IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: S P Zaoutsos 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **700** 012017

IOP Conf. Series: Materials Science and Engineering **700** (2019) 012017 doi:10.1088/1757-899X/700/1/012017

Mechanical behavior of aluminum honeycomb sandwich structures under extreme low temperature conditions

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Abstract. The current study is an effort to characterize the mechanical response of panels that are used as structural elements at low temperature applications. For the above reason, plaques of aluminum honeycomb sandwich were exposed for a certain period of time at different low temperature profiles ranging from 23ºC to -70ºC so that possible variation of their mechanical properties due to temperature exposure to be justified. Four different temperatures namely 23°C, 0°C, -40°C and -70°C were applied to these plaques prior mechanical testing that was performed at different loading modes. Specimens were obtained from these plaques in order to study the effect of low temperature on mechanical behavior and damage response of the specific sandwich structures. Extensive mechanical testing was carried out by means of tensile, compression and bending loading and the respective mechanical properties occurring from these tests were determined. From the results occurring from experimental data obtained from mechanical testing it is evident that there is a moderate decrease of ultimate strength and yield strength of the material as service temperature decreases in tensile, edgewise and flatwise compression as well as in three point bending loading modes. Moreover a drop in temperature results in a decrease in strain at rupture at tensile and compression loading.

1. Introduction

Sandwich constructions are lightweight structures that are used in many industrial and engineering applications like automotive industry, offshore and marine applications or aero-space. As the demand for low weight in combination with excellent mechanical properties increases in the above applications, extensive studies for the mechanical behavior of sandwich constructions are needed to be carried out in order to assure their structural integrity and reduce the possibility of failures.

Usually sandwich components consist of two facing layers (skins) separated by a core material. In most cases the skins are aluminium [1-3], reinforced polymers [4,5] or metals [6,7] depending on the application. In addition the core material can be a lightweight polymer foam or even a geometrically more complex material such as aluminium, sheet or polymer honeycomb. Generally the sandwich is an attractive structural design concept since, by the proper choice of materials, constructions having high ratios of stiffness-to-weight can be achieved.

However sandwich constructions usually suffer from debonding and delamination between skin and core occurring either from impact, bending, tensile or compressive loading. Other common kind of failures are buckling of the skins or intra-cell wrinkling mainly occurring from compressive or bending loading resulting once more in delamination between core and skin.

When these materials are used in offshore, marine or aerospace applications undergo important temperature variations in service. Due to difference between the coefficient of thermal expansion (CTE) of the skin and the core, as well as mechanical degradation occurring from low temperature exposure significant stresses are induced in the overall construction. Those stresses can produce microcracking and cause deterioration of the mechanical properties of the sandwich structure.
As the use of aluminum alloys is expanding in a variety of applications that are used in offshore infrastructures such as jacket structures, liquid natural gas carriers or drillships, these structures demand a detailed knowledge of the mechanical behavior of the materials that are used in the service temperature. Thus, the issue of the mechanical characterization of these materials and the understanding of their response under loading and fracture in extreme low temperatures is of great significance for their use as structural elements.

As far as the aluminum sandwich structures are concerned although their use is very popular in many engineering structures, a few researchers have studied the specific behavior that they exhibit in low temperature conditions [8, 9]. Usually aluminum preserves its structural efficiency in low temperature conditions although may lose its moderate ductility thus temperature may have an impact on the type of failure [10-12]. On the contrary, geometrical complexity of a sandwich structure may result to lower values of strength and rigidity due to the core or the skin. Moreover, interface between the core and the skin, which is usually an epoxy resin, suffers from temperature variations due to change in ductility and the resulting embrittlement of the polymeric nature of the polymeric system.
In the current study aluminum honeycomb sandwich plaques were exposed at low temperatures profiles and possible variations of their mechanical properties were experimentally investigated at different loading modes. Changes in these properties at the above mentioned conditions will justify the use of these materials in demanding applications such as offshore or aeronautics structures.

