Effect of extreme cold temperatures on the behaviour under low velocity impacts of composite sandwich panels for lunar exploration rovers

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Abstract

The effect of extreme cold temperature on the low velocity impact behaviour of composite sandwich panels with composite skins and a Nomex honeycomb core was studied. First, the effect of temperatures on the behaviour of the constituents of the sandwich panel was investigated. The tensile strength of the composite laminate decreases with temperature decreasing while the compressive strength increases. The in-plane shear strength and the in plane shear modulus also increase with temperature. Out of plane compressive modulus and compressive strength of the Nomex honeycomb core increase with temperature decreasing. Then, impacts at extreme cold temperatures were performed. Different impact conditions were studied. An increase in damage was generally observed from room temperature to -150°C.

1. Introduction

One of the main challenges associated with the development of lunar exploration rovers is the harsh moon environment. Rovers will not only have to work in a rugged terrain with rocks and craters, but will also be blind to the real nature of the ground due to the presence of a thick layer of loose lunar dust. For the Apollo 17 lunar rover vehicle, the height reached by dust displaced by the rover motion was 2 meters [1]. This dust eventually settles down and attenuates landscape variations. This can easily lead to the rover hitting a hidden surface feature and potentially damaging its structure. Moreover, the lunar environment is characterized by extreme temperature variations. On the moon, temperatures can go from 120°C to -150°C [1]. However, in some shadowed craters, temperature is estimated to be even lower. In order to explore those craters, rovers will have to sustain extreme cold temperatures for an extended period of time. This brings design challenges associated with temperature control and insulation. Composite sandwich panels with Nomex honeycomb core have been identified as a good material to overcome some of those design challenges. Moreover, composite sandwich panels are lightweight and characterized by excellent mechanical properties, which makes them first choice candidates for space applications. However, they are also known for their sensitivity to out-of-plane loadings such as impacts, which are likely to occur while working in the harsh moon environment. In addition, composite materials are affected by temperature. Indeed, temperature variations lead to the development of internal stresses. Temperature can also affect the mechanical properties of the composite. It is therefore extremely important to understand the effect of extreme temperatures on the mechanical behavior of composite sandwich panels for space applications especially under impact loadings.

Kumagai et al. [2] have studied the effect of extreme temperatures on the tensile and shear behaviour of woven carbon/epoxy laminates. They observed an increase in tensile modulus and a decrease of ultimate tensile stress at low temperature. In shear, they noted an increase of in-plane shear modulus and in-plane shear strength. Similar observations on the effect of temperature on in-plane shear behaviour were made by Kim et al. [3].

Only a few researches have studies the effect of temperatures on impact behaviour of composite sandwich panels [1-4]. Amongst them, none have studied sandwich panels with Nomex honeycomb core or temperature as cold as -150° C. However, Gómez-del Río et al. [8] have performed low velocity impact tests at -150°C but only on carbon/epoxy composite laminates. They observed an increase in damage at cold temperature. Sánchez-Sáez et al. [9] have studied the effect of extreme low temperatures on the dynamic flexural behavior of carbon/epoxy composite laminates. They observed a decrease of strength and absorbed energy with temperature decreasing. Moreover, their work showed that unidirectional laminates are more affected by temperature than woven laminates.

The aim of this project is to study the effect of extreme temperatures on the low velocity impact behaviour of carbon fibers composite sandwich panels with Nomex honeycomb core potentially used for the fabrication of lunar exploration rovers. In order to do so, an ambitious experimental campaign was developed. The first part consists of characterizing the effect of extreme cold temperatures on the constituents of the sandwich panels. Tension, compression, and shear tests were performed on the composite material. Out-of-plane compression tests were performed for the Nomex honeycomb core. The results of those tests will help understand the effect of temperatures for more complicated loading cases such as impact. The second part of the campaign consists of studying the effect of temperature on the low velocity impact behaviour of the sandwich panels. Finally, the third part of the campaign is dedicated to study the compression behaviour of the impacted sandwich panels. This paper focused on the first two parts.

2. Material

The sandwich panels studied are made of carbon/epoxy woven composite skins and a Nomex honeycomb core and have the following stacking sequence: [(±45)/(0/90)/(0/90)/(±45)/core/(±45)/(0/90)/(0/90)/(±45)]. The resin used is a 977-2 epoxy. The core has a density of 48 kg/m^3, a total thickness of 12.7 mm and 4.76 mm hexagonal cells.

