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IMPACT DAMAGE CHARACTERIZATION OF SANDWICH PANELS PRODUCED WITH CORK AND PVC TYPES OF CORE

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Summary: *Impact damage remains a major issue for composite structures; the impact of objects can create internal damage that can significantly reduce their structural strength. Aircraft structures are prone to impacts, which may result from many sources in the field, such as collisions with ground vehicles, gravel, hail, bird strike, tire fragments, among many others. The typical impact target can be found in many locations such as fuselage, nacelles, wing skins, control surfaces, etc. where the foreign impact can be near or away from internal stiffeners causing different damage levels in the structure. The impact characterization can be divided in three major items, i.e. the source velocity, impact angle, and the impact area, where is required the understanding of the event dynamics, predicting the extent of the induced damage, and estimating the structure residual strength.*

In this paper, it is analyzed the impact dynamics in sandwich panels made with two different types of core, i.e. cork and PVC, in order to characterize blunt impact events to aid in prediction of damage formation and its effect on structural strength. Moreover, it is studied the relationship between visible signs of impact and the inherent strength reduction. Results show the influence of the impact dynamics and their inherent structural damage and the different responses of different core materials given for the same impact energy.

1 INTRODUCTION

Aircrafts are subjected to several factors that can affect their integrity, such as ground impacts, bird and lightning strikes among others. One important aircraft structural component prone to these factors is the aircraft engine nacelle. Nacelles are housings that hold aircraft engines and comprise several structural components that have different functionalities such as intake air optimization at turbine entrance, braking functionalities at landing, and noise reduction. Acoustic emissions are strongly regulated by governmental identities being a major concern in nacelles design and research. One example is the new chevron jet nozzle recently developed by Boeing and NASA to reduce the exhaust noise emission [**1**]. In commercial aircrafts, noise reduction is partially performed by acoustic liners typically found in the inner barrel of the nacelles inlet cowl, which among other functionalities aims to dampen the vibration and noise from the turbine inlet and exhaust gases. Typically, these liners are sandwich structures made of a perforated aluminum sheet, an aluminum honeycomb, and a back skin made of carbon-fiber-reinforced polymer.

In the current acoustic liner design, the traditional materials selection has brought some problems related to several types of corrosion especially in aluminum alloys [**2**, **3**]. Avoiding this issue is extremely important because aluminum corrosion may de-bond the perforated aluminum sheet from the aluminum honeycomb. In this situation, the turbine may suck the de-bonded aluminum sheet into the turbine blades, which can damage the aircraft jet engine. In this research, the objective is to analyze the hypothesis in which the aluminum honeycomb can be replaced by a cork or PVC Divinycell in the acoustic liner sandwich panel in order to overcome the corrosion problems found in these structural components. It is well-known that cork has improved properties regarding fire resistance, noise isolation and vibration damping [**4-6**]. Its performance regarding impact strength however remains under study, especially in sandwich panels. Good impact strength is a pre-requisite and an important variable in nacelle design, thus here an analysis is performed regarding the impact strength of sandwich panels made of cork and PVC Divinycell in order to characterize their mechanical behavior under blunt impacts.

2 IMPACT TESTING

The main goal, as stated above, is determine the impact strength of sandwich structures to an impact event that could occur in an aircraft structure/component.

2.1 Specimen production and dimensions

The test specimens were prepared at IST, Mechanical department, starting with boards of 300 mm x 300 mm. All the specimens were sandwich structures with 2 layers of Glass fiber/epoxy multiaxial 0º/90º laminate with 240g/m^3 density. The core materials were either Cork composites Amorim CoreCork® NL10 or PVC Foam cores Divinycell H80, both with 2.0 mm thickness. One of the skins was painted with Gelcoat Crystic 253PA, for protection and aesthetic purposes. The bonding agent between the materials used was Resoltech 1040 Epoxy resin, and care was taken to insure that the specimen groups had samples from all the boards taken from production.

The boards were cut to 150X100 mm size following ASTM D7136 test method, with sandwich structure thickness averaging 4.2 mm, and 34 samples of each core material were tested, within a range of impact energies in order to ascertain the impact behavior of cork cores and its comparison with similar PVC cores.

