ENERGY ABSORPTION OF CARBON FIBER NCF REINFORCED PLASTIC CHANNELS UNDER DYNAMIC AXIAL CRUSH LOADING

B. Harvey, M. Ghazimoradi, J. Imbert-Boyd, M. Worswick, J. Montesano*
University of Waterloo, 200 University Ave, Waterloo, Ontario, Canada, N2L 3G1
**Email Address: bgjharvey@uwaterloo.ca*

Abstract

Due to their high specific energy absorption characteristics, fibrous composite materials are increasingly being considered for use in vehicle energy absorbing structures. In this study, the energy absorption capabilities of carbon fiber reinforced plastic (CFRP) composite channels subjected to axial crush loading was experimentally investigated. The open cross-section channels were processed from 8 layers of carbon fiber non-crimp fabric (NCF) and a fast-curing epoxy resin using high pressure resin transfer moulding (HP-RTM). Components with two different stacking sequences, $[0/\pm45/90]_s$ and $[\pm45/0_2]_s$, were tested under dynamic loading conditions using a crash sled. A chamfer was machined on the crush end of all channels to encourage progressive failure. In dynamic loading, a fragmentation failure mode was dominant for both stacking sequences considered. The specific energy absorbed (SEA) by the CFRP channels was dependent on the stacking sequence, with the $[\pm45/0_2]_s$ stacking sequence absorbing 61% more energy.

Introduction

Fibrous composite materials have been considered in many automotive applications due to their high specific strength and low density when compared to traditional metallic alloys, as well as the ability to tailor their properties for specific applications. Composite components can be designed to have excellent specific energy absorption characteristics, which makes these materials ideal for consideration in primary energy absorbing structures in vehicles. Nevertheless, fibrous composite materials have not been integrated into the structures of high-volume production vehicles to date, which is due to high fabrication costs and long cycle times. The development of rapid curing resins and new manufacturing processes such as high pressure resin transfer moulding (HP-RTM) may enable the integration of fibrous composites into energy absorbing structures of mass produced vehicles.

Several investigations have been performed on characterizing the performance of composite energy absorbing structures, such as crush tubes. Hull [1] studied both carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic (GFRP) cylindrical crush tubes under axial crush loading conditions, and compared their failure to traditional metal components. Hamada *et al.* [2] also investigated the performance of CFRP cylindrical crush tubes with different stacking sequences and found that specimens with an alternating stacking sequence of $[\pm10_{11}]$ and $[\pm15_{11}]$ absorbed the most specific energy. Courteau *et al.* [3] also tested CFRP crush tubes with variations in tube geometry, considering both square and circular geometries. Many other researchers [4][5][6][7] have also investigated crush tubes as energy absorbers.

A less common investigation into composite energy absorbing structures involves open channels. Bolukbasi and Laananen [8] tested graphite/epoxy plain-weave fabric composite flat plates, 90-degree angle components, and channel shaped components to determine the effect of geometry on energy absorption. They found large differences in the specific energy absorption between the various geometries when stacking sequence was held constant. Feraboli *et al*. [9] completed a similar study, comparing tubes, channels, and corners under axial crush conditions, finding that small corner sections had the highest specific energy absorption. Grauers *et al.* [10] tested NCF sinusoidal channels resulting in an average specific energy absorbed of 73.9 kJ/kg. Several other geometries of open channel were also investigated by other researchers [11][12][13][14].

Many of the previous studies conducted axial crush tests under quasi-static rates; however, in crashworthiness applications the loading rate is much higher. Thus, some research has been performed on assessing the specific energy absorption behavior of composite structures under dynamic loading conditions. Wang *et al.* [15] tested CFRP crush tubes at a rate of 10.2 m/s using a drop tower. They found that most of the specimens tested absorbed more specific energy in quasi-static loading than in dynamic loading. Luo *et al.* [16] performed similar tests at a rate of 10.2 m/s on CFRP crush tubes using a drop tower, using a different material than Wang *et al.* Jackson *et al.* [17] performed tests on curved open channels at a rate of 8.5 m/s using a high rate testing machine. They found that the open channels absorbed less energy in dynamic loading than in quasi-static loading.

