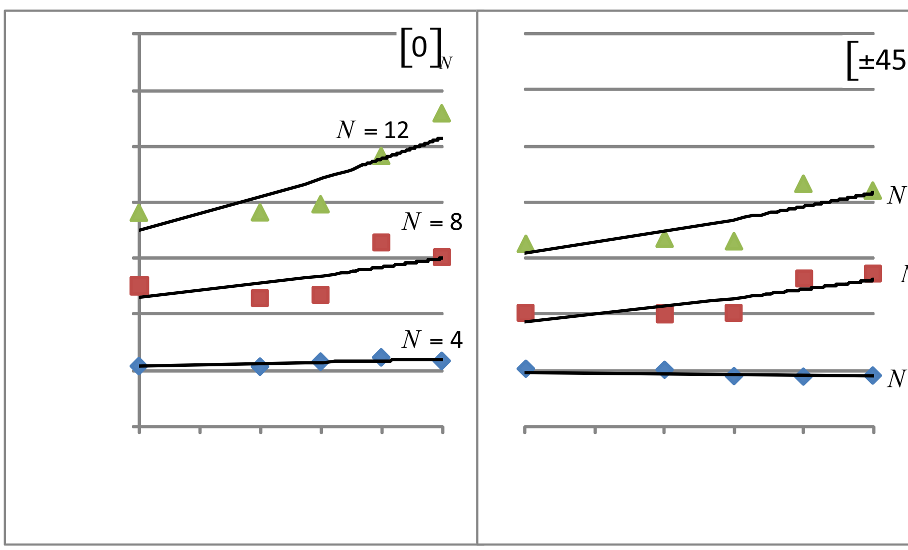

Figure 8. Effects of stroke rate on the peak loads for $[0]_N$ and $[\pm45]_N$ carbon fabric corrugated beams

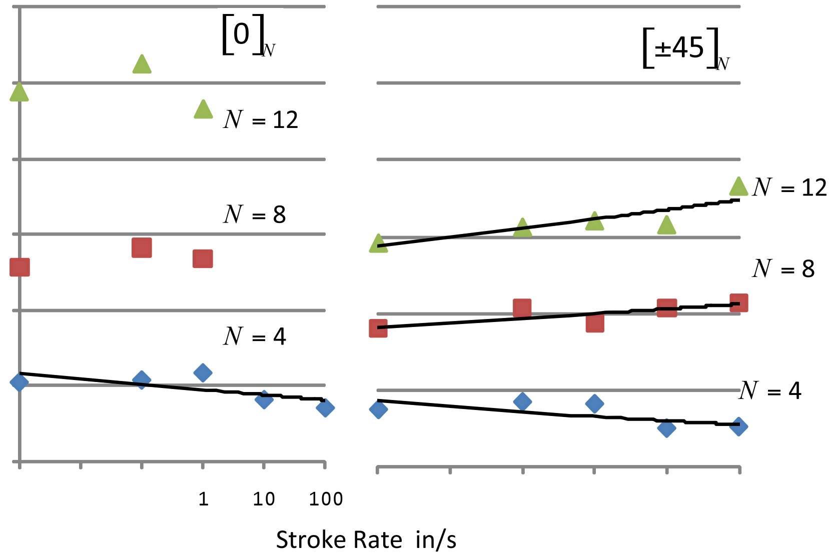

Figure 9. Effects of stroke rate on the crush loads for $[0]_N$ and $[\pm45]_N$ glass fabric corrugated beams

