IN-PLANE MECHANICAL BEHAVIOUR OF COMPOSITE MATERIAL AND OUT-OF-PLANE BEHAVIOUR OF SANDWICH PANEL UNDER EXTREME TEMPERATURES

Jean-St-Laurent, M[1], Dano, M-L[1]*, Potvin, M-J[2]
[1] Université Laval, Department of mechanical engineering, Québec, Canada
[2] Canadian Space Agency, Longueuil, Canada
* Corresponding author (marie-laure.dano@gmc.ulaval.ca)

Keywords: *carbon-epoxy composite sandwich panel, extreme temperatures, indentation*

ABSTRACT

The effects of temperature on the mechanical behavior of a carbon fiber woven composite reinforced with epoxy resin was studied. Tensile tests and shear tests were performed at room temperature (RT), -70°C and -130°C. Tensile strength decreases at low temperature for all the laminates studied. Shear strength and shear modulus increase with decreasing temperature. Quasi-static indentation was studied for a composite sandwich panel at room temperature, -70°C and -150°C. Two sizes of indentors were used. The results show that loads reached during the tests are higher at room temperature. The permanent indentation depth is similar at room temperature and -70°C, and larger at -150°C.

1 INTRODUCTION

Composite sandwich structures are increasingly used by the aerospace industry. They offer excellent mechanical properties while being very light. However, they are well known for being sensitive to out-of-plane loading, such as impacts and indentations. Moreover, the space environment is characterized by important temperature variations. A part can be exposed to temperatures as low as -150°C when out of the sun light. In flight, a plane can undergo a temperature of -70°C. Temperature variations can lead to the development of internal stresses. Temperature can also affect the properties of the composite.

Few studies have looked into the effects of temperatures as low as -150°C on the behaviour of composite materials or composite sandwich panels. Kumagai et al. [1] studied the effects of temperature on the in-plane behaviour of woven carbon-epoxy laminates. They observed an increase in the tensile modulus and a decrease in the strength as the temperature decreases from room temperature to -196°C. They also observed that shear modulus and shear strength increase with decreasing temperature. This was observed by Kim et al. [2] as well. Out-of-plane shear strength can also increase with decreasing temperature [3]. Some studies have looked into the effects of temperature on interlaminar fracture toughness of composite materials [4][5] . This property is of great interest for out-of-plane loading. It was observed that interlaminar fracture toughness decreases with temperature for composite made of unidirectional plies [4][5]. The opposite was observed for composite made of woven plies [4]. However, the crack did not propagate between the plies but into the thickness of the laminate at -196°C.

Sanchez-Saez et al. [6] studied the effects of temperature on the static and dynamic flexural behaviour of carbon-epoxy laminates at -150°C, -60°C and 20°C. They observed an increase in delaminations with decreasing temperatures. The absorbed energy and flexural strength decreased with temperature. Moreover, their work showed that unidirectional laminates are more affected by temperature than woven laminates. Im et al. [7] observed an increase in the size of the delaminated area for impact tests on carbon fiber laminates at low temperatures. The effects of low temperatures on the size of the damaged zone, was also observed by Lopez-Puente et al. [8] and Gomez del Rio et al. [9] for impacts from -150°C to room temperature on carbon-epoxy laminates. Impact tests from -150°C to room temperature on both laminates made of unidirectional plies and laminates made of woven plies have also shown that laminates made of unidirectional plies are more sensitive to low temperatures, especially when there is large orientation variations between plies [8] [9].

As for the effects of temperature on out-of-plane behaviour of composite sandwich panels, there is a limited number of studies [10]–[12]. Selehi-Khojin et al. [11] studied the effects of temperature on the impact behaviour of composite sandwich panels from -50°C to 120°C. They observed that for medium to high energy level impacts, the damaged zone is larger at -50°C.

The global objective of the herein research is to study the effects of low temperatures on the impact behaviour of composite sandwich panels used for lunar exploration rovers. Here, the effects of temperature on the mechanical behaviour of the composite material used for skins of the sandwich panel is presented. Quasi-static indentations of sandwich panels at low temperatures were also performed and are presented.