The current study aims to investigate the performance of open section CFRP hat shaped channels under dynamic axial crush loading. Channels with two different stacking sequences were considered to determine the effect on the specific energy absorption.

Material and Methodology

Material and Test Specimens

The reinforcement material used to manufacture the channels was PX35 UD300 (Zoltek Corp), which is a unidirectional non-crimp fabric comprising tows with 50k carbon fibers. The matrix material was a rapid curing epoxy resin, namely TRAC 06150 (Hexion Inc.). The channels consisted of 8 layers of the carbon fiber fabric in 2 different stacking-sequences, including $[\pm 45/0_2]_s$ and $[0/\pm 45/90]_s$.

Channels were fabricated using an HP-RTM process. After preforming the dry fabric layers, the resin was injected into the closed mold and allowed to cure for 5 minutes at 120°C. Additional details of the HP-RTM process setup can be found in [18].

The geometry of the open section hat channels is shown in Figures 1 and 2. All channels were cut to a total length of 495 mm to allow for a free crush length of 200 mm and were 2.6 mm thick. A 2.5 mm long 45° chamfer was machined into the top of each of the specimens to encourage progressive crushing. The trigger was manufactured using a 45° chamfer milling tool.

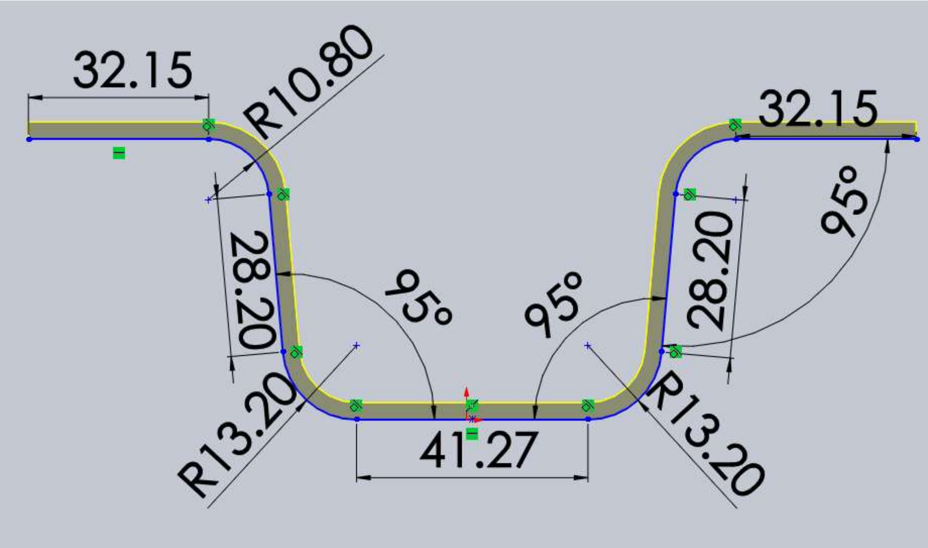

Figure 1: Composite Hat Channel Cross-sectional Dimensions

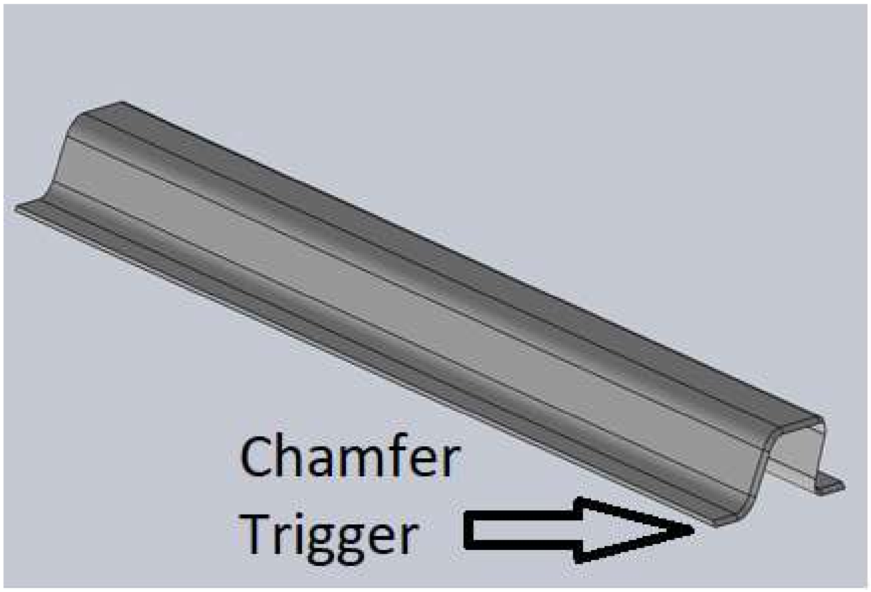

Figure 2: 3D Model of Composite Hat Channel

Experimental Setup

The dynamic axial crush tests were performed using a crash sled at the University of Waterloo (Figure 3). The impact mass and velocity of the sled were 858 kg and of 7.5 m/s, respectively. A load cell pack comprising 3 load cells was fixed to the reaction wall, which were used to measure the force of the impact. A custom steel boss secured to the load cell pack was used to clamp a 50 mm length of the channel at the base. A laser distance sensor was used to measure the displacement of the cart during the crush event. Load and displacement data was recorded using a DTS SLICE MICRO data acquisition system sampling at 10,000 Hz. The force data recorded by this system was unfiltered, however the displacement data was filtered using an SAE CFC60 filter.

