HIGH STRAIN-RATE BEHAVIOR OF NONCRIMP FABRIC COMPOSITES FABRICATED BY HP-RTM PROCESS

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Abstract

This study investigates the influence of high strain-rate loading (at strain rates exceeding 1000 s^{-1}) on the transverse tensile strength of a thermoset composite reinforced by unidirectional non-crimp carbon fabric and manufactured using high-pressure resin transfer molding (HP-RTM) process. The transverse strengths at high strain-rates have been obtained using the split-Hopkinson bar apparatus and were compared with the data from quasi-static experiments. Results of the study are important for the development of high-fidelity numerical models for crash simulations with composite parts fabricated by HP-RTM process.

Introduction

Recent studies indicate that automobiles account for about one-quarter of overall carbon dioxide emissions, a major contributor to the greenhouse effect. A strategic approach to reducing the fuel consumption and, therefore, CO2 emissions, is reducing the weight of automobiles through the use of lightweight materials. In this regard, composites, such as plastics reinforced by continuous carbon fibers, have been identified as key materials for enabling substantial weight reductions in mass produced vehicles [1]. As a result of high specific strength and stiffness, these materials allow significant weight savings when used to replace metals in frame parts, roof, and floor segments, as well as many other automobile components [2-5]. In addition to low weight, carbon-fiber composites may provide higher passenger safety owing to better energy dissipation capabilities in case of collision, as compared with conventional metallic materials [6-9].

For a long time, the main challenge of using continuous-fiber composites in high volume production vehicles was a lack of a sufficiently rapid manufacturing technique(s). However, newly developed high-pressure resin transfer molding (HP-RTM) processes, may enable the integration of composites into vehicles while maintaining the volume production rates typical for the automotive industry: curing of a composite part can be completed within less than one minute with HP-RTM process [10, 11]. Unidirectional stitch-bonded fabrics are the standard type of reinforcement for HP-RTM process, as they allow for a rapid build-up of part thickness.

Despite of the growing importance of HP-RTM for automotive industry, as of today there is a lack of experimental data in the literature for composites fabricated by this manufacturing process, including both quasi-static and high strain-rate properties. In order to partially fill this gap, this paper reports results of transverse tensile strength tests of a unidirectional non-crimp carbon fabric-reinforced thermoset composite fabricated by HP-RTM process at quasi-static and high strain-rate loading conditions.

Materials and manufacturing

As a reinforcement, ZOLTEK™ PX35 UD300 unidirectional fabric was used in this study. The fabric is produced from ZOLTEK PX35 50K Continuous Tow Carbon Fiber and, as per manufacturer data, has areal density of 333 g/m2. The fibers in the tows are spread to achieve dry fabric thickness of 0.37 mm and are stich-bonded. Fig. 1 exemplifies the design of the used unidirectional fabric. Dieffenbacher PreformCenter was used for precise cutting of carbon UD fabric at 0° cutting angle to the size of the mold.

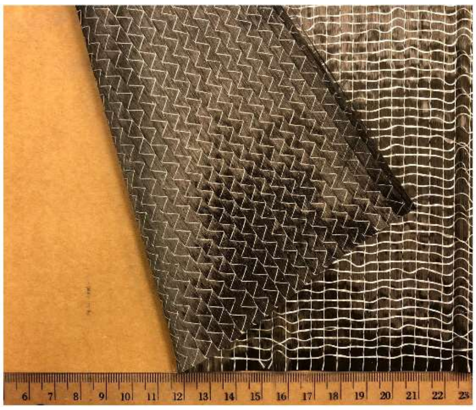
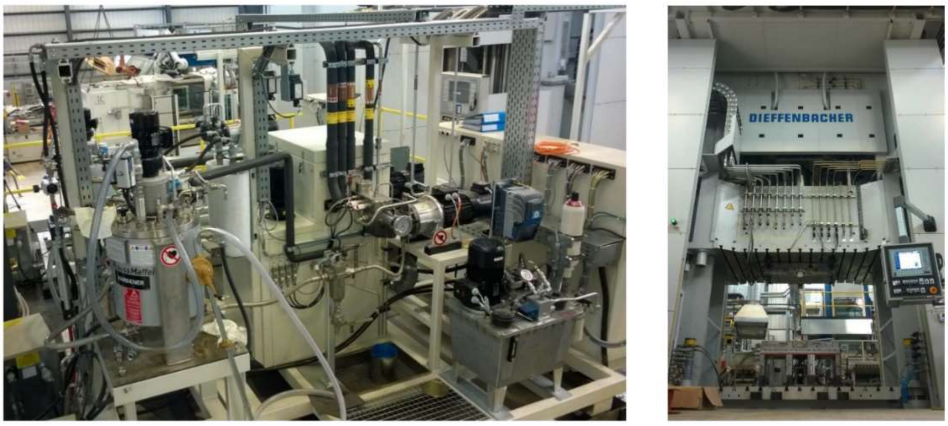