2. Materials and Methods

Sandwich panel used in the study consisted of two aluminum sheets of 3000 series type and a lightweight thicker aluminum honeycomb core material of 3003 type, of a mean weight 6,3 kg/m^2.
The nominal dimensions of each panel were a standard width of 1000 mm with a width tolerance 0/2.0 mm and a standard length 1000 mm with a length tolerance 0/3.0 mm. The thickness of each panel was measured at 20 mm with a tolerance of ± 0.2 mm. Aluminum thickness top and back cover sheet had 1 mm thickness while typical mechanical properties of the sandwich panel aluminum elements are shown in Table 1.

Table 1. Aluminum honeycomb panel technical data

	Aluminum skin	Core
Aluminum type	Aluminum 3000 series	Aluminum alloy 3003
Ultimate tensile strength Rm [N/mm^2]	159,31	
Modulus of elasticity, E [N/mm^2]	35288	
Compressive strength [MPa]		195
Core density [kg/m^3]	38,4	38,4
Cell size [mm]		9,5

3. Experimental Procedure

3.1. Conditioning of aluminium sandwich specimens

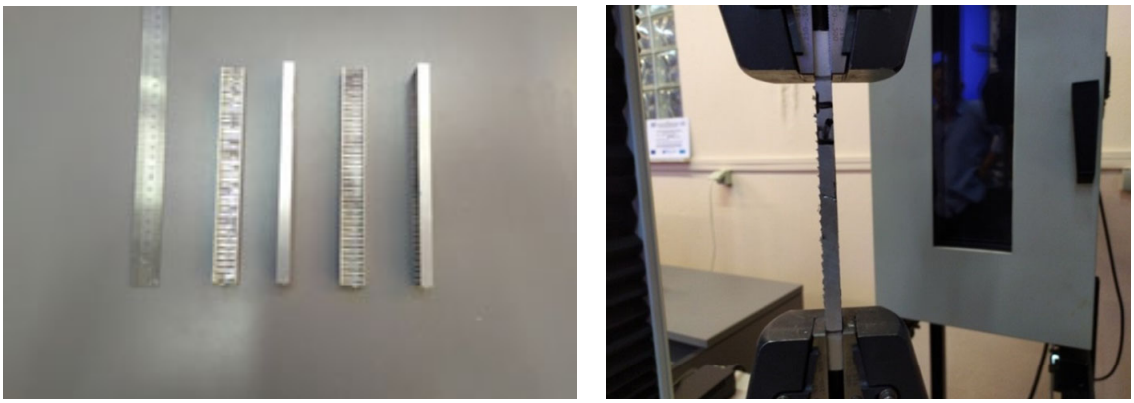
Specimens in the desired dimensions were cut from the aluminum honeycomb sandwich plaques, set in an environmental chamber Votch VC^3 4060 and exposed for a certain period of time of 10 months at low temperatures profiles ranging from 23ºC to -70ºC so that possible variations of their mechanical properties to be experimentally investigated. Four different temperatures namely 23°C, 0°C, -40°C and -70°C were applied to these plaques in order to study the effect of low temperature on the mechanical response and damage of aluminum sandwich structures. Temperature was measured in each series of

specimens for all the exposure period in order to assure temperature was kept constant and that no temperature variation was observed during the temperature exposure period.

3.2. Quasi-Static Mechanical Test

A test program was applied in all specimens through a series of mechanical tests that were performed in order to characterize the aluminum honeycomb sandwich material at different quasi static loading modes. Mechanical testing in the desired loading modes was performed in an ISTRON 3382 Universal Testing Machine of a load capability of 100 kN (22,400 lbf). The device is equipped with a data acquisition system controlled from Instron Bluehill® Lite Software to record load and displacement.

3.2.1. *Tensile tests.* Tensile tests were conducted in order to determine tensile mechanical properties of the material at different temperature profiles so that the possible mechanical degradation of the structure to be determined. The tests were performed according to the ASTM standard D 638-02A [13] with nominal dimension of the specimens were 10 mm X 20 mm X 200 mm. and a crosshead speed rate of 0.5 mm/min.



