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EXPERIMENTAL CHARACTERIZATION OF CAI STRENGTH OF LAMINATED COMPOSITE SHELLS

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Abstract. *This work presents an experimental characterization of the curvature effects on the Compression After Impact (CAI) strength of laminated composite shells. Impact tests were carried out using composite shells with three different curvatures (k=0 m^{-1}, k=0.01 m^{-1}, k=0.005 m^{-1}) at three different impact energy levels for each curvature named low, medium and high impact energies. The impact tests were performed using an in-house drop test tower available in the Aerospace Structures Laboratory at ITA. A CAI testing setup was designed and implemented to evaluate the impact induced damage tolerance of the composite shells. The experimental results indicate that the compressive residual strength of the composite shells is significantly affected by the shell curvature.*

Keywords: *Composite materials, CAI, Damage Tolerance*

1. INTRODUCTION

Nowadays the demand for lighter structures in the aeronautical segment in order to reduce weight and optimize aircraft performance the use of laminates composites is increasing (Boeing, 2006). Composite structures are usually subjected to impact induced damage. The impact induced damage may occur due to collisions of small fragments on land hitting the fuselage or maintenance procedures. These impacts can cause barely visible damages in the structure, such as, delamination, inter-laminar failure and eventually resin cracking and fiber breakage which can in a critical situation, lead to catastrophic failure. In recent years a considerable effort has been dedicated to better understand the impact induced damage tolerance of composite laminates.

In many situations the level of impact at which visible damage is formed is much higher than the level at which substantial loss of residual properties occurs (Freitas and Reis, 1998). The delamination at low impact energies cause little effect on the tensile strength but significantly reduce the compressive strength of composite laminates. The compression after impact strength reduction is mainly caused due to laminate buckling around the delaminated areas. Therefore several researches have been conducted to identify the impact response and post-impact compression behavior in order to improve the impact damage tolerance of laminated composites.

Industry standards (ASTM D7137, 2012) present the guideline to determine the compression residual strength properties of damaged polymer matrix composite plates, but this guideline is only for flat rectangular composites and there are no standards for curved composite laminates. The results obtained from this test, according to the ASTM D7137, 2012 are highly dependent upon several factors, which include specimen geometry, layup, damage type, damage size, damage location, and boundary condition. They also assert that this test could be applied for undamaged samples but historically the results shows undesirable failure modes.

Several works have been published in order to understand the effects caused by impact loads in the residual strength of compressed plates (Short, *et al.*, 2002). Unfortunately few articles include pressurization and curvature effects. Ambur and Starnes, 1998 studied the response and failure modes of curved carbon laminates with 8 and 16 layers almost isotropic when submitted to low impact energy levels. The result shows that the required energy level to start the damage is function of the thickness and the curvature. The results also showed that residual strength for impacted flat or with small curvature reduced 3% and 15% respectively when compared with no impacted samples.

Kuilkarni, *et al.*, 2011, carried out impact tests with internal pressurization on fiber glass laminates. At the end of the study the author concluded that the internal pressurization increases the impact resistance and this phenomenon is equivalent to increase the laminate thickness. Furthermore Kuilkarni, *et al.*, 2011, also observed that the damaged area is a function of both impact energy level and pressure. The largest damaged area was observed for higher levels of pressurization as well as the lowest compression after impact residual strength.

L. Ballère, *et al.*, 2009 studied the residual strength after CAI on tubes made of carbon fiber. After the impact the damage was characterized using ultrasound techniques. At the end of the experimental analysis L. Ballère, *et al.*, 2009 concluded that the residual compressive strength is a function of position and number of damaged layers. He also concluded that up to determined impact energy level corresponding to 4/7 of damaged layers (lower than 40J), the laminate does not present significant reduction in residual strength. Moreover for higher impact energy levels the author noticed that the residual strength was substantially decreased.