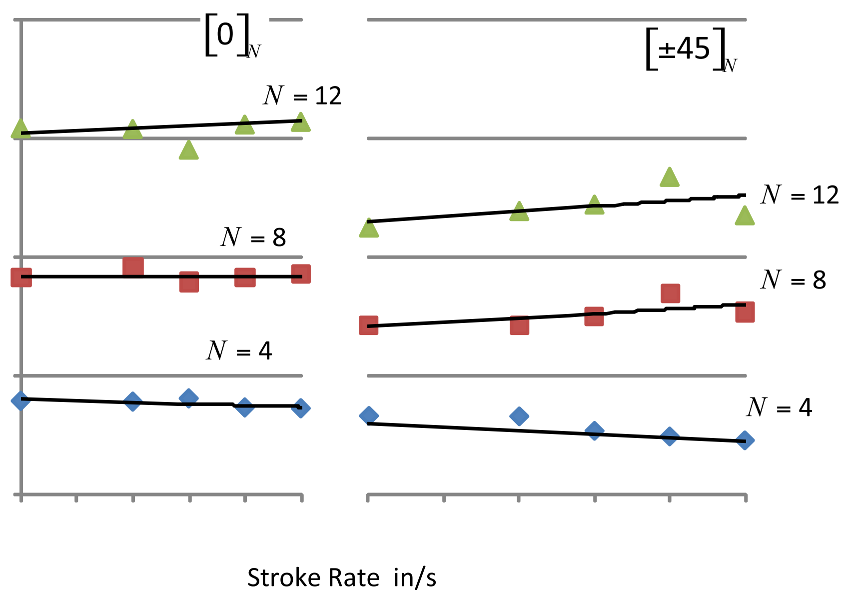

Figure 10. Effects of stroke rate on the crush loads for $[0]_N$ and $[\pm45]_N$ carbon fabric corrugated beams

3.1.2 Failure modes

The progressive failure of the corrugated beam was dominated by failure modes which included the delamination induced splaying mode, tearing of the plies to accommodate the splay formation and shear fractures resulting in spalling of the laminate as illustrated in figure 11. In addition wrinkling induced bending failures were also observed in $[\pm45]_4$ carbon specimens.