(a) (b)

Figure 1. Specimens a) before and b) during tensile tests.

3.2.2. Compressive tests. Flatwise compressive tests were performed on specimens that were cut for this purpose from the aluminum panels according to ASTM standard ASTM C-365-94 [14]. Testing was performed at crosshead speed rate of 0.5 mm/min on specimens with nominal dimensions of 100mm X 100 mm X 20 mm (Figure 1a). The edgewise compressive tests allowed evaluating the in-plane bending behavior of the sandwich panels. Edgewise compressive tests were performed according to ASTM standard C-364-94 [15] on three specimens of the same temperature exposure, with dimensions of 100 mm X 200 mm x 20 mm each (Figure 2a), at a crosshead speed rate of 6 mm/min.

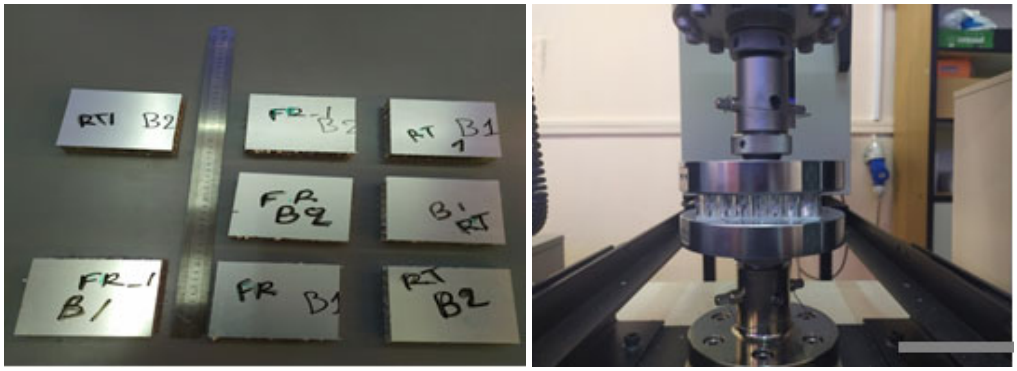


Figure 2. Specimens a) before and b) during flatwise compression tests.

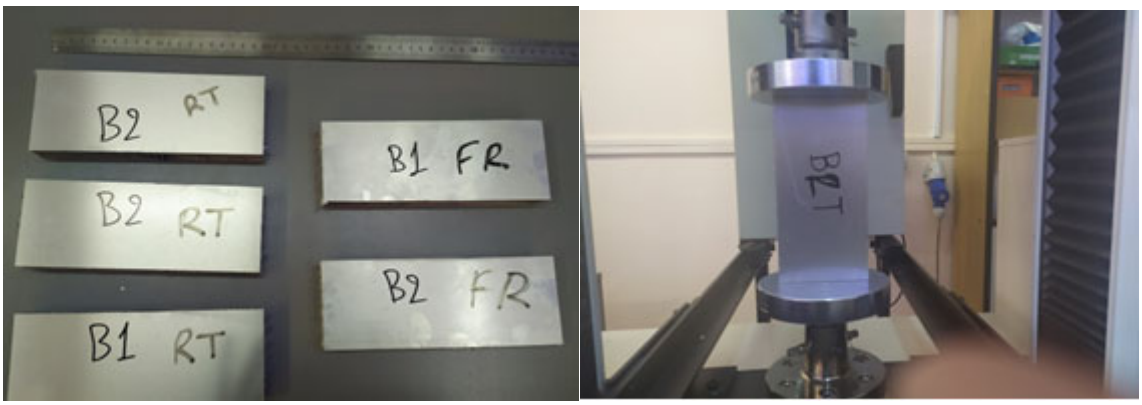


Figure 3. a) Specimens for edgewise compression b) Edgewise compression testing in aluminum sandwich specimen.