2 MATERIALS

The composite material studied is made of a plain weave carbon fibers fabric with 977-2 epoxy resin. Mechanical properties were studied for a $[(0/90)]_5$ laminate in tension, where the first and second number represent respectively the warp and fill directions present in one single ply. Shear properties were obtained with a $[(+45/-45)]_5$ laminate. Tensile tests were also performed on a [(+45/-45)/(0/90)/(0/90)/(+45/-45)]s laminate.

The sandwich panel studied is made of two skins of the previously presented composite and a Nomex honeycomb core with hexagonal cells. The stacking sequence of the skin is [(+45/-45)/(0/90)/(0/90)/(+45/-45)]. The core is 12.7 mm thick and has a density of 48 kg/m^3. The cell size is 4.76 mm. The laminate 0°- direction is aligned with the core ribbon direction.

3 EXPERIMENTAL SET-UP

All tests were performed on a tensile machine MTS Insight® 100 SL. For the tests at cold temperatures, an environmental chamber is placed around the testing area of the machine (Figure 1). The chamber is cooled with liquid nitrogen. Specimens are never in direct contact with liquid nitrogen. The load cell is placed outside of the chamber. However, to ensure that the fixture inside the chamber connected to the load cell does not influence the load measurements, a heating ring was installed on the connecting rod between the load cell and the fixture (Figure 1). The temperature of the connecting rod outside the chamber was maintained at 24°C.

4 TENSILE AND SHEAR TESTS

4.1 Methodology

Tensile tests were performed according to ASTM standard D3039 [13]. Specimens were respectively 1.13 mm and 1.77 mm thick for the $[(0/90)]_5$ and the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_s$ laminates. Aluminium tabs with 15° angle were bounded to the specimens using epoxy Hysol 120 HP. Strains were measured with a 3d digital image correlation (DIC) system. At cold temperatures, the same system was used. Images were taken through the window of the thermal chamber. A 100KN load cell was used to record the load. Tests were all performed at a speed of 2 mm/min.

Tests were conducted at room temperature, -70°C and -130°C. The latter is the minimum temperature that can be sustained by our tensile fixture. Tests were started 15 minutes after the specimen reached the test temperature. For the $[0]_5$ laminate, tests were performed along the 0°- and 90°- directions, corresponding respectively to the warp and fill directions. In the case of the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_s$ laminate, tests were only performed along the 0°- direction. For each case studied, between three and five specimens were tested.

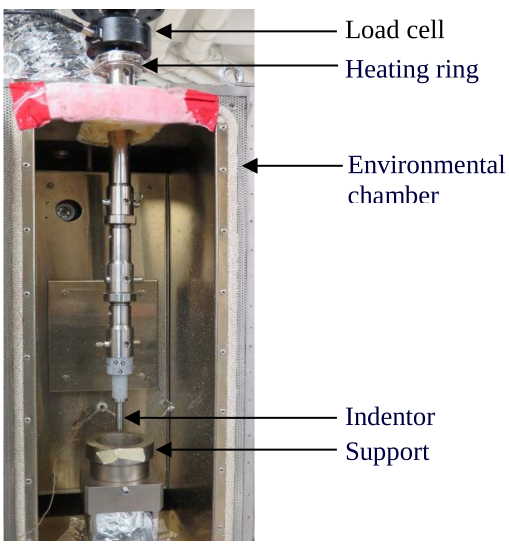

Figure 1. Experimental set-up.

Shear tests were performed according to the ASTM standard D3518 [14]. Shear properties are obtained by a tensile test on a $[(+45/-45)]_5$ laminate. Shear tests were performed at room temperature, -70°C and -130°C. Aluminium tabs were used for the shear tests as well. Sliding of the specimen was observed otherwise. Strains were measured in the longitudinal and transverse directions in order to obtain the shear strain. The same 3d DIC system was used to measure them. A load cell of 10 KN was used to record the load for room temperature tests and a 100 KN was used for -70°C and -130°C tests. Shear tests were performed at a speed between 3 mm/min and 4 mm/min. According to the ASTM Standard D3518 [14], when the shear strain reaches a value higher than 5%, the test data are no longer valid. In that case, the maximum shear stress is considered to be the stress at 5% of deformation.