2.2 Test methodology

The tests were carried out according to ASTM D7136 Standard test method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event, with a hemispherical ended cylindrical projectile, dropped from a known, variable height between guide rails onto clamped sandwich specimens. A variable mass was attached to the projectile and a piezoelectric load cell gave the variation of impact force with time. An optical gate gave the incident velocity of the impact head, and hence the velocity, displacement and the energy could be calculated from the measured force-time data by successive numerical integrations, knowing the impact mass. The tests were performed using a fully instrumented Rosand IFW5 falling weight machine as seen in Figure 1, with various weights and drop heights in order to be able to obtain both punctured specimens, in order to analyze the damage type on the lower face, and non-punctured specimens, for energy, force and Barely Visible Impact Damage (BVID) comparison.

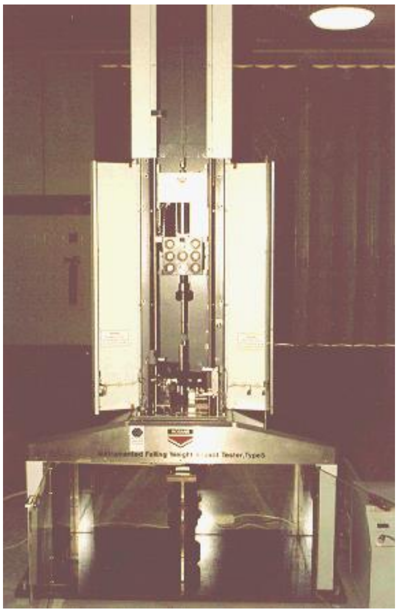

Figure 1 - Rosand IFW5 falling weight machine

2.3 Potential Impact energy

In order to study all of the impact effects, multiple potential impact energies were used during the tests. The test method determines a specific ratio of impact energy of 6.7 J/mm. However the test method was designed with monolithic composite structures in mind which are more resistant than sandwich composites. As such tests were performed with varying impact energies to determine the influence of the impact energy on the sandwich structures, please see Table 1.

Potential Energy			
E	100%	26.8	J
E	50%	13.4	J
E	33%	8.9	J
E	25%	6.7	J
E	16%	4.5	J
E	10%	2.6	J

Table 1 – Potential impact energies tested

The 64 specimens were divided, with 34 tests with NL10 cores and 34 with Divinycell H80 Foam core, with 9 initial tests for tune up, followed by 5 tests per core per potential energy level, with the exception of the impact tests at $1/6^{th}$ the specific energy ratio.

2.4 Test results

From Table 2 to Table 6 are presented the Averages, standard deviation and Coefficient of Variation of Force and Absorbed energy from the specimens for each level of Potential Energy tested.

100% Energy	Cork		PVC	
	Force	Abs Energy	Force	Abs Energy
Average	1660.5	11.6	1752.7	11.7
StdDev	203.4	1.7	184.4	1.1
CV [%]	12.3	14.5	10.5	9.5

Table 2 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy. 100% potential energy

50% Energy	Cork		PVC	
	Force	Abs Energy	Force	Abs Energy
Average	1473.68	11.23	1562.92	11.44
StdDev	62.20	0.87	63.66	0.49
CV [%]	4.22	7.76	4.07	4.28

Table 3 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy. 50% potential energy

33% Energy	Cork		PVC	
	Force	Abs Energy	Force	Abs Energy
Average	1305.07	8.25	1356.34	8.20
StdDev	98.42	0.06	27.02	0.04
CV [%]	7.54	0.68	1.99	0.54

Table 4 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy. 33% potential energy

25% Energy	Cork		PVC	
	Force	Abs Energy	Force	Abs Energy
Average	1167.02	6.02	1054.60	6.04
StdDev	84.22	0.03	66.38	0.01
CV [%]	7.22	0.56	6.29	0.18

Table 5 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy. 25% potential energy

16% Energy	Cork		PVC	
	Force	Abs Energy	Force	Abs Energy
Average	1041.13	4.21	1016.48	4.28
StdDev	44.77	0.11	89.54	0.02
CV [%]	4.30	2.57	8.81	0.52

Table 6 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy. 16% potential energy

Tables show some very interesting results; there is no statistically significant difference between the NL10 Cores and the Divinycell cores. There is no difference between the absorbed energy at 100% and 50% potential energy meaning that the specimens only begin to resist perforation somewhere below the 50% potential energy of the carried out tests, and that the maximum energy absorption by these specimens is about 11 J.