3.2.3. Flexural tests. Quasi-static three-point bending tests were carried out on specimens from aluminum sandwich panels according to ASTM C-393-94 [16] in order to study the bending behavior of the sandwich panel. The nominal dimensions of each specimen were 75 mm x 200 mm x 20 mm (Figure 4) while the crosshead speed rate of the test was set as 2 mm/min. A group of three specimens at each temperature condition was tested in order to assure that the repeatability of the experimental procedure.

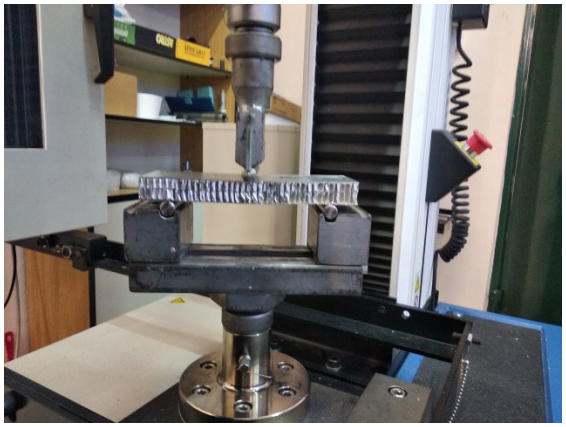


Figure 4. Specimen tested at three point bending loading mode.

4. Results and Discussion

Experimental stress-strain curves of the tested sandwich specimens occurring from respective tensile tests are shown in Figure 5. Additionally from Figure 6a it can be seen that the tested material preserves its ultimate tensile strength as the temperature drops from 23 ºC to -70 ºC. The same observation is also evident for the yield tensile strength. Tensile failure in the aluminum sandwich specimens loaded in tension took place in form of breakage of the skin as it can be seen if Figure 7. By comparing the tensile failure points for all temperatures, we can observe that at low temperature tensile failure occurs at almost the same value of stress but in lower values of strain implying that the material becomes less ductile as temperature decreases (Figure 6b).

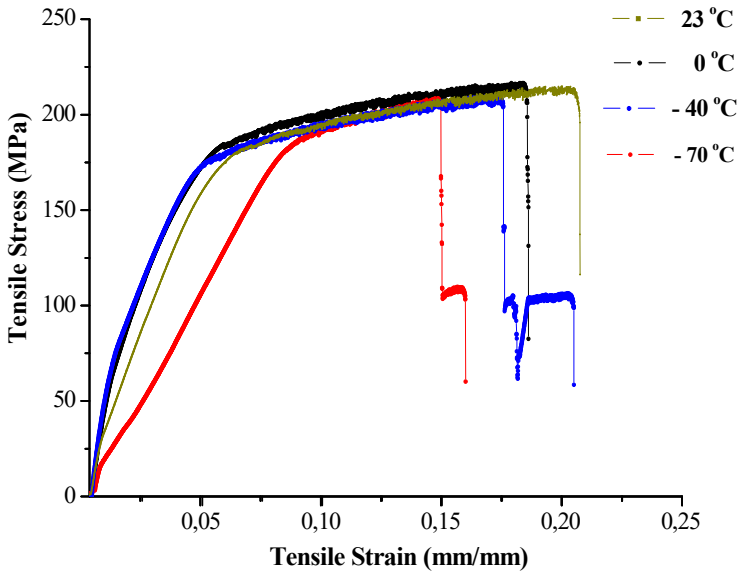


Figure 5. Variation of tensile stress versus tensile strain at different test temperatures.