3. Experimental characterization of the composite material

3.1 Tests description

Tensile tests were performed on two laminates: $[(0/90)]_5$ and [(+45/-45)/(0/90)/(0/90)/(+45/-45)]s. The first laminate was tested along the 0°- and 90°-directions while the second was tested along the 0°- direction. The 0°- and 90°- directions correspond respectively to the warp and fill direction of the (0/90) plies. For the compression tests, the same laminates were studied in the same directions, but with a greater number of plies: $[(0/90)]_{12}$ and $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_{2s}$. A combined loading compression fixture was used [10]. The shear properties were obtained by a tensile test on a $[(+45/-45)]_5$ laminate.

Tensile and shear tests were performed at room temperature (RT), -70°C, and -130°C. The latest is the minimum temperature that can be sustained by the tensile fixture used. Compression tests were performed at RT, -70°C, and -150°C. For the test at cold temperature, an environmental chamber was placed around the fixture. The chamber is cooled with liquid nitrogen. In order to avoid that the temperature inside the chamber influences the load cell measurements, a heating ring was used. It keeps the temperature of the connector between the load cell and the fixture constant throughout testing.

For tensile and shear tests, 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. In compression, strain gages were used to measure the longitudinal strain on both faces of the specimen.

3.2 Results

This section presents the main conclusions associated with the characterisation of the in-plane mechanical properties of the laminates at different temperatures. Tensile and shear properties of the $[(0/90)]_5$ laminate are given in Table 1, while the tensile properties of the [(+45/-45)/(0/90)/(0/90)/ (+45/-45)]s laminate are given in Table 2. Compressive properties are given in Table 3 and 4.

Ultimate tensile stress decreases with temperature decreasing for both laminates tested. For the $[(0/90)]_5$ laminate, the strength decreases by 23 % and 20% for the 0°- and 90°-directions respectively. The tensile elastic modulus of the $[(0/90)]_5$ laminate in both directions are not significantly affected by temperature. For the [(+45/-45)/(0/90)/(0/90)/ (+45/-45)]s laminate, the tensile modulus increases by 9 % from RT to -130°C.

The ultimate compressive stress shows a completely different behaviour with temperature decreasing. Indeed, an important increase of the ultimate compressive stress is observed for both laminates. In the case of the $[(+45/-45)/(0/90)/(0/90)/ (+45/-45)]_{2s}$ laminate, the ultimate compressive stress increases by 60% from RT to -150°C. As for the compressive elastic modulus, results are similar as those obtained in tension. There is a small increase of elastic modulus for the $[(+45/-45)/(0/90)/(0/90)/ (+45/-45)]_{2s}$ laminate and there is no significant effect for the $[(0/90)]_{12}$ laminate.

The in-plane shear behaviour of the composite is more brittle with decreasing temperature. At -150°C, the shear strain at failure is around 3%, while at room temperature no failure was observed after 5% of strain, the validity limit of the test. The shear modulus and shear strength increase with temperature decreasing.

Table 1. Tensile and shear properties in function of temperature for the $[(0/90)]_5$ laminate.

	Room Temperature		-70°C		-130°C	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
E_1^T (GPa)	56.63	0.52	57.49	1.49	57.78	0.37
σ_1^T (MPa)	604	34	535	32	467	18
E_2^T (GPa)	53.44	0.75	54.53	0.12	55.32	0.71
σ_2^T (MPa)	528	17	448	28	423	31
G_{12} (GPa)	3.76	0.04	4.16	0.01	5.55	0.21
τ_{12} (MPa)	72.0	0.5	112.1	2.8	123.8	1.4

Table 2. Tensile properties in function of temperature for the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_s$ laminate.

	Room Temperature		-70°C		-130°C	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
E_x^T (GPa)	40.15	0.18	41.79	0.31	43.85	0.55
σ_x^T (MPa)	499	3	417	16	393	35

Table 3. Compressive properties in function of temperature for the $[(0/90)]_{12}$ laminate.

	Room Temperature		-70°C		-130°C	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
E_1^C (GPa)	52.04	0.44	51.74	0.87	52.99	1.26
σ_1^C (MPa)	615	47	784	25	853	54
E_2^C (GPa)	53.20	0.70	53.62	1.82	56.05	1.54
σ_2^C (MPa)	663	34	815	40	898	36

Table 4. Compressive properties in function of temperature for the $[(+45/-45)/(0/90)/(0/90)/(+45/-45)]_{2s}$ laminate.