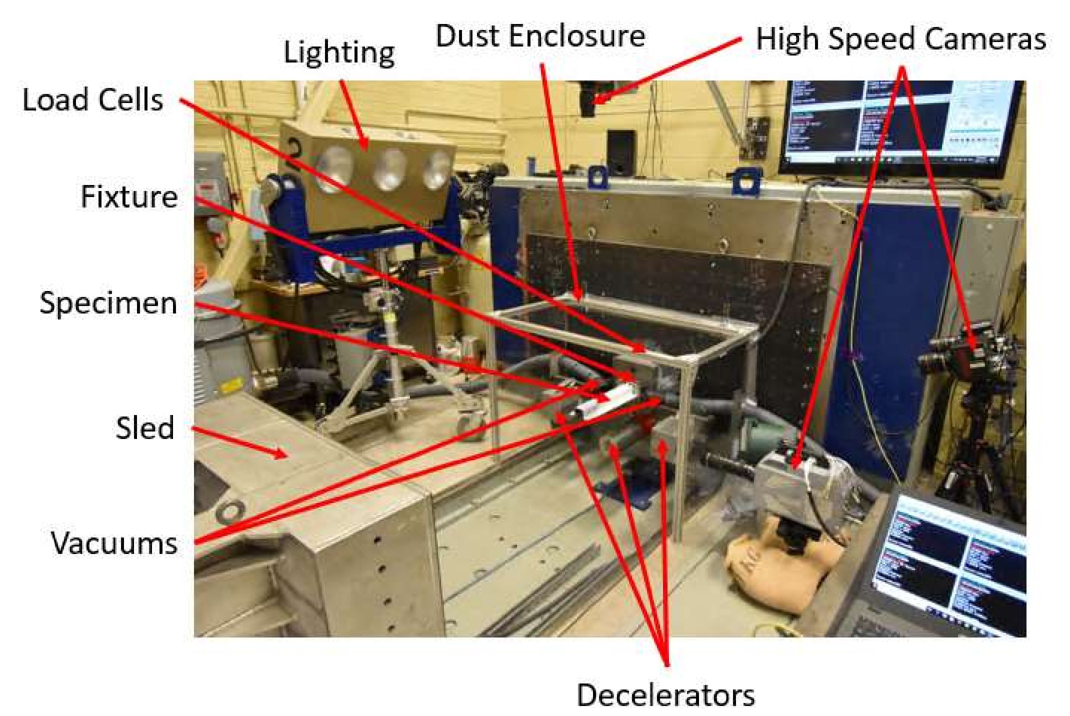

Figure 3: Composite Hat Channel Set up on the Crash Sled

Multiple high-speed cameras were used to capture crushing of the specimens during each test. A Photron SA4 camera was positioned above the specimen and captured images with a rate of 10,000 frames per second. Two additional Photron AX100 high-speed cameras were positioned to capture the component from the side with a rate of 10,000 frames per second. A Photron SAZ with a rate of 100,000 frames per second was used to capture magnified images of the crush trigger and monitor the crack propagation through the side of the part. The cameras and data acquisition systems were activated simultaneously by a laser triggered mounted under the sled on the rail system.

The specimens were allowed to freely crush for 200 mm after which the sled was decelerated using aluminum honeycomb. A plexi-glass enclosure was placed around the component to contain any fragments and carbon dust generated by the impact. Two vacuums were used to trap any floating carbon dust during and after the impact.

Results

The resultant force-displacement and energy-displacement graphs for six tested hat channels with the $[\pm 45/0_2]_s$ stacking sequence are shown in Figure 4, while a summary of the results is presented in Table 1. The average peak force and steady state crush force were 107.1±5.4 kN and 73.3±4.6 kN, respectively. The average absorbed energy, the integral of the force-displacement response, was 13.3±0.72 kJ with an average of 78.0±3.4 kJ/kg specific energy absorbed.