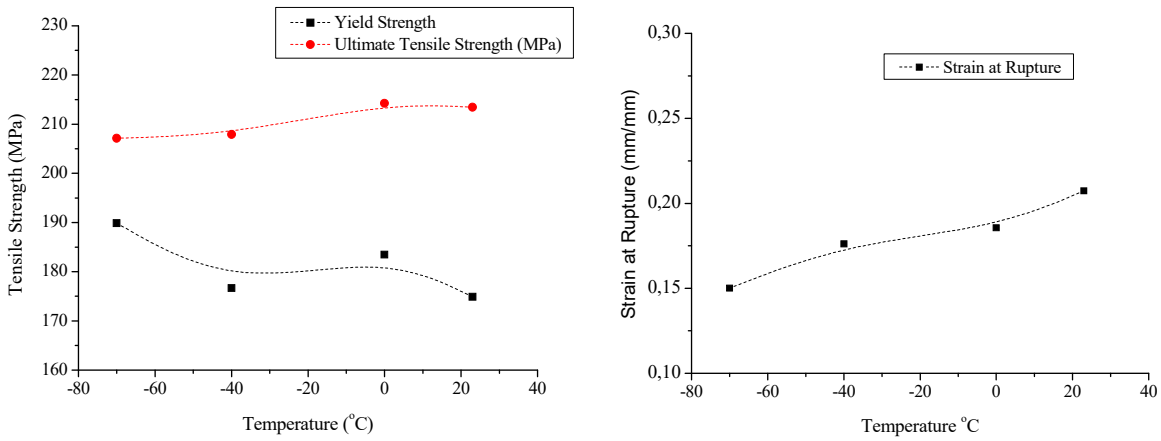


Figure 6. a) Variation of a) Yield tensile strength and ultimate tensile strength and b) Strain at rupture as a function of temperature.

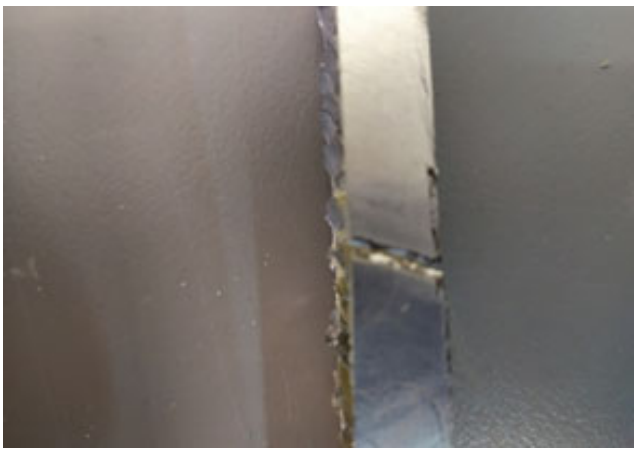


Figure 7. View of a specimen after a tensile test at -70 ºC.

Compression stress versus compression strain curves in the edgewise direction are depicted in Figure 8 respectively. The ultimate and yield compressive strength is decreased especially in the case of -40 and -70 °C as it can be seen in Figure 9a. In that case strain at rupture also exhibits lower values as temperature a decrease denoting that the material loses in ductility (Figure 9b).

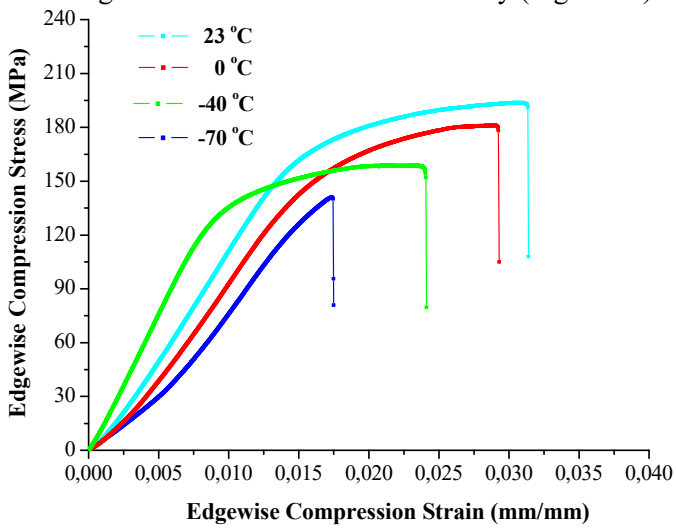


Figure 8. Stress-strain curves occurring from edge wise compression for specimens that were exposed at different temperature