	Room Temperature		-70°C		-130°C	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
E_x^C (GPa)	36.77	0.42	38.72	0.41	41.18	0.10
σ_x^C (MPa)	491	26	667	36	786	18

4. Experimental characterization of the Nomex honeycomb core

4.1 Test description

Out-of-plane compression tests were performed on the Nomex honeycomb core, on stabilized specimens with the composite skins. The specimens tested were 50 mm by 50 mm. Tests were performed at RT, -70°C, and -150°C.

4.2 Results

Figure 1 shows typical equivalent stress-strain curves for the out-of-plane compression tests of the stabilized Nomex specimens at RT, -70°C, and -150°C. The out-of-plane behaviour of the Nomex honeycomb core can be divided in three parts: first the linear elastic region before the collapse of the cells' walls, then the plateau area and finally the densification associated with an increase in apparent modulus. Figure 1 shows the complete behaviour and the linear elastic region. There is an increase in out-of-plane elastic modulus with temperature decreasing. Also, the ultimate stress before the collapse of the cells' walls is also increasing with decreasing temperature. Stresses in the plateau's area are slightly lower at -150°C and -70°C.

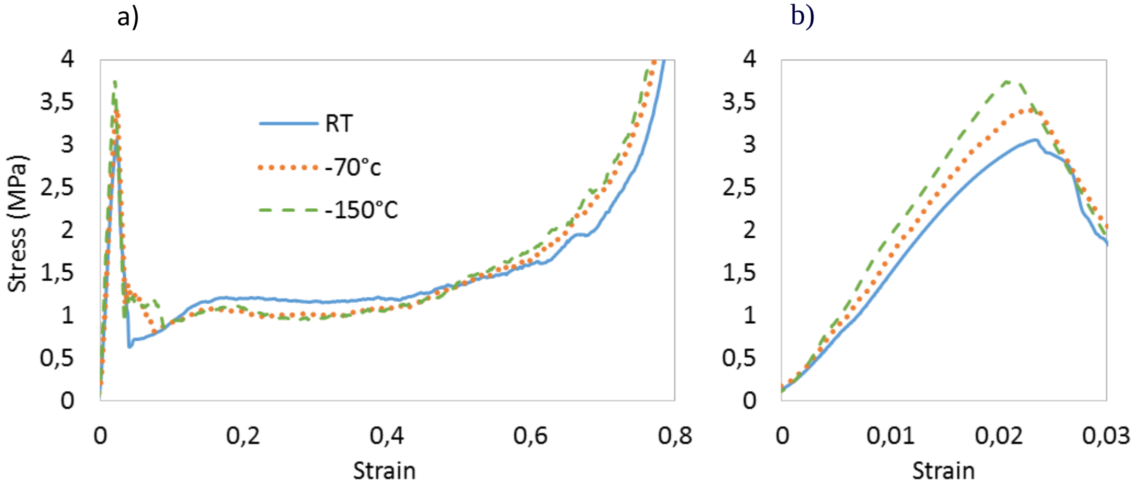

Figure 1: Equivalent out-of-plane compression stress-strain curves at RT, -70°C, and -150°: a) complete behaviour and b) linear elastic region.

5. Impact tests

5.1 Test description

Impact tests were performed on a drop weight tower with a thermal chamber modified to cool down to -150°C. The thermal chamber is cooled with liquid nitrogen. A total of five impact conditions were tested at RT, -70°C, and -150°C. Two hemispherical impactors with a diameter of 12.7 mm and 25.4 mm were used. The first impactor was used with a combination of two masses: 5 kg and 10 kg, while the second impactor was used with a combination of three masses: 5 kg, 10 kg, and 20 kg. All impact tests, were performed at a velocity of 1m/s. During impact, specimens were clamped on a steel fixture with an inner diameter of 76.2 mm. An anti-rebound system was used to prevent a second impact on the specimens.