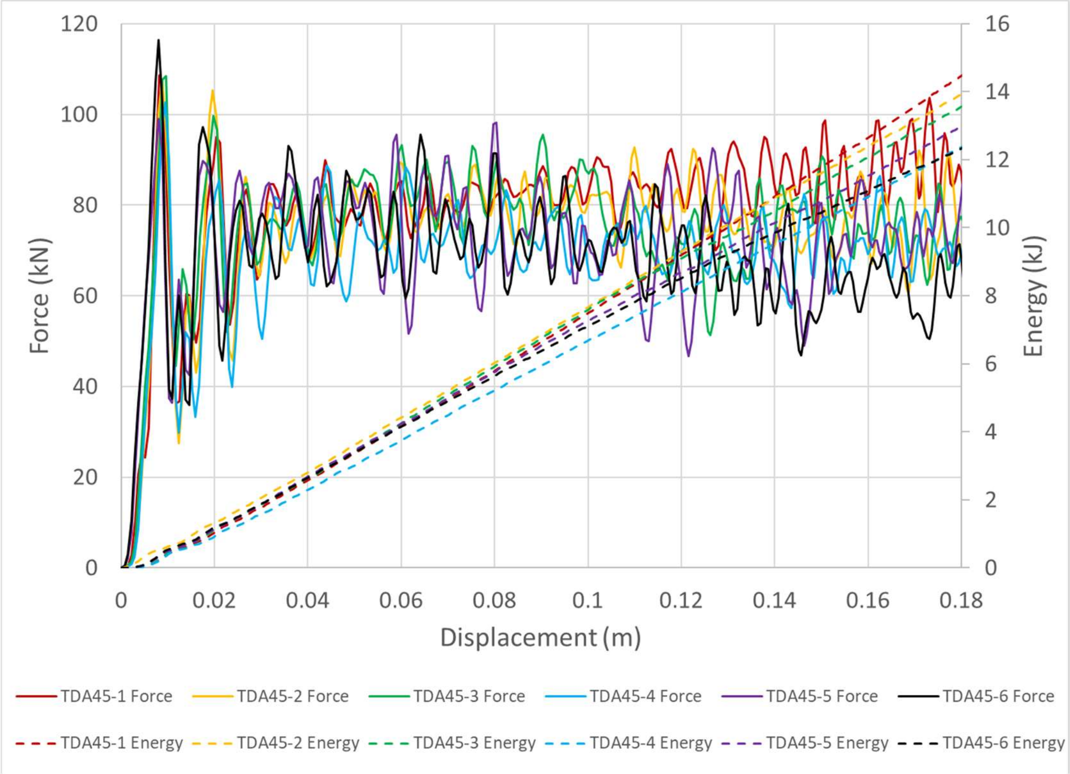

Figure 4: Dynamic Axial Crush Results for the Hat Channels with [±45/0_2]$_s$ Stacking Sequence

Table 1: Summary of Dynamic Axial Crush Results for [±45/0_2]$_s$ Hat Channels

Specimen Name	Channel Mass (g)	Peak Force (kN)	Steady State Force (kN)	Specific Energy Absorbed (kJ/kg)
TDA45-1	421.3	108.5	81.2	84.5
TDA45-2	416.2	107.6	75.9	82.1
TDA45-3	425.6	108.4	75.1	79.0
TDA45-4	423.7	102.7	68.9	72.8
TDA45-5	424.2	99.1	71.2	75.8
TDA45-6	414.6	116.3	67.7	74.0
Average	420.9	107.1	73.3	78.0

For the five tested hat channels with a $[0/\pm45/90]_s$ stacking sequence, the resultant force-displacement and energy displacement graphs are presented in Figure 5, with a summary of the results presented in Table 2. These hat channels exhibited a lower average peak force (82.5±9.0 kN) and steady state crush force (40.0±3.3 kN) when compared to the hat channels with the $[\pm45/0_2]_s$ stacking sequence (107.1±5.4 kN and 73.3±4.6 kN, respectively). As a result, 37.8% less energy was absorbed by hat channels with this stacking sequence, with an average energy absorbed of 8.5±0.7 kJ and an average specific energy absorbed of 48.5±4.1 kJ/kg.