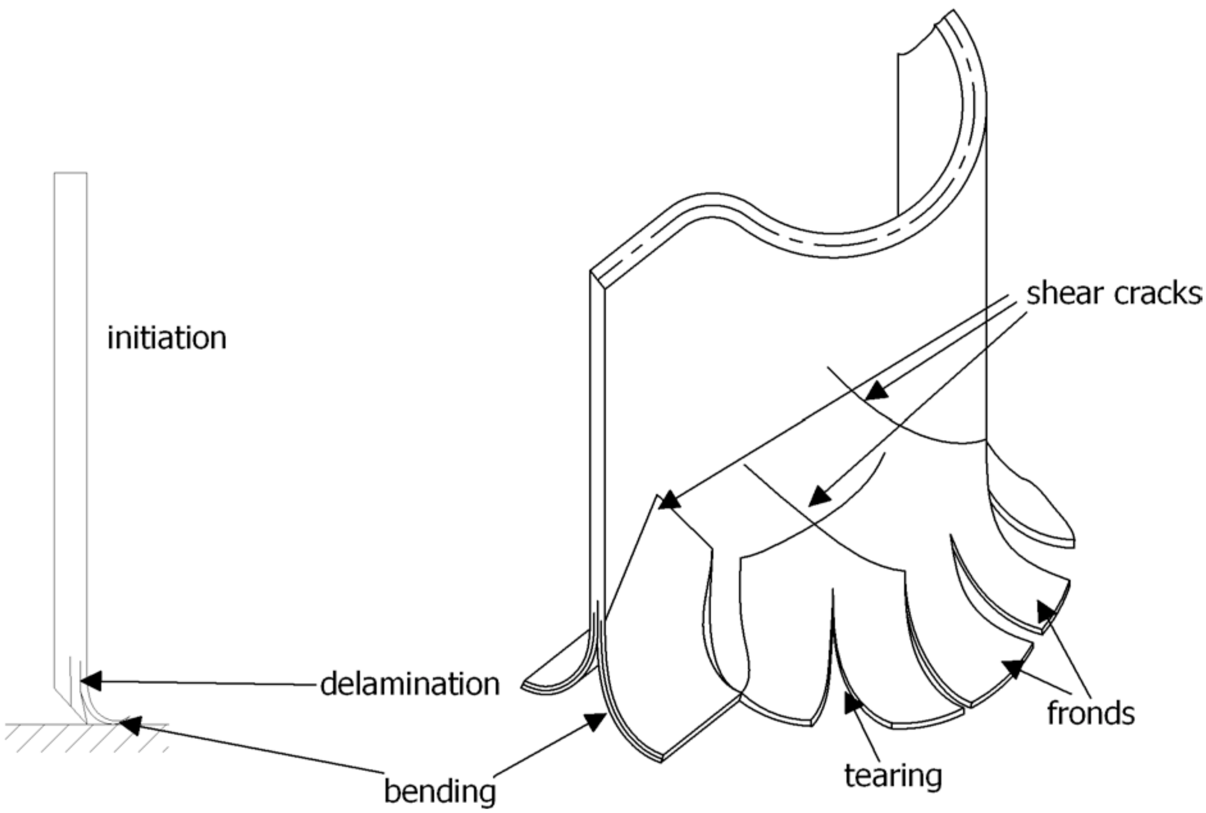

Figure 11. Observed failure modes in corrugated beams[10].

The failure modes observed in fiberglass and carbon beams tested at different speeds is shown in figures 12 and 13 respectively. The failure initiated in the form of delamination at the chamfered edge due to the eccentric loading of the chamfered region. The bending of the delaminated sub-laminates on either side of the beam required the tearing of the sub-laminates. The fronds formed from the splaying process further underwent bending failure facilitating additional energy absorption. This mode was prevalent in $[0]_N$ specimens of both materials. Thus, multiple failure modes are prevalent in corrugated beams, each of which could have different rate sensitivity. While the material strengths in tension and compression exhibit an increasing trend with strain rate, the fracture toughness exhibits an opposite trend with the crack tip opening rate as shown in Figure 2. Thus the rate sensitivities of the two modes could negate each other and thus make the crushing process insensitive to test speed. The crack initiation in the chamfered region is a function of the material strength, the rate sensitivity of which is reflected in the observed increase in peak loads with test speed. However, in the $[\pm 45]_N$ specimen, large shear cracks formed ahead of the crushing zone resulting in chipping of the laminates which manifested as large fluctuations in the crushing load.

Test Speed (in/s)	$[0]_{12}$ specimens	$[\pm45]_{12}$ specimens
0.001		
0.1		
1		
10		
100		