Prior to every test, specimens were dried at 50°C for at least 24 hours in order to ensure that humidity would not affect the results.

4.2 Results: Tensile Tests

Figure 2 presents typical stress-strain curves for the 0°- (Figure 2a) and 90°- (Figure 2b) directions of the $[(0/90)]_5$ laminate at room temperature, -70°C and -130°C. For all temperatures, in both directions, the behaviour is linear elastic until failure. The ultimate strength shows an important decrease with temperature. Figure 3 presents the stress-strain curves obtained from tensile tests of the $[(+45/-45)(0/90)/(0/90)/(+45/-45)]_s$ laminate. The ultimate strength is also affected by temperature. There is a slight increase in the tensile modulus with decreasing temperature as well.

Table 1 presents the in-plane mechanical properties obtained from the tensile tests as a function of temperature. From room temperature to -130°C, the tensile strength decreased by 22.6 % and 19.7 % in the 0°- and 90°- directions respectively. For the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_s$ laminate, the tensile strength decreased by 21.2% from room temperature to -130°C. The results are coherent, since the rupture in the $[(+45/-45)/ (0/90)/(0/90)/(+45/-45)]_s$ laminate is governed by the rupture of the 0°- direction plies. The tensile modulus of the [(+45/-45)/(0/90)/ (0/90)/(+45/-45)]s laminate increases by 8% from room temperature to -130°C.

4.3 Results: Shear Tests

Figure 3 presents the shear stress-strain curves for the three temperatures studied. Shear modulus and shear strength increase with decreasing temperature. For the room temperature and -70°C tests, the maximum shear stress is taken at a 5% strain even if the complete failure of the specimens did not occur. For the -130°C tests, the complete failure of the specimens was around 3.2% of strain. Table 2 presents the shear properties obtained as a function of temperature. There is a 32% increase of the shear modulus from room temperature to -130°C, while the shear strength increases by 42,0 %.

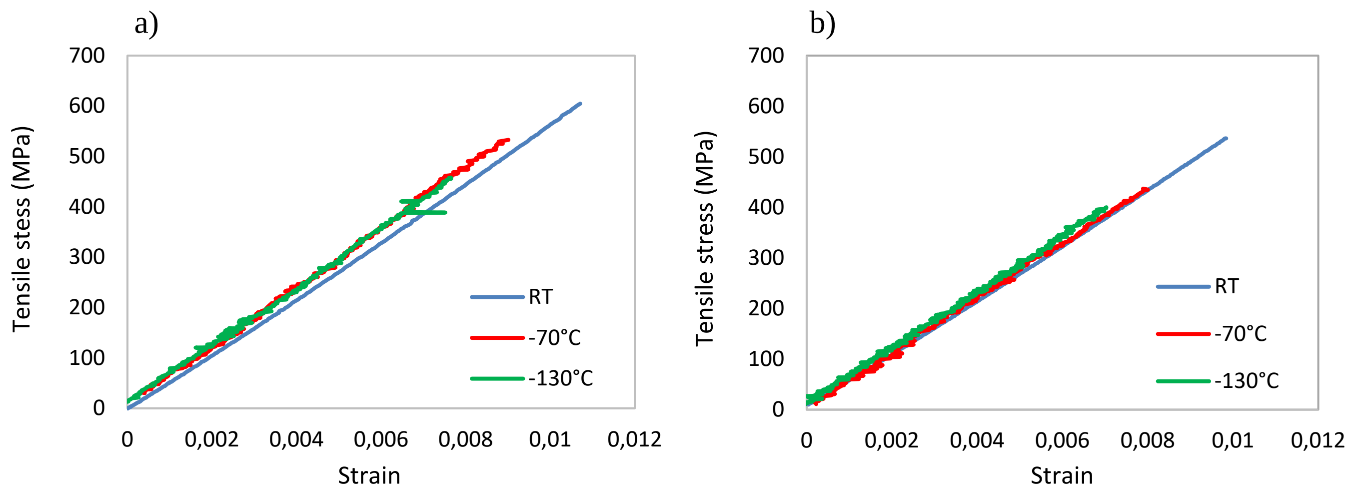

Figure 2. Stress-strain curves for the $[(0/90)]_5$ laminate in the a) 0°- direction and b) 90°- direction.