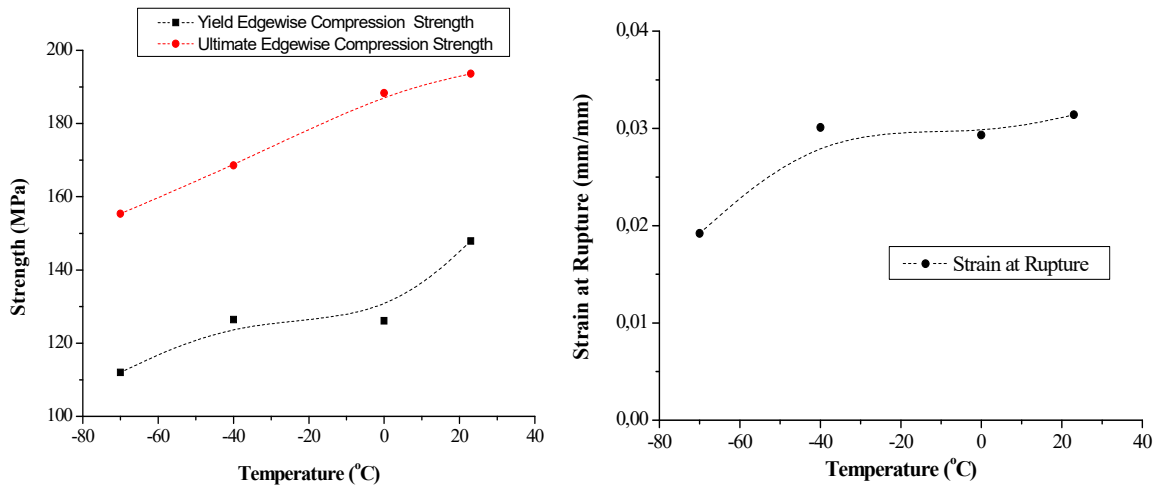


Figure 9. Graphical representation of a) ultimate edgewise compression strength and yield edgewise compressive strength and b) strain at rupture for compression test, as a function of temperature exposure.

The fracture mode of the specimens subjected to edge wise compression is characterized by buckling instability of the skins, followed by delamination and by crushing of the skins near the hydraulic machine's plates as it can be seen Figure 10. A complete delamination between the skins and the core was observed in all temperature levels.

The stress strain curves of aluminum sandwich material subjected to flatwise compression at different test temperatures are graphically represented in Figure 11. As the temperature decreased the flatwise compression strength slightly decreases, and the flat wise compression strain at rupture drops as represented in Figures 12a and 12b respectively. This is probably due to the fact that aluminum does not change its properties in brittleness radically even at low temperature. The specimens showed core failure at any temperature. The fracture pattern of the test specimens of the sandwiches subjected to flatwise compression is shown in Figure 13. The damage induced in the specimen mainly concerns the aluminum core leading to collapse of its cells and the failure of the sandwich panel.

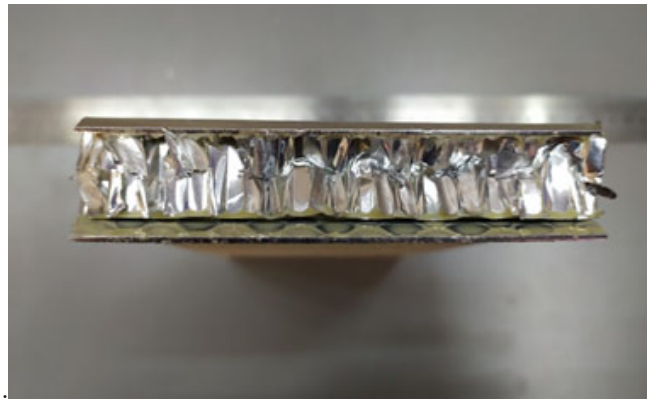


Figure 10. View of a specimen after an edgewise compression test at -70 ºC.