Figure 1 – Unidirectional CFRP fabric PX35 UD300 (scale in mm)

As a matrix, a fast-cure epoxy system EPIKOTE™ Resin TRAC 06150 in combination with a hardener EPIKURE™ Curing Agent TRAC 06150 and internal release agent HELOXY™ Additive TRAC 06805, was used in this study. This system is specifically designed by HEXION for mass-production of automotive structural parts and has the curing time of 5-10 min [12]. Used mixing ratios were 100:24:1.2 parts by weight for the resin, hardener and internal release agent, correspondingly.



(a) (b)

Figure 2 – Manufacturing equipment at the Fraunhofer Project Center at the University of Western Ontario: a) HP-RTM line; b) hydraulic press

Traditional resin transfer molding is a slow process: the final part may take hours or days to cure and may require the use of an autoclave to increase production time. However, HP-RTM is designed to impregnate the preform in seconds such that highly reactive polymer systems can be used and cured within minutes. In this study, HP-RTM equipment available at the Fraunhofer

Project Center at the University of Western Ontario was used to fabricate material samples. The equipment included a KraussMaffei HP-RTM line combined with a 2,500-ton Dieffenbacher hydraulic press, both shown in Fig 2.

(a) (b)

Figure 3 – Flat mold (a) and the manufactured panel (b)

During the manufacturing cycle resin and hardener were combined at high pressure of 120 bar and injected under vacuum at high flow rate (40 g/s) into a closed mold containing dry UD fabric. Pressures applied to the mold varied from 1500kN during the injection to 4500kN during the curing. The mold itself, as well as the manufactured panel are shown in Fig. 3. The fabricated flat panel contained 7 layers of UD fabric, which were aligned, in terms of the fiber direction, with the long side of the panel. In addition to the composite panel, a neat resin panel was fabricated in a separate run.

Microstructure characterization and mechanical testing

The microstructure of the composite was studied using the optical microscopy (Fig. 4). The material has average tow width of 4.1 mm and tow height of 0.43 mm. The microstructure features 0.14 mm-thick (in average) resin-rich layers between the tows and relatively thick resin pockets at the tow-ends. This results in the average composite volume fraction of fibers $v_{f, C} = 0.45$, which is significantly lower as compared with the in-tow fiber volume fraction, which has been preliminary estimated as being equal to 0.589.