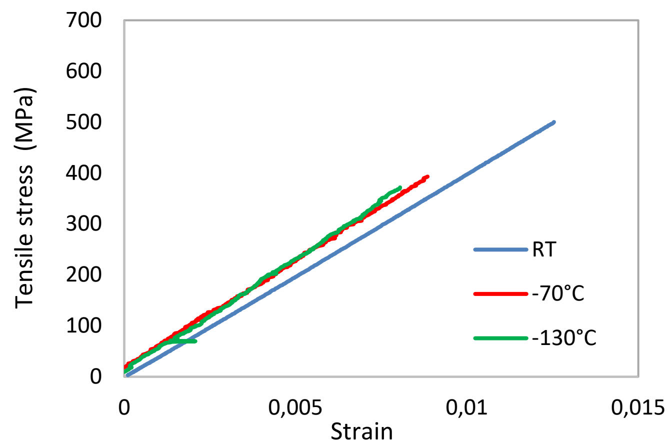

Figure 3. Stress-Strain curves for the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_s$ laminate in the 0°- direction.

Laminate	Properties	Room Temperature		-70°C		-130°C	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
$[(0/90)]_5$	E_1 (GPa)	56.63	0.52	57.49	1.49	57.78	0.37
	σ_1^T (MPa)	603.98	34.16	534.84	32.32	466.67	18.33
$[(90/0)]_5$	E_2 (GPa)	53.44	0.75	54.53	0.12	55.32	0.71
	σ_2^T (MPa)	527.80	16.62	447.80	27.68	423.30	31.06
[(+45/-45)/(0/90)/(0/90)/(+45/-45)]s	E_x (GPa)	40.15	0.18	41.79	0.31	43.85	0.55
	σ_x^T (MPa)	498.60	2.67	416.80	16.01	392.90	34.84

Table 1. In-plane tensile properties for the [(0/90)]5 and [(+45/-45)/(0/90)/(0/90)/(+45/-45)]s laminates.

5 QUASI-STATIC INDENTATION

5.1 Methodology

Quasi-static indentation tests of the sandwich panels were performed at room temperature, -70°C and -150°C. Specimens were 102 mm by 152 mm and 14.5 mm thick. They were simply resting on a circular support with an inner diameter of 76.2 mm (Figure 1). Two semi-hemispherical indentors were used with respectively 25.4 and 12.7 mm diameters. Tests were performed at a speed of 1.25 mm/min.

Two preliminary tests were performed at room temperature, one with each indentor in order to determine the maximal applied displacement for the subsequent tests. For the 25.4 mm diameter indentor, a depth of 6 mm was chosen, while for the 12.7 mm diameter indentor a depth of 5 mm was chosen. For room temperature tests, two specimens per indentor were tested in addition to the one for the preliminary test. At cold temperatures, three tests per indentor were performed. All tests included complete unloading.

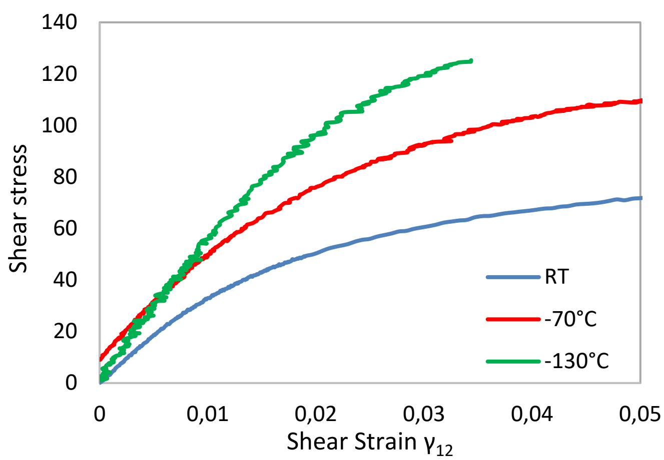

Figure 4. Shear stress-strain curves at room temperature, -70°C and -130°C.