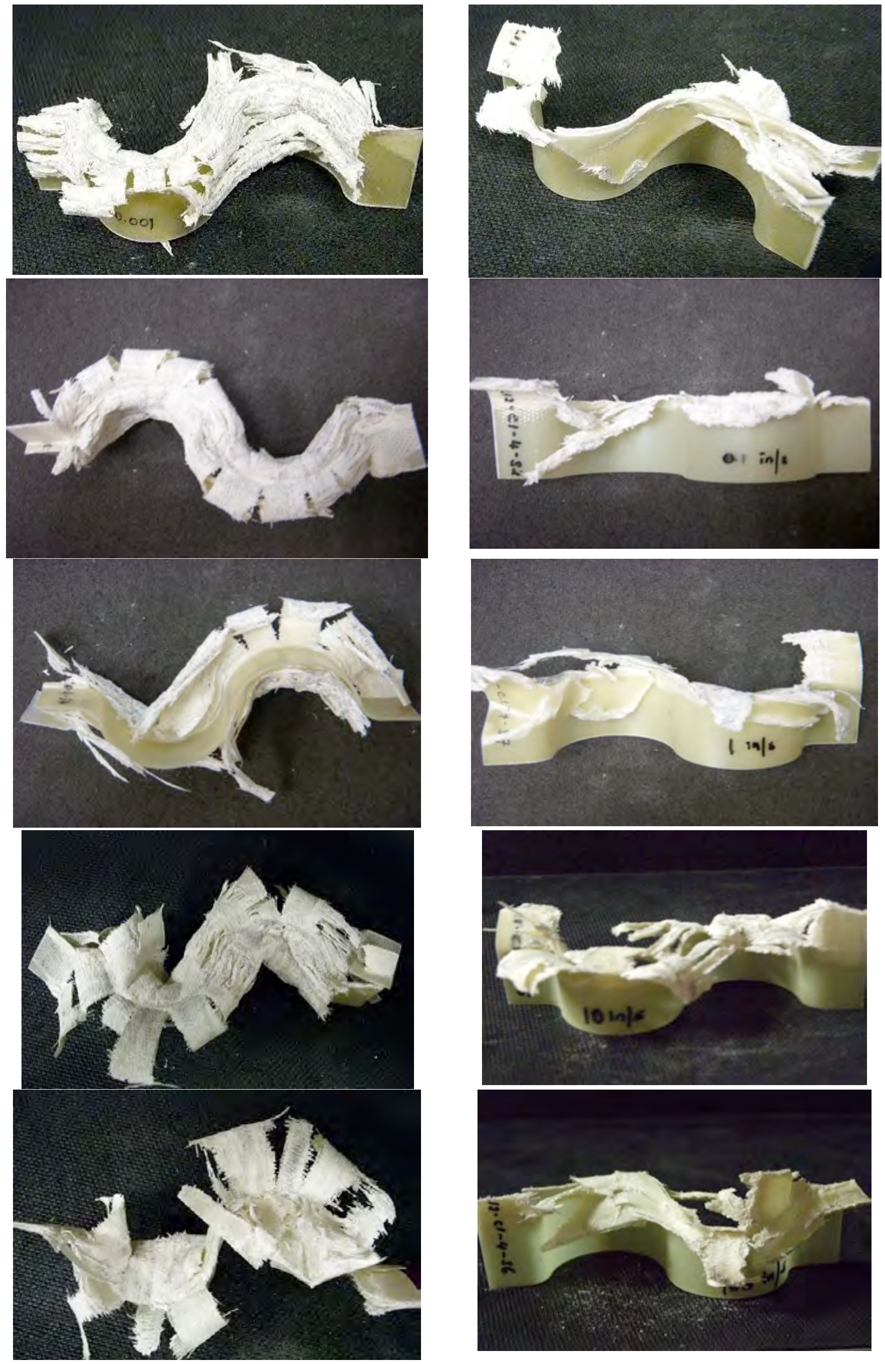

Figure 12. Failure modes in fiberglass specimens at different test speeds

Test Speed (in/s)	$[0]_{12}$ specimens	$[\pm 45]_{12}$ specimens
0.001		
0.1		
1		
10		
100		

Figure 13. Failure modes in carbon specimens at different test speeds

3.2 Scaling studies

The tensile strengths of Newport fiberglass $[0]_4$ and $[\pm45]_S$ specimens with different gage lengths tested at two stroke rates are shown in figure 14. Both laminate configurations exhibited a reduction in failure strength which is consistent with the observations reported in open-literature[2,3]. Due to the differences in the gage widths of the specimen, the strengths are plotted as a function of the gage volume. The test results for $[0]_4$ specimens indicate an increase in strength with increasing strain rate for all specimen sizes. However, no rate effects were evident for the $[\pm45]_4$ specimens. Additional tests at higher test speeds have been recently completed and data reduction is under progress.