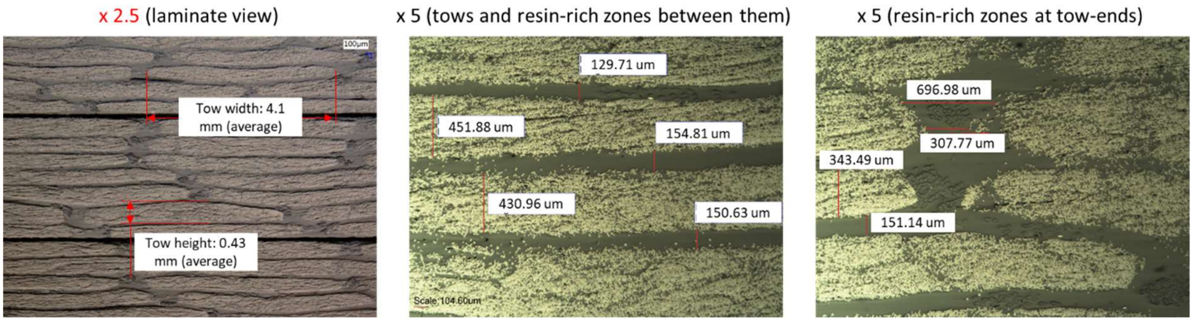


Figure 4 – Microstructure of the UD fabric CFRP composite

Test specimens were waterjet cut from the manufactured panel as shown in Fig. 5. For quasi-static transverse tension tests, standard ASTM D3039 M rectangular specimens were used. For the split-Hopkinson bar tests two groups of specimens, different in terms of length only, were cut from the panel. In the following, shorter ones will be referred to as SHBS and longer SHB specimens will be referred as SHBL.

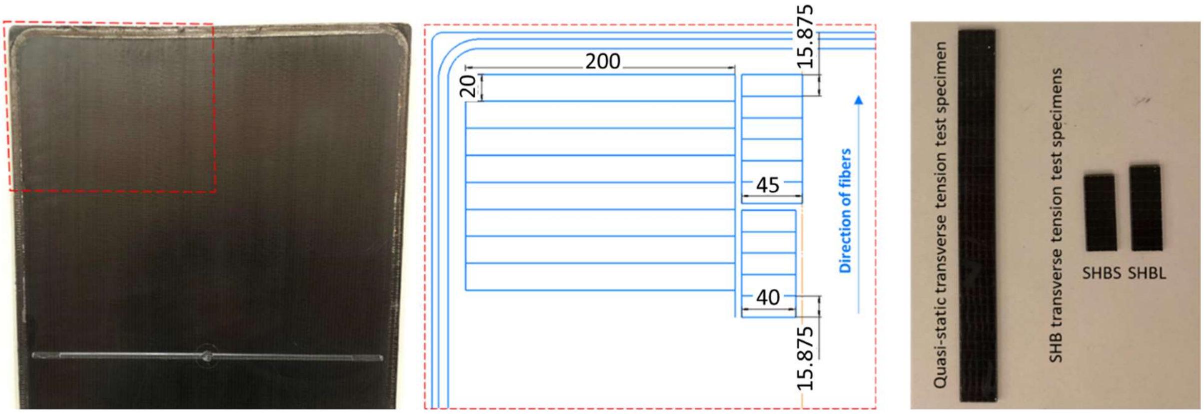


Figure 5 – Dimensions and cutting directions of the specimens with respect to the panel (left) and manufactured specimens for mechanical testing (right)

A 90 kN servo-hydraulic test frame was used for the quasi-static transverse tension tests. Strain measurements in these experiments were performed using the 2D digital image correlation (DIC). The test setup is shown in Fig. 6. Specimens were loaded in tension at a constant speed of 3 mm/min until failure. Stress-strain diagrams obtained in these tests, as well as the corresponding failure modes are shown in Fig. 7. Mean quasi-static transverse strength was found to be equal to 51.88 MPa.