Properties	Room Temperature		-70°C		-130°C	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
G_{12} (GPa)	3.758	0.043	4.161	0.006	5.547	0.206
τ_{12}^{R} (MPa)	71.95	0.52	112.08	2.77	123.83	1.36

Table 2. In-plane shear properties.

The displacement of the indentor was measured using two different techniques. The cross head displacement of the tensile machine was used. The values obtained were validated with a 3d DIC system. Displacement measurements were the same at room temperature, -70°C and -150°C. In order to simplify the tests, the crosshead displacement was therefore used.

During the tests, two thermocouples were used to measure temperature. One was placed in the chamber on the top surface of the specimen, the other on the bottom surface. After complete cooling of the chamber, the two thermocouples reached a different constant value. The temperature measured on the top surface of the specimen was higher than the one on the bottom surface. At -70°C, a 5°C difference was measured. The specimen top surface was at -70°C while the bottom surface was at -65°C. At -150°C, the difference was larger: 11°C. The top surface was at -150°C while the bottom surface was at -139°C. One explanation for those differences could be the thermal bridge between the part of the steel fixture inside of the chamber and the one outside of the chamber.

After the tests, a 3d DIC system was used to measure the residual indentation depth.

5.2 Results

Figure 5 and Figure 6 present typical load-displacement curves obtained respectively with the 25.4 mm and 12.7 mm diameter indentors at room temperature, -70°C and -150°C. The curves show that the load reaches higher values at room temperature than at -70°C and -150°C fort both size of indentors. For the 25.4 mm indentors (Figure 5), the curve obtained from the -150°C test is very similar to the one from the -70°C test. However at the beginning of the tests, it seems that there is more damage at -150°C, since the load doesn't rise as fast. Moreover, upon unloading, the load reaches a value of zero earlier for the -150°C curve. For the 12.7 mm indentor (Figure 6), the load for the -150°C curve starts to decrease significantly before the displacement reaches 5 mm. This was observed for two specimens out of three. Moreover, the behavior of the panel before damage seems to be more rigid with decreasing temperature. The displacement after unloading is more important for the -150°C tests as well.

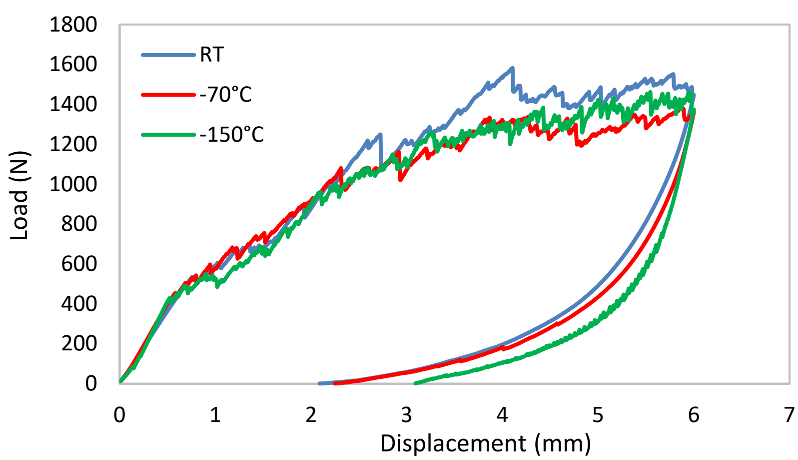

Figure 5. Load-displacement curve for the 25.4 mm diameter indentor.

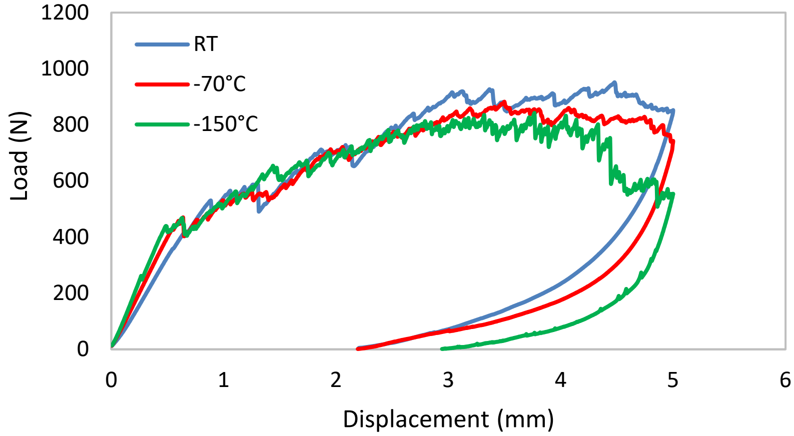

Figure 6. Load-displacement curve for the 12.7 mm diameter indentor.