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Mendes, *et al.*, 2012 developed an analytical study of the curvature influence on compression after impact strength of carbon fiber laminates. In their study four different curvatures were tested in different energy levels using a damage model proposed by Donadon, *et al.*, 2008. At the end of the work Mendes, *et al.*, 2012 realized that the proposed model showed consistent results and also concluded that higher the curvatures more impact damage tolerant is the laminate. This work presents an experimental analysis in order to validate the numerical results presented by Mendes, *et al.*, 2012. Samples were manufactured in three different curvatures (k=0 m^{-1}, k=0.01 m^{-1}, k=0.005 m^{-1}) and then impacted in low, medium and high energy impact levels with and without pressurization. Later on all samples were inspected with C-Scan technique and then submitted to compression after impact testing. During the compression test a 3D optical system was used in order to measure the out-of-plane displacement field in order to verify buckling. The experimental results indicate that the compressive residual strength of the composite shells is significantly affected by the shell curvature and pressurization.

2. EXPERIMENTAL TESTS

2.1 Manufacturing of the composite plates

As discussed before several references can be found for CAI strength of flat composite laminates but, there are few references regarding CAI strength laminate composite shells and even less references studying the effects of curvature combined with pressurization on the impact resistance and damage tolerance of composite laminated. Yokoyama, 2012 studied the impact resistance of laminate composite shells. In order to validate the numerical results the authors designed special purpose testing fixtures for testing the composite shells. Figure 1 depicts the moulds used to manufacture the composite shells. The samples were manufactured using the RIFT (Resin Infusion under Flexible Tooling) process. Three different curvatures ($k=0\ m^{-1}$, $k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$) were manufactured using Hexcel carbon fiber (AGP193-P) and Huntsman epoxy resin (Araldite LY 5052 / Aradur 5052). For the curing process the laminates were retained at 25°C for 24 hours followed by 4 hours at 100°C.

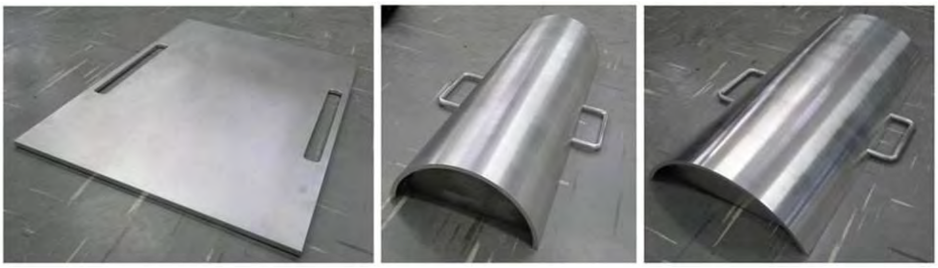

Figure 1. Manufacturing Mold ($k=0\ m^{-1}$, $k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$)

In order to compare with non impacted composite shells 9 additional samples were manufactured using the same raw-material, same lamination sequence $[(0,\pm45,90)_2/0]_s$, same process, same equipments and also the same curing cycle used by Yokoyama, 2012.

After curing all samples were cut using an in-house diamond saw cutting machine designed at ITA. At least 10,0 mm of each edge were removed to avoid areas with low concentration of resin before the final cut in the appropriate dimension. The samples thickness were measured using micrometer and the obtained values were between 4,24 and 4,60 mm. Figure 2 shows the non impacted samples used as reference.

Figure 2. Manufactured samples used as reference ($k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$, $k=0\ m^{-1}$)

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2.2 Impact test

The impact test was performed using an in-house drop tower test available at ITA. Figure 3 show the drop tower test and Figure 4 show the testing fixture developed to perform the impact tests.

Figure 3. Drop Tower Test

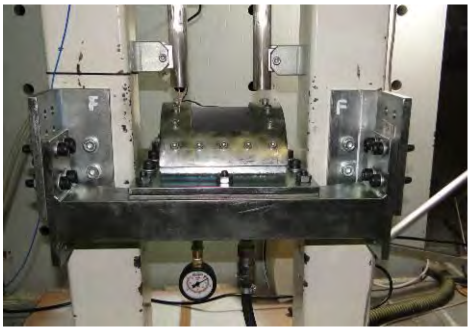

Figure 4. Impact test fixture with manometer

The impact test was performed in the three different levels of energy named low (12J), medium (20J) and high (35J) impact energies for each curvature ($k=0\ m^{-1}$, $k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$) with and without pressurization. The energy level was adjusted performing a pre-test in an aluminum plate in order to compensate the friction loss between the impactor and the drop tower test. Figure 5 shows the pressurization system used on samples impacted with pressurization.