2.4.1 100% potential impact energy

Figure 2 shows the impact damage occurred in upper faces due to 100% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 2 – Impact damage on the face subjected to impact NL10 Core (left) and Divinycell Core (right) at 100% Potential Energy

The damage on the upper faces is similar in both specimens with a circular indentation with penetration of the gel coating. The penetration of the impactor ruptures the glass fiber in a cruciform pattern coincident with the main orientation of the fibers. The indented area is similar for both types of specimens, a result expected since the penetrator entered fully into the specimen.

Figure 3 shows the impact damage occurred in lower faces due to 100% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 3 - Impact damage on the lower face NL10 Core (left) and Divinycell Core (right) at 100% Potential Energy

In the lower faces it can be seen a different behavior of the sandwich structure responses. In the Cork core the rupture takes a decidedly oval shape, while in the Divinycell cores the shape is circular. Analysis of both types of specimens seems to suggest that while the DivinyCell cores compress and rupture, due to the high stress concentrations upon impact, the NL10 Cores develop a crack in response to the stresses that propagates in one direction until the impactor passes through. This crack is formed along the Glass fiber plies and is dependent of the orientation, *i.e.*, the crack forms in either 0º or 90º depending on specimens, although its orientation is not dependent of the boundary conditions.

2.4.2 50% potential energy

Figure 4 shows the impact damage occurred in upper faces due to 50% potential energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 4 - Impact damage on the face subjected to impact NL10 Core (left) and Divinycell Core (right) at 50% Potential Energy

At 50% impact energy the damage in the upper face appears somewhat milder, although the impactor passed through the top face of the specimen. In both cores the damage of the upper face presents a similar pattern with a cruciform pattern of rupture appearing coincident with the glass fibers orientation.

Figure 5 shows the impact damage occurred in lower faces due to 50% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 5 - Impact damage on the lower face NL10 Core (left) and Divinycell Core (right) at 50% Potential Energy

In the lower faces, there is much more significant visible damage in the NL10 specimens with a larger area of damage and rupture of at least one layer of glass fiber in all specimens. On the Divinycell specimens, the visible damage area is smaller and there is no apparent penetration of the lower faces of the specimens.

2.4.3 33% potential energy

Figure 6 shows the impact damage occurred in upper faces due to 33% potential energy in the Cork core sandwich and the Divinycell core sandwich.

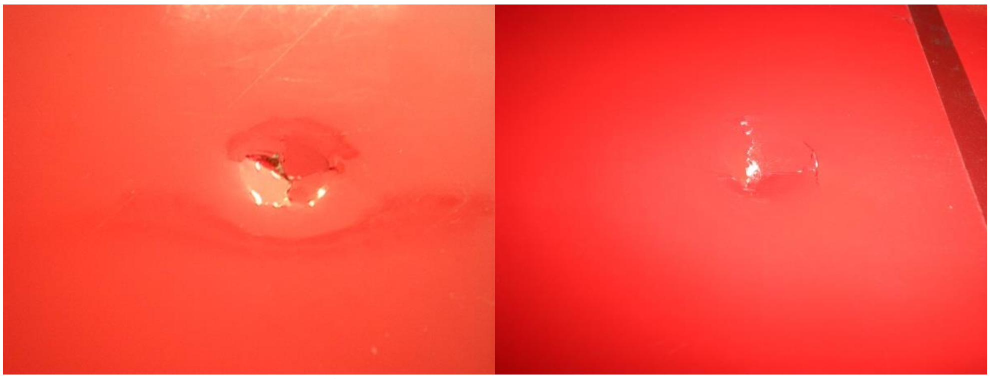

Figure 6 - Impact damage on the face subjected to impact NL10 Core at 33% Potential Energy

At 33% potential energy the visible damage is still present with rupture of the top faces in both core specimens. Again present is the cruciform pattern of rupture oriented with the glass fiber orientation with gel coating damage mirroring the rupture and around the impactor edge.