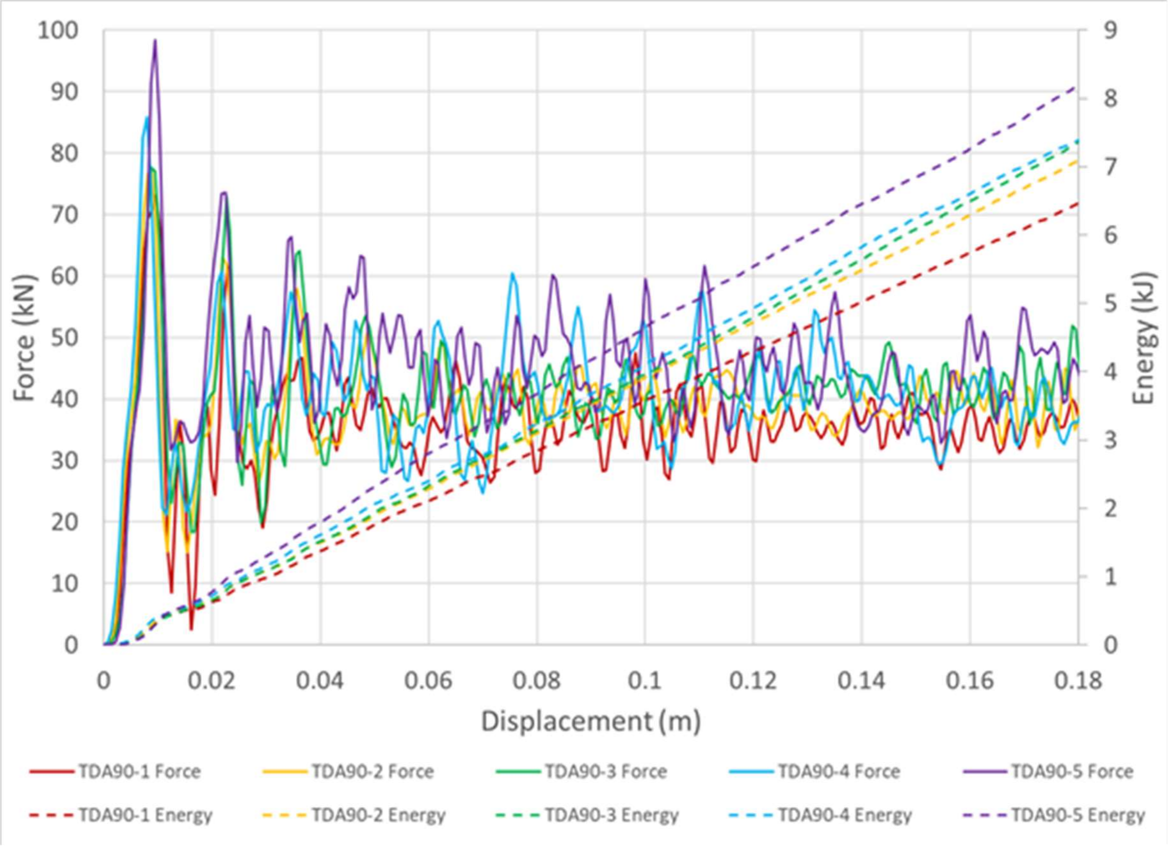

Figure 5: Dynamic Axial Crush Results for the Hat Channels with $[0/\pm45/90]_s$ Stacking Sequence

Table 2: Summary of Dynamic Axial Crush Results for $[0/\pm45/90]_s$ Hat Channels

Specimen Name	Channel Mass (g)	Peak Force (kN)	Steady State Force (kN)	Specific Energy Absorbed (kJ/kg)
TDA90-1	431.7	73.7	35.2	42.7
TDA90-2	429.6	77.1	38.5	46.3
TDA90-3	433.0	77.7	40.7	49.4
TDA90-4	432.8	85.9	40.4	49.0
TDA90-5	423.4	98.5	45.4	55.1
Average	430.1	82.5	40.0	48.5

Components with both stacking sequences exhibited a fragmentation failure mode, represented by rapid crack growth causing small pieces of the hat channels to detach from the part. In this failure mode energy is absorbed through the rapid spreading of cracks throughout the part and delamination between layers. Post-crush images of the hat channels with the $[\pm45/0_2]_s$ stacking sequence and the $[0/\pm45/90]_s$ stacking sequence can be found in Figure 6 and Figure 7, respectively. For the $[\pm45/0_2]_s$ channels, all layers fragmented into smaller pieces, with a localized portion of the damaged channel remaining. Thus, it is likely that the four 0° layers at the center of the stacked plies significantly improved energy absorption performance. For the $[0/\pm45/90]_s$ channels, the outer 0° layers delaminated forming thin fronds, while the remaining layers fragmented. Thus, cracks were less likely to propagate through the outer 0° layers, resulting in lower energy absorption when compared to the hat channels with $[\pm45/0_2]_s$ stacking sequence.