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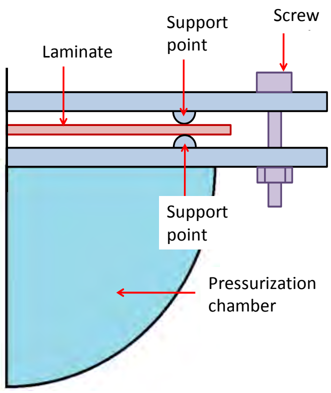

Figure 5. Pressurization system

2.3 Ultra sound inspections

The damage created by impact test was inspected using C-Scan ultrasound equipment available at ITA laboratory. The ultrasound test was used to measure the damaged area. Figure 6 shows some examples of the ultrasound test results.

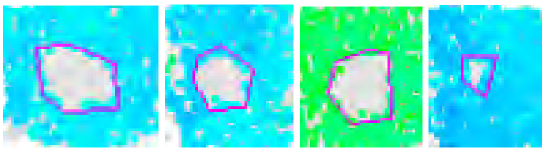

Figure 6. Example of Ultrasound test results

2.4 Compression Test

To perform the compression test a mechanical fixture was designed using SolidWorks, Fig. 7. This fixture was designed to support both composite shells ($k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$) in a vertical position, Fig. 8. All fixture parts were manufactured using AISI Steel 4340 and then tempered and quenched to reach superficial hardness of 38 to 42 RC. Later on all parts received superficial protection.

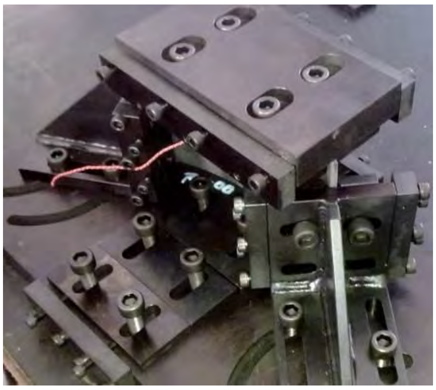

Figure 7. Fixture developed to perform compression test

Figure 8. Different curvatures assembled on fixture ($k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$)

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The lateral support was designed to support the composite shell, to avoid buckling, and also to guarantee the same boundary condition (simply supported), Fig. 9.

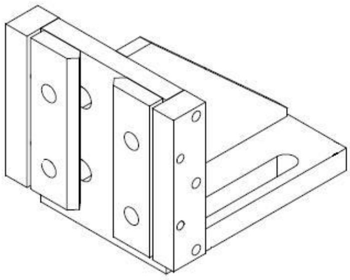

Figure 9. Lateral support

It was necessary to manufacture different parts to support different curvatures on the upper and lower part of the CAI testing fixture, Fig. 10.

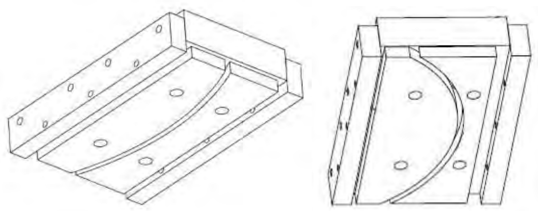

Figure 10. Upper support with different parts to hold different curvatures ($k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$)

To perform the compression test on flat panels ($k=0\ m^{-1}$) the same CAI fixture proposed by ASTM D7137, 2012 was used, Fig. 11.

Figure 11. Fixture used to perform compression test on flat composite laminates ($k=0\ m^{-1}$)

A 200 tons BALDWIN testing machine was used to perform the CAI tests. A 250 kN load cell was used to measure the load and LVDT was used to measure the machine cross-head displacement, as shown in Fig. 12. Both equipments were manufactured by HBM. HBM MGCPlus system with CATMAN software was also used to acquire the data.