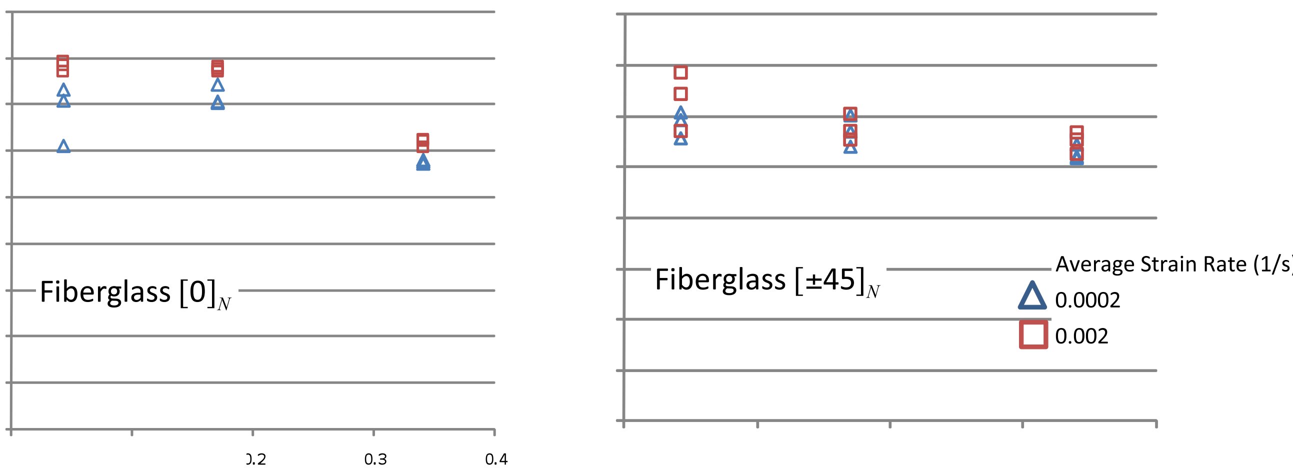

Figure 14. Geometric scaling effects on the tensile strength of $[0]_4$ and $[\pm45]_S$ fiberglass specimens

The tensile strengths of carbon unitape $[0]_4$ and $[+45/-45]_S$ specimens with different gage lengths tested at two stroke rates are shown in figure 15. While a slight reduction in strength was observed with increasing gage length for the $[0]_4$ specimens, no discernible trends were seen for $[+45/-45]_S$ specimens. In addition, at the two strain rates shown in the figure, the rate sensitivity was not evident. Additional tests at higher test speeds are under progress.

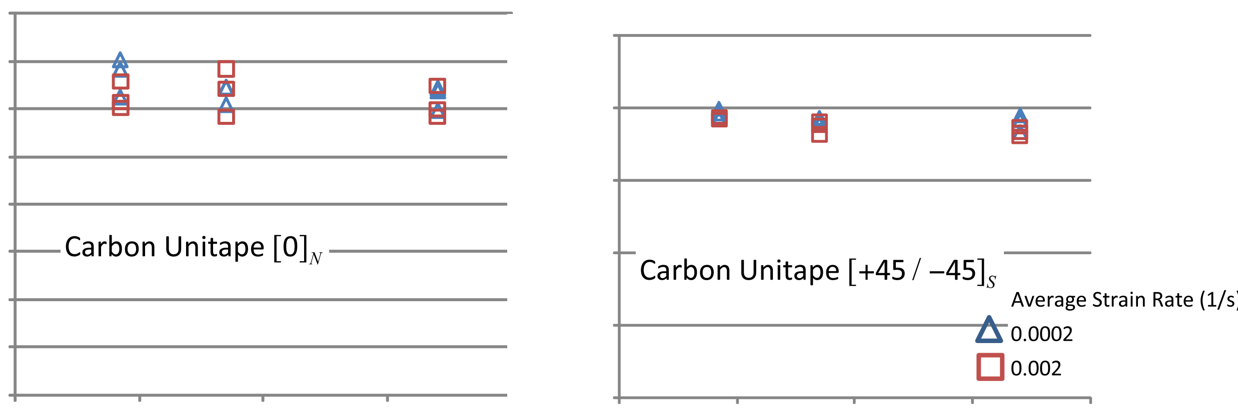

Figure 15. Geometric scaling effects on the tensile strength of $[0]_4$ and $[\pm45]_S$ carbon unitape specimens

4. CONCLUSIONS

The effects of test speed on the crushing behavior of laminated corrugated beams have been studied experimentally. Test results indicate that the peak load corresponding to the failure initiation and transition to the crushing region, increases with test speed while the sustained crushing load exhibited a marginal dependence (both increasing and decreasing) on test speed. Contrasting failure modes were observed in the corrugated beams, with the delamination and ply tearing induced splaying mode being dominant in the $[0]_4$ specimens while shear cracking was observed in $[\pm45]_4$ specimens. The limited test data on tensile coupons generated to date indicate the presence of geometric scaling effects on the test data, consistent with previous reports in open literature. The tensile strengths were observed to decrease with increasing gage length/gage volume.

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