Figure 6 – Test setup for the quasi-static experiments

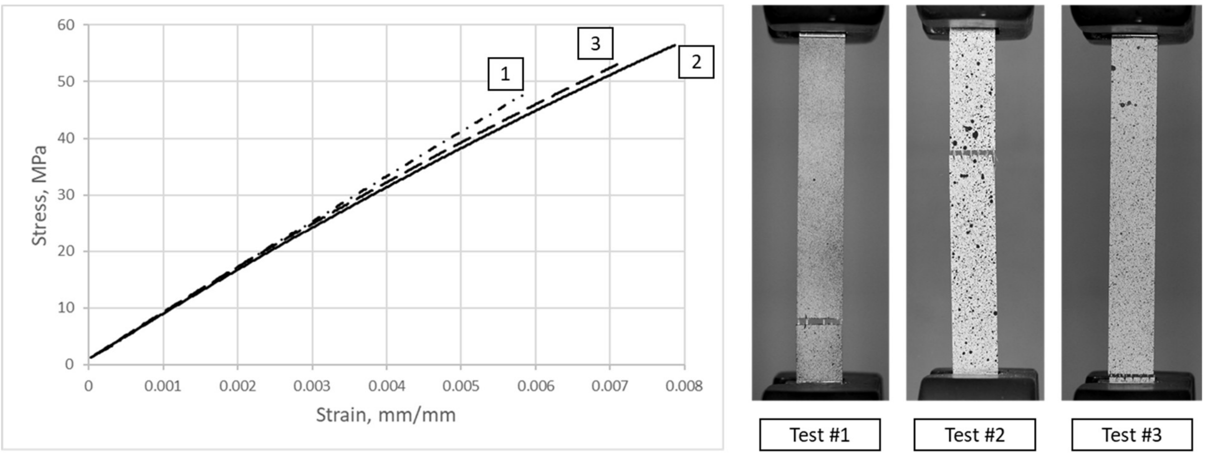


Figure 7 – Failure modes of the specimens in transverse tension and off-axis tension tests

High strain rate testing was conducted using the split-Hopkinson tensile bar (SHTB) apparatus at the University of Waterloo (Fig. 8). The SHTB uses a gas gun to propel a concentric hollow striker towards an end cap located at the free end of the incident pressure bar. Upon impact, a generated tensile incident loading pulse is travels towards the specimen. As the incident wave reaches the specimen, a portion of it is transmitted into the sample, causing it to deform at high strain rates, with the remainder being reflected. Strain gauges placed on the incident and transmitter bars measure the incident, reflected and transmitted waves (Fig. 9). The waves are then analyzed using the Hopkinson bar equations to determine the stresses and strains experienced by the sample.

Figure 8 – split-Hopkinson tensile bar apparatus

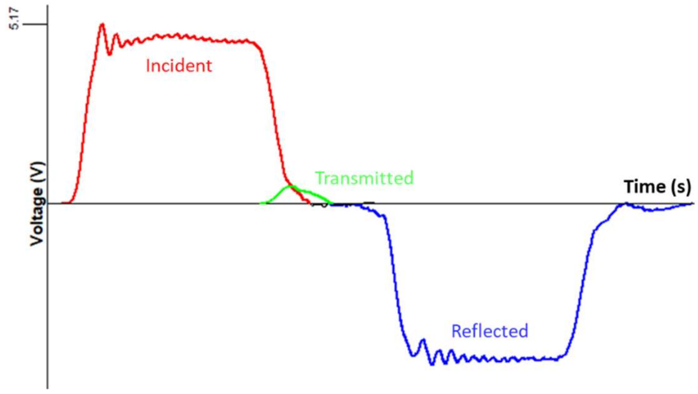


Figure 9 – Incident, transmitted and reflected pulses recorded by strain gages of the split-Hopkinson bar

The strain rates for these tests were relatively constant and the average measured values for shorter and longer samples were equal to 1925 and 1230 s^{-1}, correspondingly. Deformation of the specimens during the tests was recorded using a high-speed camera. Several consecutive images recorded by the camera during one of the tests are shown in Fig. 10. Formation of the longitudinal (with respect to fiber direction) crack and stitching pullout are noticeable in the high-speed imagery. All tested samples exhibited the failure in the vicinity of the bars, as shown in Fig. 8 and 10.