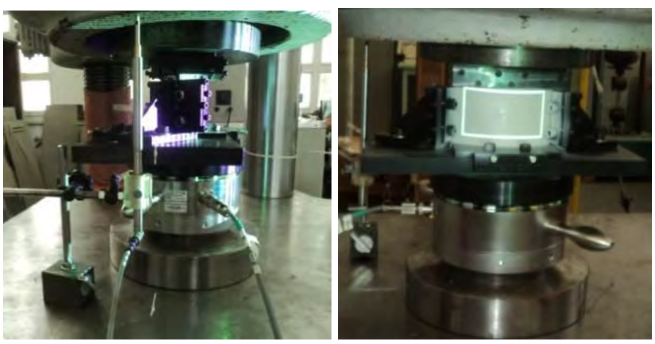

Figure 12. CAI test setup

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ASTM D7137, 2012 standard recommends that the onset of panel instability or excessive bending invalidates the test. For the test results to be considered valid, percent bending shall be less than 10%. In order to verify the buckling a 3D optical system was used to measure the out-of-plane displacements during the tests Fig. 13.

Figure 13. 3D optical system.

All laminated composite shells were assembled in the compression fixture in a way that all boundary condition were simply supported and free to expand laterally. This condition is important mainly due to Poisson's ratio. Based on this the design accounts for a gap of at least 1,5 mm between the sample and the lateral support, Fig. 14.

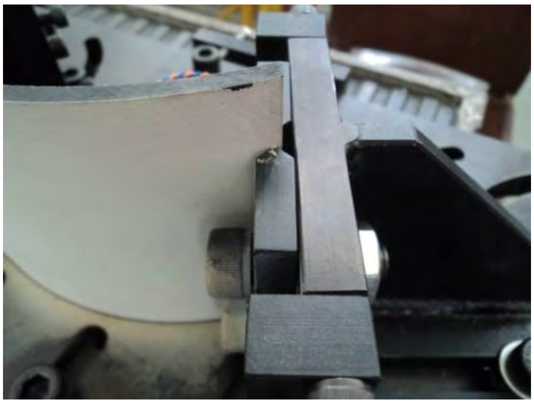

Figure 14. Details of the lateral support

For flat composite laminates the 3D optical system was not used because buckling was already verified by Amorim, 2011. In order to minimize this effect an anti buckling system was included (two steel plates, one on each side of the sample) Fig. 15.

Figure 15. Boundary condition for flat samples and anti buckling system

3. RESULTS

3.1 Ultrasound test results

Figure 16 shows the results of the ultrasound inspections for all composite laminates impacted (k=0 m-1, k=0.01 m-1, k=0.005 m-1).

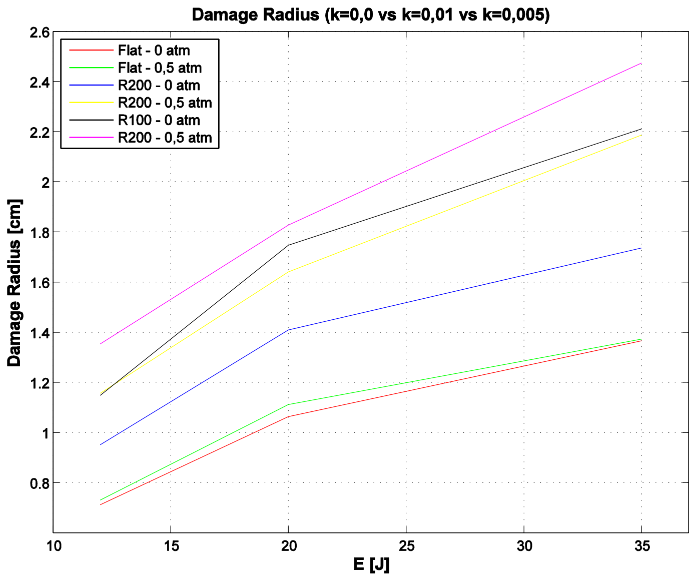

Figure 16. Damaged radius ($k=0\ m^{-1}$, $k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$)

According to Fig. 16 the damaged area clearly increases as the curvature and energy impact level increases. Another interest point observed on the studied conditions is that the damaged areas for pressurized shells were larger for curvatures ($k=0.01\ m^{-1}$, $k=0.005\ m^{-1}$) in comparison with flat plates. The experimental results indicate that the pressure does not affect the damage area of the flat composite laminates ($k=0\ m^{-1}$).