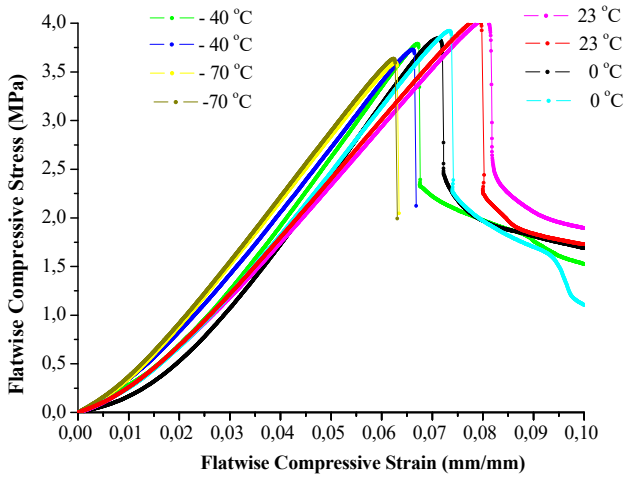


Figure 11. Stress-strain curves occurring from flatwise compression tests at different temperature profiles.

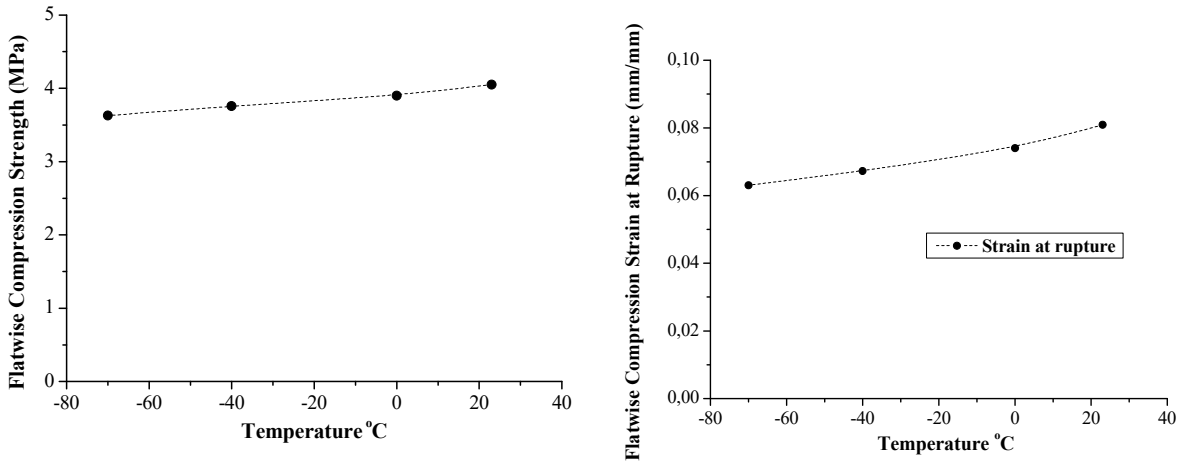


Figure 12. Graphical representation of a) ultimate flatwise compression strength and b) strain at rupture for compression flatwise test, as a function of temperature exposure.

Figure 13. View of a specimen after a flatwise compression test at -70 ºC.

The stress versus strain curves of the sandwich panels with aluminum honeycomb core and skins under three-point bending testing for different tested temperature profiles are shown in Figure 14. These curves can be divided into two groups, the former with an inelastic evolution at 23 ºC and 0 ºC and the later with an elastic evolution at -40 ºC and -70 ºC (Figure 15). However both ultimate bending strength and yield bending strength exhibit a moderate sensitivity in the changes of temperature as it can be seen in Figure 15. The ultimate bending strength of aluminum sandwich panels is governed by the instability of the top skins under compressive forces as it can be seen in Figure 16.