5.1 Results

Load versus time and load-displacement curves were studied for all impact conditions. In all cases, the behaviour is stiffer at -150°C and -70°C than at room temperature. There is no noticeable distinction between -70°C and -150°C. Also, for most of the test conditions, loads are slightly lower at -150°C. For many of the specimens tested at -150°C, important load drops were observed. Maximum displacements are also a little higher at -150°C. The effect of temperature is more important for the 12.7 mm diameter impactor. The above mentioned points are more pronounced for this impactor. Also, for the mass of 10 kg at -70°C and -150°C, the impactor hits the bottom skin. This is visible on the load versus time curves which show a second bell (Figure 2). Moreover, the smooth curve for the second impact at -70°C indicates a limited amount of damage on the second skin. At -150°C, load drops are presented in the second part of the curve. It indicates the presence of damage.

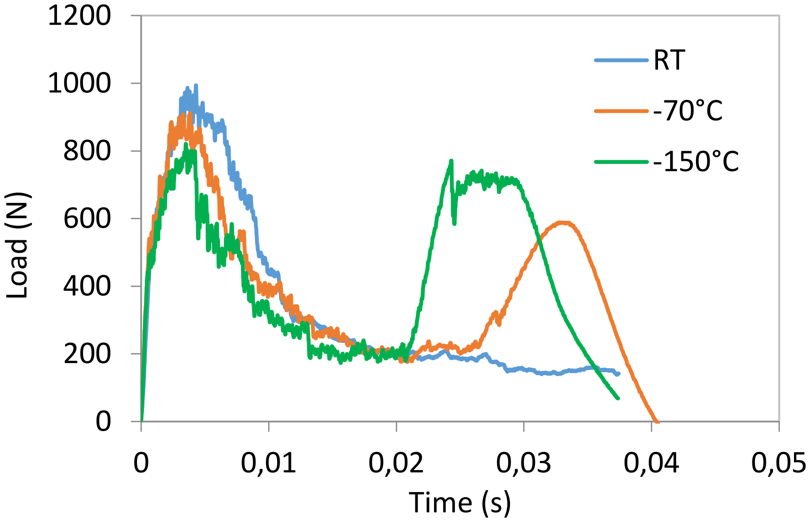

Figure 2. Typical load-time curves for the 12.7 mm diameter impactor with a 10 kg mass at RT, -70°C, and -150°C.

5.2 Damage Evaluation

5.2.1 Visual inspection

Visual inspections of all the specimens were performed. More cracks were generally observed on the upper skin with decreasing temperature, except for the 25.4 mm diameter impactor with a 5 kg mass. In that case, damages were barely visible at all three temperatures. Figure 3 presents the damage observed at RT, -70°C, and -150°C for the 25.4 mm diameter impactor with the 10 kg mass. For the 12.7 mm impactor with the 10 kg mass, there are visible damages on the bottom skin for the specimens impacted at -150°C.

a) RT b)-70°C c)-150°C

Figure 3. Typical damage for specimens impacted with the 25.4 mm diameter impactor and the 10 kg mass.

5.3.1 Residual depth of indentation

The residual depth of indentation was measured with a 3D digital image correlation system. Table 5 presents the residual depth of indentation for the 12.7 mm impactor with a 5 kg mass and the 25.4 mm diameter impactor with the 5kg and 10 kg masses. For the two other impact conditions, damage was too extensive to properly measure the residual depth of indentation. Residual depths of indentation are similar at RT and -70°C for the 24.5 mm diameter impactor, but go deeper at -150°C. For the 12.7 mm diameter impactor, an increase in residual depth of indentation is observed from RT to-150°C.

Table 5. Residual depth of indentation in millimeters in function of temperature.

		RT		-70°C		-150°C	
Impactor	Load	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
12.7 mm	5 kg	0.72	0.09	1.05	0.29	1.89	0.32
25.4 mm	5 kg	0.25	0.04	0.25	0.04	0.33	0.04
	10 kg	1.18	0.15	1.23	0.18	1.91	0.36

6. Conclusion

Experimental characterization of the constituents of the sandwich panel has shown that temperature has an important effect on the strength of the composite skins. In tension, the strength decreases with temperature, while in compression the opposite is observed. The in-plane shear behaviour of the laminate tested is also highly affected by temperature. A more brittle behaviour is observed at extreme cold temperature. For the Nomex honeycomb core, it is the elastic part of the out-of-plane behaviour that is most influenced by temperature.

Results of the impact tests show that the specimens impacted with the 12.7 mm diameter impactor are more affected by extreme low temperature than the one impacted with the

25.4 mm diameter impactor. Also, the preliminary damage observations and measures show that there is more damage at -150°C for all impact conditions.

7. Acknowledgments

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

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