3.2 Determination of CAI Strength

Figure 17, Fig. 18 and Fig. 19 shows the CAI results. These figures compare the equivalent damage radius versus impact energy versus CAI strength.

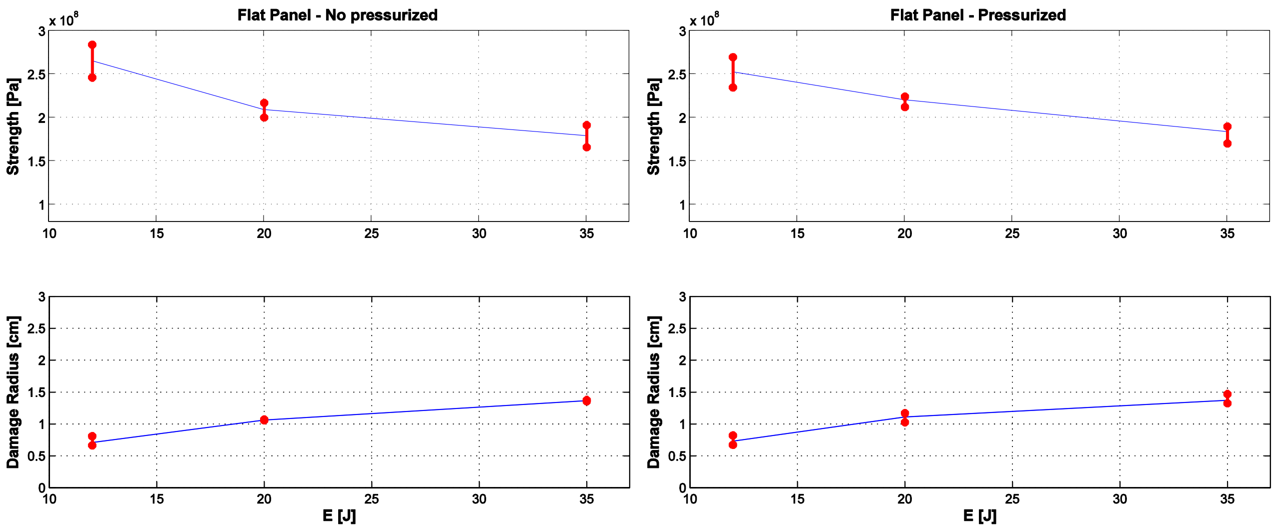

Figure 17. Flat composite laminate ($k=0\ m^{-1}$) – Damaged radius vs Impact Energy vs Compression strength (with and without pressure)