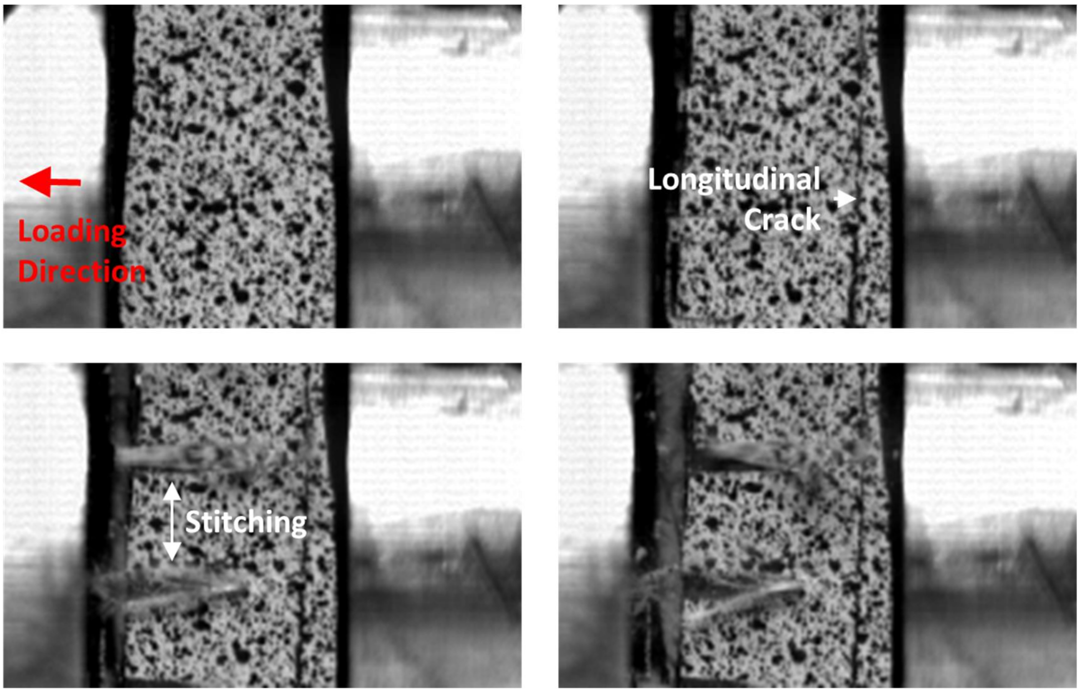


Figure 10 – Failure of a composite sample recorded by the high-speed camera

Measured values of the tensile transverse strength of the composite material are provided in Table 1 and also shown graphically in Fig. 11. As can be deduced from presented data, the material exhibits strain-rate sensitivity in the matrix-dominant transverse direction.

Table 1: Measured tensile transverse strength of the composite at different strain rates

	Test 1 (MPa)	Test 2 (MPa)	Test 3 (MPa)	Mean (MPa)	Std. Dev (MPa)	CV, %
QS	46.43	56.31	52.91	51.88	5.02	9.67
SHBL (1230 s^{-1})	65.14	56.98	61.86	61.33	4.11	6.70
SHBS (1925 s^{-1})	60.96	54.13	71.72	62.27	8.87	14.24

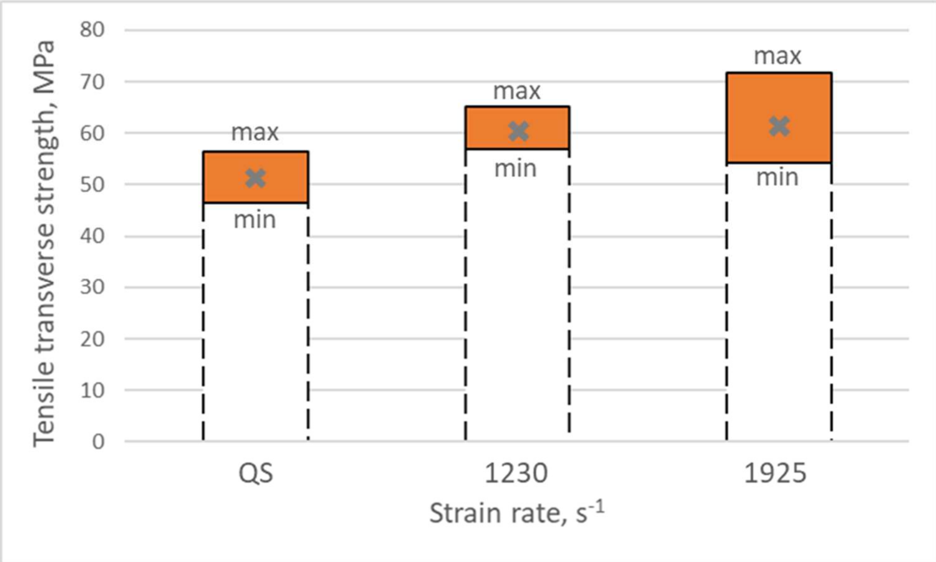


Figure 11 – Transverse strength of the composite material as a function of strain rate (“min” and “max” correspond to the minimum and maximum values observed in the experiments; “x” represents the mean value)