Figure 7 shows the impact damage occurred in lower faces due to 33% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 7 - Impact damage on the lower face NL10 Core (left) and Divinycell Core (right) at 33% Potential Energy

On the lower faces there is a significant difference in visible damage between cores. In most cork specimens there is visible damage to the lower faces, with facing damage in at least one layer of glass fiber, and some debonding. On the Divinycell cores there is little if any visible damage.

2.4.4 25% and 16% potential energy

Specimens impacted at 25% and 16% show damage on the upper face, with cracking on the gel coating and little ply damage at both energy levels. If not for the presence of gel coating the damage could be construed as BVID. In the lower faces there is no visual damage, and inspection of the faces after debonding shows no layer damage in any of the specimens. Given that only the 25% and 16% potential energy levels could be considered BVID, further analysis and testing was performed in both test specimens. Further tests were performed at 10% potential impact energy although there was the fear that with drop heights lower than 20 mm the variation in drop height distance would be too small for measuring.

Figure 8 and Table 7 present the results of the maximum stress and Figure 9 and Table 8 show the average absorbed energy by energy level and by material.

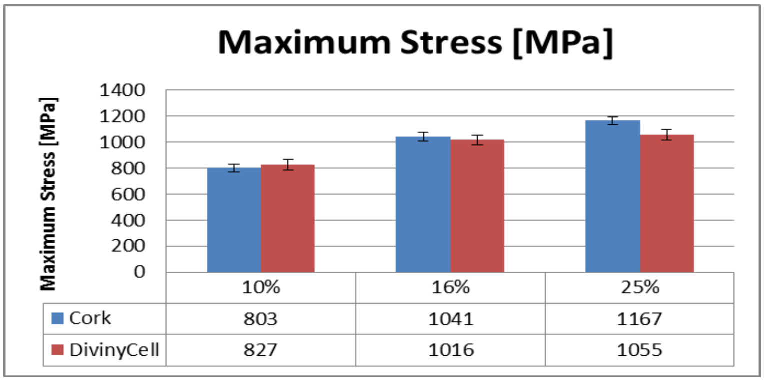

Figure 8 – Maximum stresses on impact per energy level.

Maximum Stress	10%		16%		25%	
	Cork	PVC	Cork	PVC	Cork	PVC
Average	803	827	1041	1016	1167	1055
StdDev	40	25	47.5	95	49.5	75
CV [%]	5.0%	3.0%	4.6%	9.4%	4.2%	7.1%

Table 7 -Maximum Stress on impact per energy level

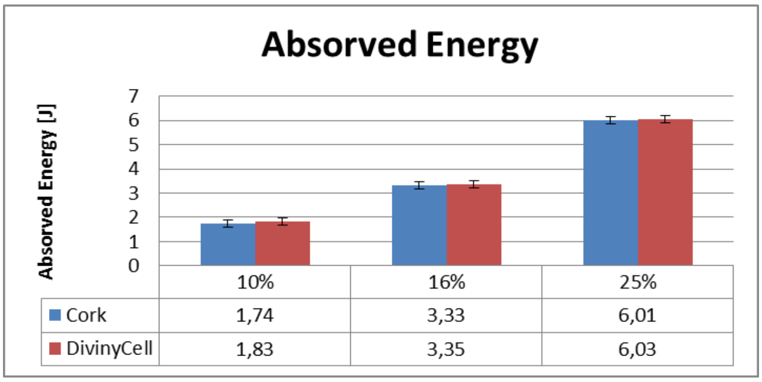

Figure 9 – Absorbed energy per energy level.

Absorbed Energy	10%		16%		25%	
	Cork	PVC	Cork	PVC	Cork	PVC
Average	1.74	1.83	3.33	3.35	6.02	6.04
StdDev	0.03	0.01	0.11	0.02	0.03	0.01
CV [%]	1.7%	0.5%	3.3%	0.6%	0.5%	0.2%

Table 8 - Absorbed energy on Impact per energy level

In terms of maximum stress the cork cored panels have the same values as the Divinycell cores at the 10% and 16% energy levels given the standard deviation measured. At 25% Energy cork cores sustain a higher stress than the Divinycell cores and at this level there is already visible damage on the facings. The absorbed energy, see Figure 9, shows that there is no discernible difference between cores which implies that almost all of the energy is absorbed by the faces of the sandwich structure. The 10% potential impact energy tests were not considered for the rest of the work, as doubts still lingered on the correct positioning of the impactor.