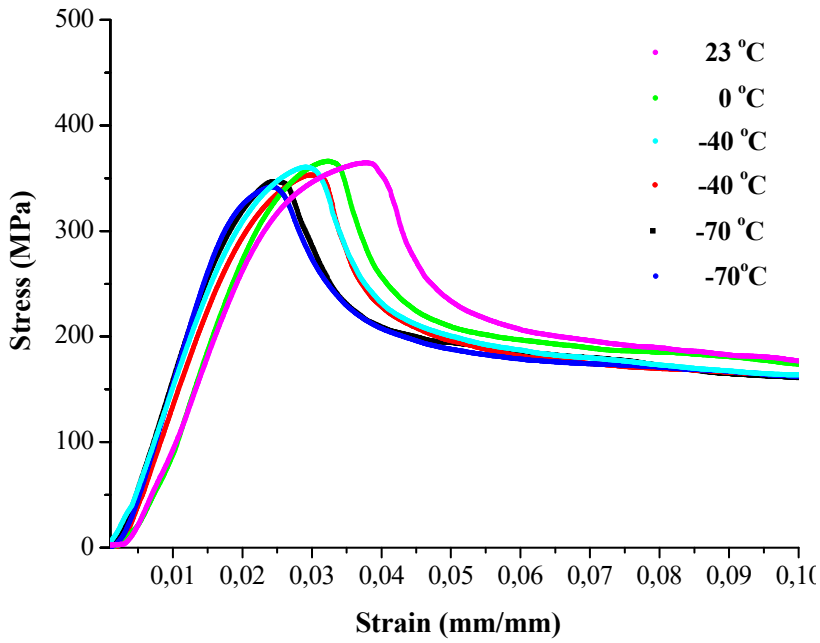


Figure 14. Stress-strain curves occurring from three point bending tests for specimens that were exposed at different temperature.

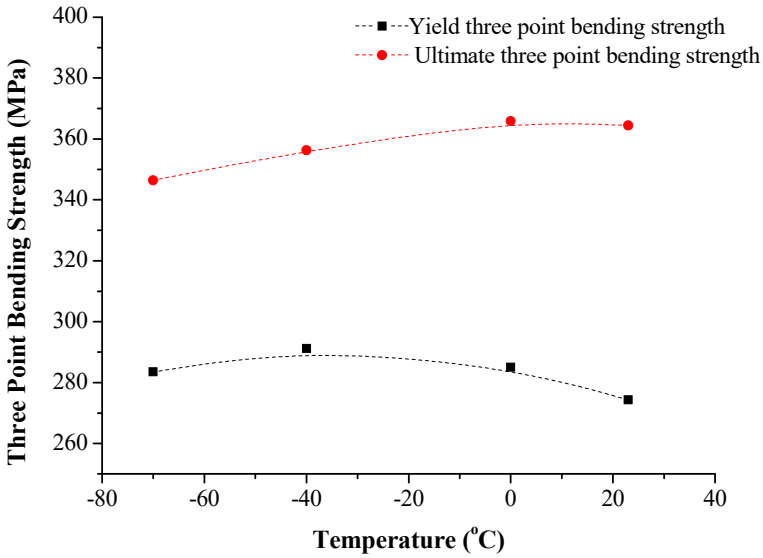


Figure 15. Graphical representation of ultimate flatwise compression strength and yield flatwise compression strength, as a function of temperature exposure.

Figure 16. View of a specimen after a three point bending test at -70 °C.

5. Conclusions

Mechanical tests were performed in aluminum honeycomb specimens that were prior exposed to different temperature conditions in order to study the effect of this type exposure in the strength of and the overall mechanical behavior of the tested materials.

Ultimate tensile strength and yield strength are not affected from changes of temperature; while in the case of compression loading the respective values of strength seem to be decreased as temperature decreases. However, in all cases strain at failure is decreasingly affected by temperature conditions a fact that is attributed to the embrittlement of the material as temperature drop in value. As far as the bending strength is concerned the values of ultimate strength and yield strength are not affected by the temperature.The experimental data can be used for the selection of lighter and stiffer combination of sandwich panels according to the temperatures and loading conditions.

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