Conclusions

Based on the limited number of experiments presented in this paper, it can be preliminarily concluded that the studied thermoset composite reinforced by unidirectional non-crimp carbon fabric and manufactured using HP-RTM process exhibits, as compared with the quasi-static properties, approximately 18% and 20% increase of the tensile transverse strength at strain rates of 1230 s^{-1} and 1925 s^{-1}, correspondingly. As all specimens tested at high strain rates failed in the vicinity of the constrained ends, where stress concentration is most likely present, it may be expected that increase of the transverse strength of the material with strain rate can be even more pronounced than reported in this study. The reported results, therefore, should be considered as the lower-boundary estimates of the transverse tensile strength of the material at the corresponding strain rates. Nevertheless, the results of this study represent an important step towards developing and calibrating numerical crash simulation models with high strain rate capabilities for unidirectional non-crimp fabric composite materials. Ongoing work includes dynamic testing of the same material at intermediate strain rates, as well as additional testing in both compression and shear.

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Bibliography

1. Jarod C. Kelly, John L. Sullivan, Andrew Burnham, Amgad Elgowainy, Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions, Environment Science and Technology 2015; Volume 49, Pages 12535-12542, https://doi.org/10.1021/acs.est.5b03192
2. G. Davies, Materials for Automobile Bodies, Elsevier, Oxford, 2000.
3. R. Brooks, S.M. Shanmuga Ramanan and S. Arun, Composites in Automotive Applications: Design, In Reference Module in Materials Science and Materials Engineering, Elsevier, 2017, https://doi.org/10.1016/B978-0-12-803581-8.03961-8.
4. Alastair Komus and Natassia Beley, Composite Applications for Ground Transportation, In Reference Module in Materials Science and Materials Engineering, Elsevier, 2017, Current as of 8 May 2017, https://doi.org/10.1016/B978-0-12-803581-8.09950-1.
5. Haibin Ning, Selvum Pillay, Uday K. Vaidya, Design and development of thermoplastic composite roof door for mass transit bus, Materials & Design, Volume 30, Issue 4, 2009, Pages 983-991, http://dx.doi.org/10.1016/j.matdes.2008.06.066.
6. G. Lu, T. X. Yu. Energy Absorption of Structures and Materials, 1st Edition. Woodhead Publishing, 2003.
7. A.G Mamalis, M. Robinson, D.E. Manolakos, G.A. Demosthenous, M.B. Ioannidis, J. Carruthers, Crashworthy capability of composite material structures, Composite Structures, Volume 37, Issue 2, 1997, Pages 109-134, http://dx.doi.org/10.1016/S0263-8223(97)80005-0.
8. A.G. Mamalis, D.E. Manolakos, M.B. Ioannidis, D.P. Papapostolou, On the crushing response of composite sandwich panels subjected to edgewise compression: experimental, Composite Structures, Volume 71, Issue 2, 2005, Pages 246-257, http://dx.doi.org/10.1016/j.compstruct.2004.10.006.
9. W.C. Huang, C.S. Cha, I.Y. Yang, Optimal crashworthiness design of CFRP hat shaped section member under axial impact, Mater. Res. Innovations, Volume 15, 2011.
10. Christian Fais, Lightweight automotive design with HP-RTM, Reinforced Plastics, Volume 55, Issue 5, 2011, Pages 29-31, http://dx.doi.org/10.1016/S0034-3617(11)70142-4.
11. COMPOSITES EUROPE highlights solutions for mass production of automotive composites, Reinforced Plastics, Volume 55, Issue 4, 2011, Pages 45-46, http://dx.doi.org/10.1016/S0034-3617(11)70115-1.
12. https://www.hexion.com/en-AU/applications/composites/automotive/structural/