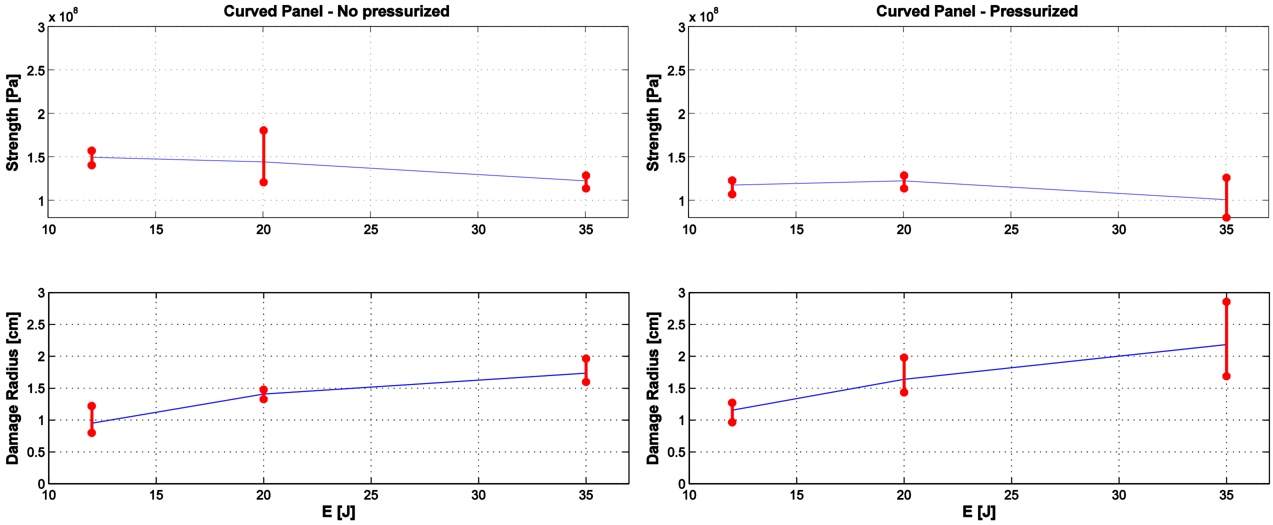

Figure 18. Medium curved composite laminate (*k=0.005 m*$^{-1}$) – Damaged radius vs Impact Energy vs Compression strength (with and without pressure)

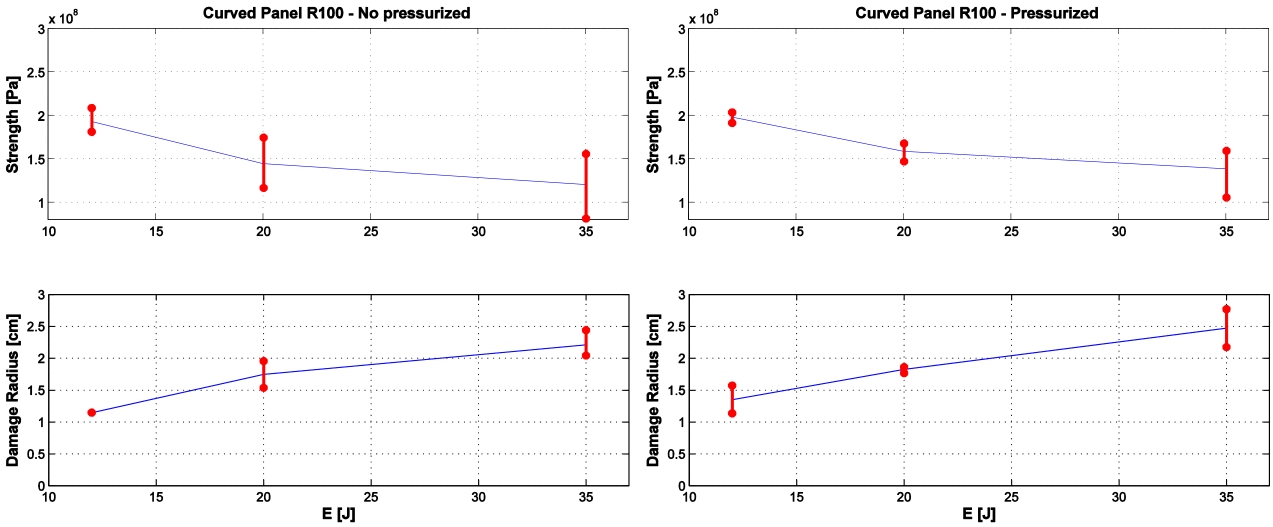

Figure 19. High curved composite laminate (*k=0.01 m*$^{-1}$) – Damaged radius vs Impact Energy vs Compression strength (with and without pressure)

As explained in section 3.1 as the impact energy level increases the damage area increases. On the other hand as the damage area increases the failure load decreases, as expected. All results were very consistent showing this phenomenon. It is also worth mentioning that for flat laminates (*k=0 m*$^{-1}$), Fig. Figure 17 shows that there was no considerable difference in damage area between pressurized and no pressurized samples. Nevertheless in terms of CAI strength the failure load was higher for pressurized samples. According to Fig. Figure 18, for medium curvature laminates (*k=0.005 m*$^{-1}$) the damaged area was larger for the pressurized samples and consequently the compression strength was lower as expected. Finally for higher curvature laminates (*k=0.01 m*$^{-1}$) the damage area was also larger for the pressurized specimens in comparison with unpressurized shells but the CAI strength was lower for pressurized samples.