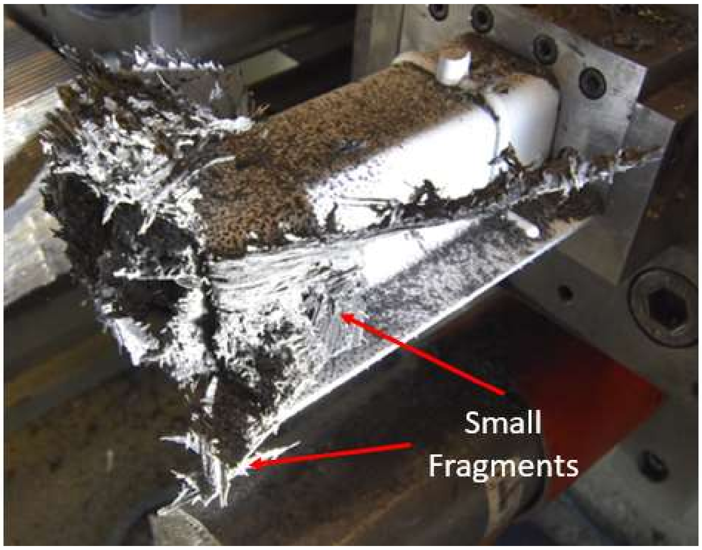

Figure 6: Post Crush Image of Hat Channel Specimen with $[\pm45/0_2]_s$ Stacking Sequence

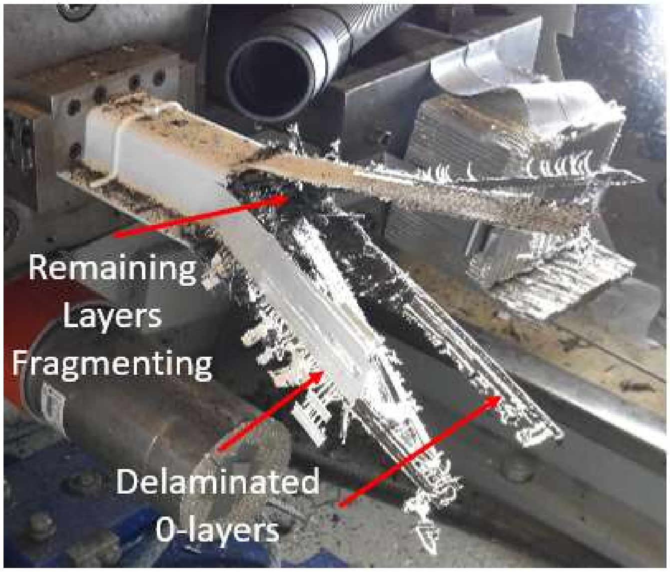

Figure 7: Post Crush Image of Hat Channel Specimen with $[0/\pm45/90]_s$ Stacking Sequence

Conclusions

The CFRP hat channels with the $[\pm45/0_2]_s$ stacking sequence created 29.8% higher peak forces and 83.3 % higher steady state forces when compared to hat channels with a $[0/\pm45/90]_s$ stacking sequence. This higher force and similar masses for the channels caused the channels with the $[\pm45/0_2]_s$ stacking sequence to absorb an average of 37.8% more specific energy than channels with the $[0/\pm45/90]_s$ stacking sequence. Both stacking sequences failed through a fragmentation failure mode, however the hat channels with the $[\pm45/0_2]_s$ stacking sequence saw the outer 0-layers delaminate. The large difference in SEA between the 2 stacking sequences emphasizes the importance of stacking sequence on the energy absorption performance of composite structures. Ongoing work includes performing axial crush tests at quasi-static loading rates on channels with the same geometry and stacking sequences, as well as for components with different geometries.

Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for financial support through Collaborative Research and Development Grant No. CRDPJ 507776 – 16, the Ontario Advanced Manufacturing Consortium and the Ontario Centres for Innovation, as well as sponsors Honda R&D Americas, Hexion Inc., Zoltek Corp. and LAVAL International. Amir Zhumagulov, Eckhard Budziarek, and Tom Gawel (University of Waterloo) are also acknowledged for supporting the conducted experiments. The Fraunhofer Project Center for Composites Research (Canada) is acknowledged for fabricating the composite channels.