3 C-SCAN ANALYSIS

The C-Scan imaging proved to be a challenge since the sandwich is composed by materials with different densities that muddle the ultrasound signal as it passes through all the materials. The C-Scan Machine is presented in Figure 10.

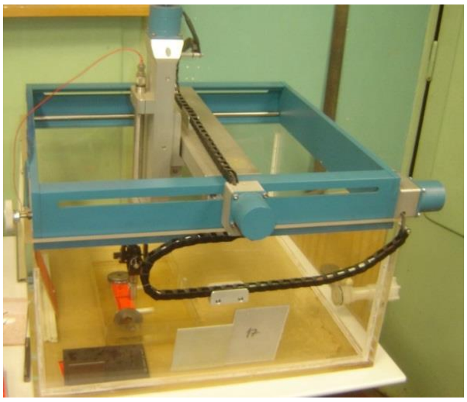

Figure 10 C-Scan Machine

As such, only a clear picture of the top layer was obtained. Figure 11 shows a typical C-Scan image of cork at 25% potential energy level, and Figure 12 the typical C-Scan energy of DivinyCell at 25% potential energy.

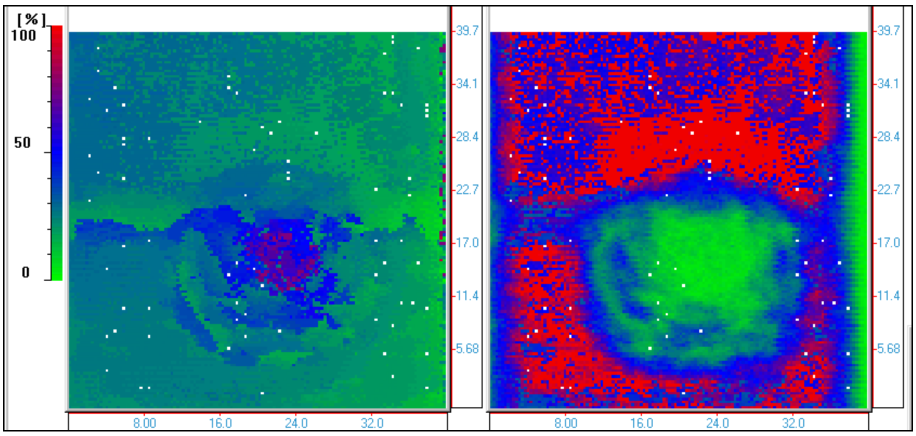

Figure 11- Time of flight and amplitude variations at 25% energy level Cork

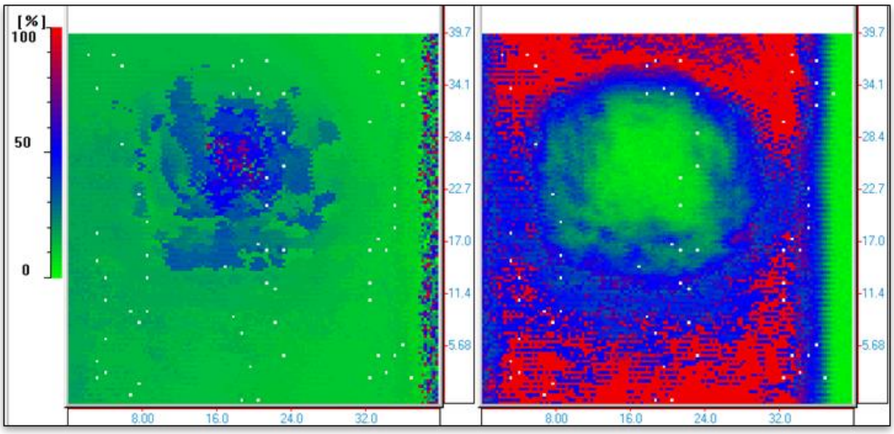

Figure 12 Time of flight and amplitude variations at 25% energy level DivinyCell

The right side of the figures show the indentation level of the impact, consistent between all tests at a determined energy level, with the left side showing the inner damage in the glass fibers.