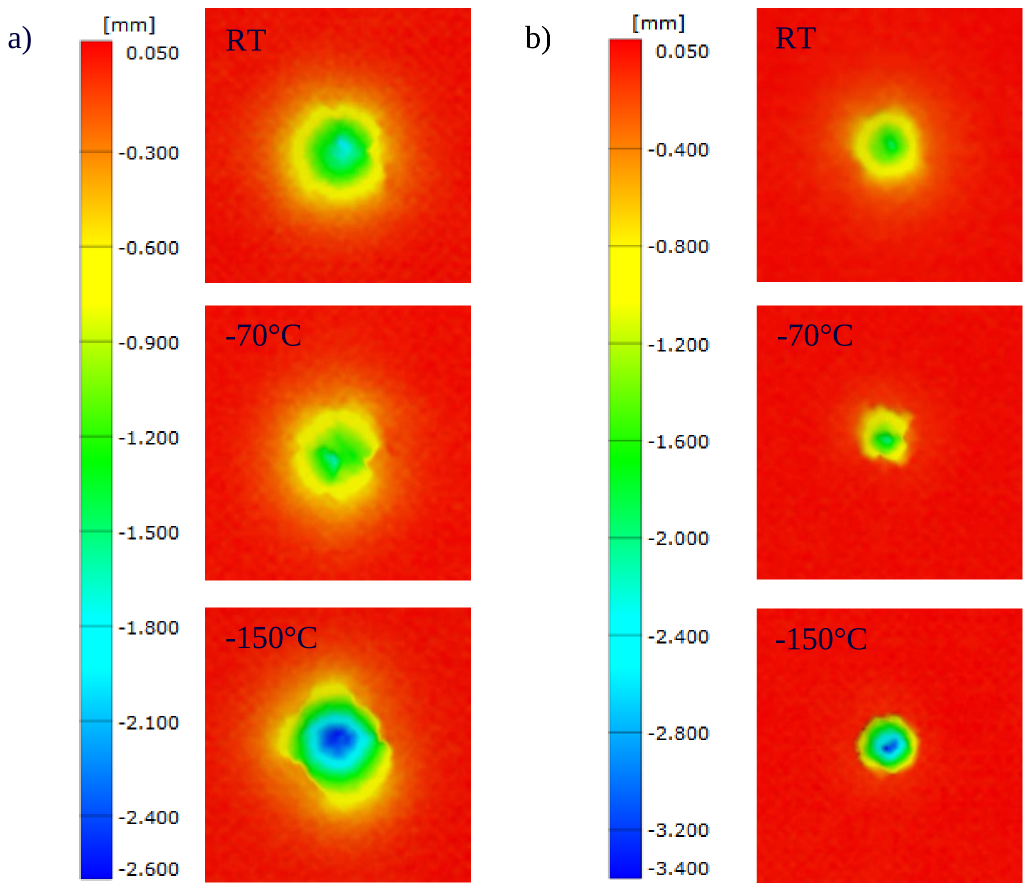

Figure 7. Residual depth of indentation for a) the 25.4 mm diameter and b) 12.7 mm diameter indentors.

Indentor	RT	-70°C	-150°C
12.7	-1.77	-1.72	-3.15
25.4	-1.78	-1.65	-2.79

Table 3. Residual indentation depth in mm.

Figure 7 presents the residual depth of indentation on the specimens for all configurations while the average maximum residual indentation depths are indicated in Table 3. The residual indentation depth is almost the same at room temperature and -70°C for both indentors. However, the -150°C residual indentation depth is significantly larger in both cases.