Bibliography

1. D. Hull, "A Unified Approach to Progressive Crushing of Fibre-Reinforced Composite Tubes" *Compos. Sci. Technol.*, vol. 40, pp. 377–421, 1991.
2. H. Hamada, S. Ramakrishna, and H. Sato, "Effect of fiber orientation on the energy absorption capability of carbon fiber/PEEK composite tubes," *Journal of Composite Materials*, vol. 30, no. 8. pp. 947–963, 1996.
3. M. Courteau, D. Adams, and J. M. Starbuck, "Effects of Crush Fialure Mode on Energy Absorption in Carbon/Epoxy Tubes," *SAMPE J.*, no. March/April 2019, pp. 26–37, 2019.
4. A. G. Mamalis, D. E. Manolakos, M. B. Ioannidis, and D. P. Papapostolou, "Crashworthy characteristics of axially statically compressed thin-walled square CFRP composite tubes: Experimental," *Compos. Struct.*, 2004.
5. S. Ramakrishna, "Microstructural design of composite materials for crashworthy structural applications," *Mater. Des.*, vol. 18, no. 3, pp. 167–173, 1997.
6. C. McGregor, R. Vaziri, A. Poursartip, and X. Xiao, "Axial crushing of triaxially braided composite tubes at quasi-static and dynamic rates," *Compos. Struct.*, vol. 157, pp. 197–206, 2016.
7. J. S. Kim, H. J. Yoon, and K. B. Shin, "A study on crushing behaviors of composite circular tubes with different reinforcing fibers," *Int. J. Impact Eng.*, vol. 38, no. 4, pp. 198–207, 2011.
8. A. O. Bolukbasi and D. H. Laananen, "Energy absorption in composite stiffeners," *Composites*, vol. 26, no. 4, pp. 291–301, 1995.
9. P. Feraboli, B. Wade, F. Deleo, and M. Rassaian, "Crush energy absorption of composite channel section specimens," *Compos. Part A Appl. Sci. Manuf.*, vol. 40, no. 8, pp. 1248–1256, 2009.
10. L. Grauers, R. Olsson, and R. Gutkin, "Energy absorption and damage mechanisms in progressive crushing of corrugated NCF laminates: Fractographic analysis," *Compos. Struct.*, vol. 110, no. 1, pp. 110–117, 2014.

11. W. C. Hwang, C. S. Cha, and I. Y. Yang, “Optimal crashworthiness design of CFRP hat shaped section member under axial impact,” *Mater. Res. Innov.*, vol. 15, no. SUPPL. 1, 2011.
12. M. David, A. F. Johnson, and H. Voggenreiter, “Analysis of crushing response of composite crashworthy structures,” *Appl. Compos. Mater.*, vol. 20, no. 5, pp. 773–787, Oct. 2013.
13. P. Feraboli, “Development of a corrugated test specimen for composite materials energy absorption,” *J. Compos. Mater.*, vol. 42, no. 3, pp. 229–256, 2008.
14. M. W. Joosten, S. Dutton, D. Kelly, and R. Thomson, “Experimental and numerical investigation of the crushing response of an open section composite energy absorbing element,” *Compos. Struct.*, vol. 93, no. 2, pp. 682–689, 2011.
15. Y. Wang, J. Feng, J. Wu, and D. Hu, “Effects of fiber orientation and wall thickness on energy absorption characteristics of carbon-reinforced composite tubes under different loading conditions,” *Compos. Struct.*, vol. 153, pp. 356–368, 2016.
16. H. Luo, Y. Yan, X. Meng, and C. Jin, “Progressive failure analysis and energy-absorbing experiment of composite tubes under axial dynamic impact,” *Compos. Part B Eng.*, vol. 87, pp. 1–11, 2016.
17. A. Jackson, S. Dutton, A. J. Gunnion, and D. Kelly, “Investigation into laminate design of open carbon-fibre/epoxy sections by quasi-static and dynamic crushing,” *Compos. Struct.*, vol. 93, no. 10, pp. 2646–2654, 2011.
18. A. Cherniaev, Y. Zeng, D. Cronin, and J. Montesano, “Quasi-static and dynamic characterization of unidirectional non-crimp carbon fiber fabric composites processed by HP-RTM,” *Polym. Test.*, vol. 76, no. April, pp. 365–375, 2019.