The maximum measured out-of-plane displacements during the compression tests was 0.8 mm indicating that there was no buckling during the tests.

Figure 20, Fig. 21 and Fig. 22 show the normalized results in terms of the non impacted compression load samples.

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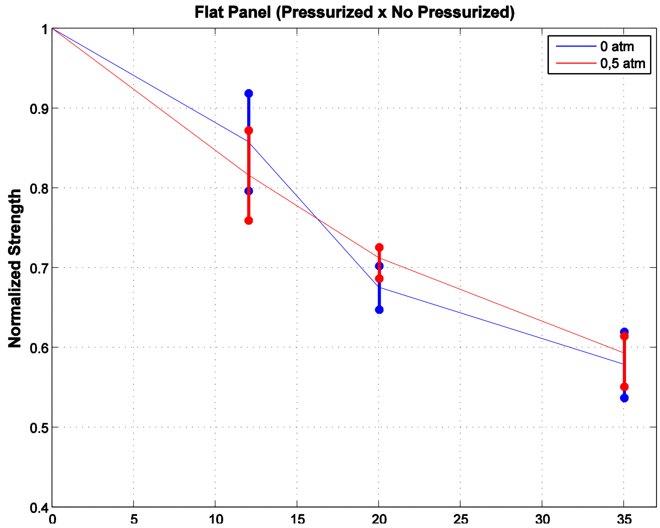

Figure 20. Flat composite laminate ($k=0\ m^{-1}$) – Normalized by non impacted sample

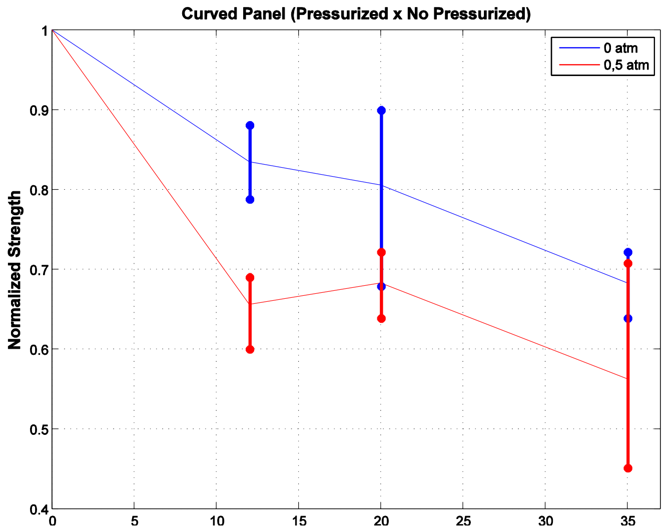

Figure 21. Medium curvature composite laminate ($k=0.005\ m^{-1}$) – Normalized by non impacted sample

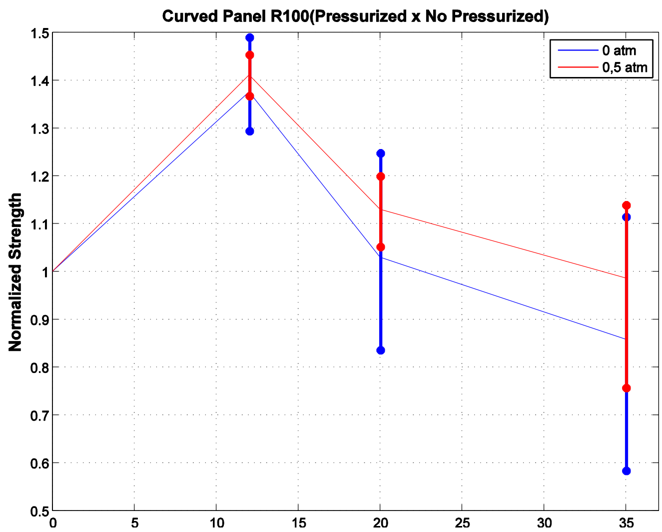

Figure 22. High curvature composite laminate ($k=0.01\ m^{-1}$) – Normalized by non impacted sample

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It was evident the difficulty to have consistent results for samples with $k=0.01\ m^{-1}$, Fig. 22. This was due to several factors, such as poor quality of the non-impacted laminates, ultra-sound inspection, cutting process, and mainly due to the influence of the boundary conditions during compression test.