6 CONCLUSION

Tensile tests and shear tests at -130°C, -70°C and room temperature show that temperature has a major influence on strength. Important reduction of the tensile strength were observed for the $[(0/90)]_5$ and $[(+45/-45)/(0/90)/(0/90)/ (+45/-45)]_s$ laminates. In shear, the modulus and the strength show significant increase from room temperature to -130°C.

Temperature also affects the quasi-static indentation of the sandwich panels. During the tests, the loads were globally higher at room temperature than at -70°C and -150°C. The residual depth is larger at -150°C. Tests results demonstrate the needs for more thorough investigations of the effects of temperature on the out-of-plane behaviour of composite sandwich panels for applications at cold temperatures.

7 ACKNOWLEDGMENTS

The authors fully acknowledge the support from NSERC and the Canadian Space Agency which makes this work possible.

8 REFERENCES

[1] S. Kumagai, Y. Shindo, H. Katsumi and T. Takeda. “Mechanical characterization of CFRP woven laminates between room temperature and 4k”. *JSME Int. J.*, vol. 46, no. 3, pp. 359–364, 2003.

[2] M.-G. Kim, S.-G. Kang, C.-G. Kim and C.-W. Kong. “Tensile Properties of Carbon Fiber Composites with Different Resin Compositions at Cryogenic Temperatures”. *Adv. Compos. Mater.*, vol. 19, no. 1, pp. 63–77, 2010.

[3] S. Kichhannagari.“Effects of extreme low temperature on composite materials”. University of New Orleans, 2004.

[4] W. S. Johnson, M. M. Pavlick and M. S. Oliver. “Determination of interlaminar toughness of IM7 / 977-2 composites at temperature extremes and different thicknesses”. NAG-1-02003/E-1 8-A1 9, 2005.

[5] S. G. Kalarikkal, B. V. Sankar and P. G. Ifju. “Effect of cryogenic temperature on the fracture toughness of graphite epoxy composites”. *J. Eng. Mater. Technol.*, vol. 128, no. 2, pp. 151-157, 2006.

[6] S. Sánchez-Sáez, E. Barbero and C. Navarro. “Analysis of the dynamic flexural behaviour of composite beams at low temperature”. *Compos. Sci. Technol.*, vol. 67, no. 11–12, pp. 2616–2632, 2006.

[7] K. Im, C. Cha, S. Kim and I. Yang. “Effects of temperature on impact damages in CFRP composite laminates”. *Compos. Part B Eng.*, vol. 32, no. 8, pp. 669–682, 2001.

[8] J. López-Puente, R. Zaera and C. Navarro “The effect of low temperatures on the intermediate and high velocity impact response of CFRPs”. *Compos. Part B Eng.*, vol. 33, no. 8, pp. 559–566, 2002.

[9] T. Gomez del Rio, R. Zaera and C. Navarro. “Prediction of the effect of temperature on impact damage in carbon / epoxy laminates”. *J. Phys. IV Fr.*, vol. 110, pp. 699–704, 2003.

[10] M. D. Erickson. “Effect of Temperature on the Low-velocity Impact Behavior of Composite Sandwich Panels”. *J. Sandw. Struct. Mater.*, vol. 7, no. 3, pp. 245–264, 2005.

[11] A. Salehi-Khojin, M. Mahinfalah, R. Bashirzadeh and B. Freeman. “Temperature effects on Kevlar/hybrid and carbon fiber composite sandwiches under impact loading”. *Compos. Struct.*, vol. 78, no. 2, pp. 197–206, 2007.

[12] P. Yang, S. S. Shams, A. Slay, B. Brokate and R. Elhajjar. “Evaluation of temperature effects on low velocity impact damage in composite sandwich panels with polymeric foam cores”. *Compos. Struct.*, vol. 129, pp. 213–223, 2015.

[13] “ASTM Standard D3039, 2008, Tensile Properties of polymer matrix composite materials’’. ASTM International, West Conshohocken, Pa,2008, DOI: 10.1520/D3039_D3039M-08,www.astm.org.

[14] “ASTM Standard D3518, 2013,‘In-plane shear response of polymer matrix composite materials by tensile test of +-45° Laminate”. ASTM International, West Conshohocken, Pa, 2013, DOI:10.1520/D3518_D3518M-13.” www.astm.org.