Since the results obtained for the composite shells with higher curvature were not consistent, one needs to consider a comparison between the flat and medium curvature shell only. Taking into consideration the pressurization effect, the pressurized samples were less tolerant to impact induced damage. This phenomenon may be explained by the fact that the pressurization in the back face of the sample increases apparent the bending stiffness of the laminate, increasing the damage area and consequently reducing the failure load. Comparing pressurized versus non pressurized samples the CAI reduction was 18.1% for curved pressurized samples and almost no difference was observed for flat laminates (less than 1.0%).

Comparing the curved versus flat laminates, the curvature effect was beneficial for non pressurized samples increasing the damage tolerance. The CAI strength increased 11.6% for non pressurized medium curvature compared to flat samples. On the other hand the CAI strength reduced 9.6% for pressurized medium curvature laminate shells in comparison with flat laminates.
Figure 23, Fig. 24 and Fig. 25 show failure pattern after the compression impact tests.

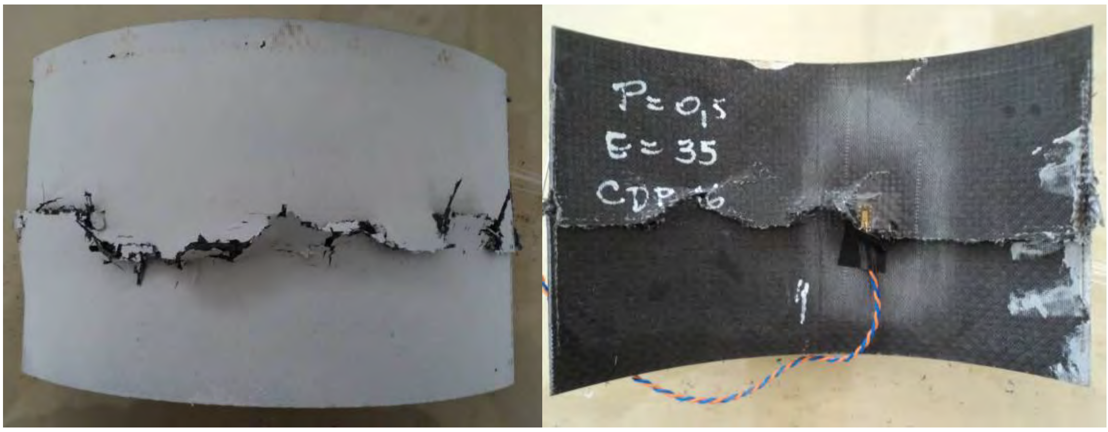

Figure 23. Curved sample after CAI ($k=0.01\ m^{-1}$)

Figure 24. Curved sample after CAI ($k=0.005\ m^{-1}$)

Figure 25. Flat sample after CAI (*k=0.00* m^{-1})

4. CONCLUSIONS

Experimental studies were carried out in laminated composite shells in three different curvatures (k=0 m^{-1}, k=0.01 m^{-1}, k=0.005 m^{-1}) and in three different energy levels, namely low, medium and high impact energies. The results indicated that buckling effects were not critical for curved samples as expected because curvature generally improves buckling strength. The results also indicated that the impact tolerance was significantly affected by:

1. Curvature;
2. Boundary conditions;
3. Pressurization;

The damage tolerance of medium curvature composite shells was improved for impact cases without internal pressure. The experimental results indicate that the pressurization effect reduces the impact damage tolerance of composite shells. It was expected to have a beneficial effect since the pressurization is similar to increase the laminates thickness. This effect may be explained since during the impact test all pressurized samples presented larger damage areas.

The results obtained for this study indicates that the curvature has a beneficial effect and pressurization has a detrimental effect on the CAI strength of laminate composite shells. Therefore, these factors should be taken into consideration during the design phase in order to increase safety, reduce weight and optimize aeronautical structures.

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