C-Scans were also performed at 16% potential energy level to determine the impact damage as seen in Figure 13 and Figure 14.

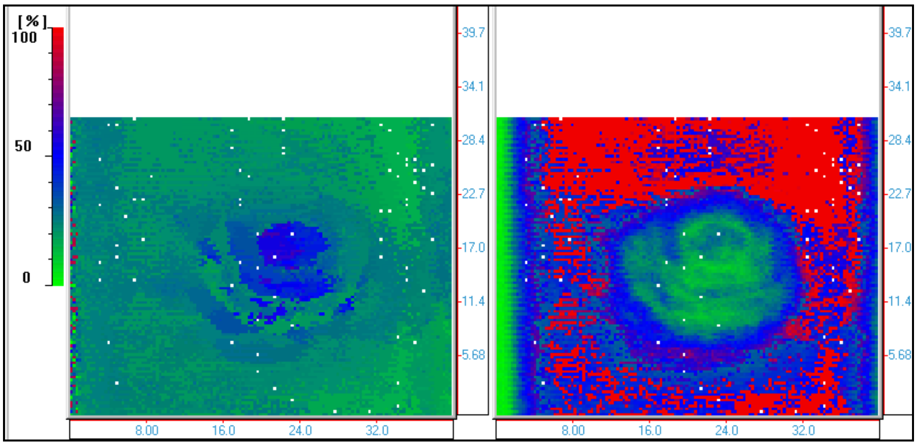

Figure 13 - Time of flight and amplitude variations at 16% energy level Cork

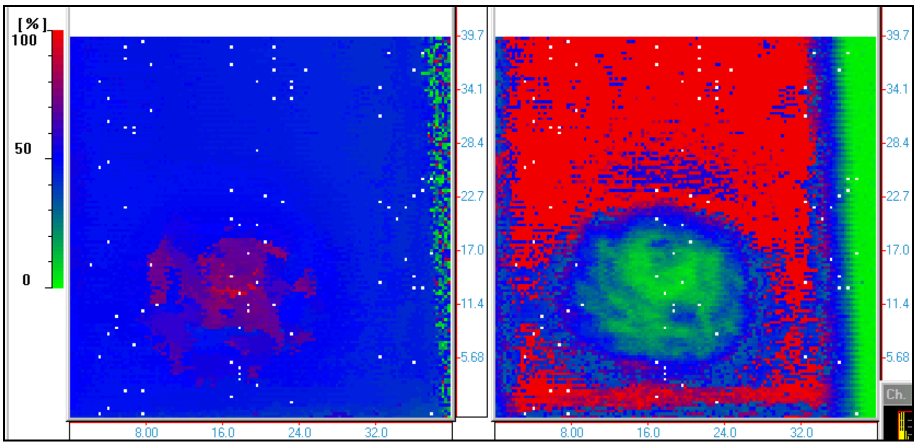

Figure 14 Time of flight and amplitude variations at 16% energy level PVC

Once again the tests were consistent at the 16% energy level. To better understand the damage incurred in the sandwich structure, the delaminated area and maximum diameter of the impact area were measured. Those results are shown in Table 9 and Table 10.

Area Delaminated	16%		25%	
	Cork	PVC	Cork	PVC
Average	255.2	380	475.2	670
StdDev	35.53	51.55	34.77	59.56
CV [%]	13.9%	13.6%	7.3%	8.9%

Table 9 – Delaminated area per impact energy and per core material

Max Diameter	16%		25%	
	Cork	PVC	Cork	PVC
Average	18.00	22.5	24.20	29.81
StdDev	1.22	1.33	1.10	1.55
CV [%]	6.8%	5.9%	4.5%	5.2%

Table 10 – Maximum diameter of the impact area per impact energy and per core material

The results of the delaminated area and the maximum diameter of the impact area are very interesting. Given that the cork cores sustained about the same stresses at the same level of energy, it was to be expected that the area delaminated, i.e., the area that effectively resists the impactor, would be equal to the delaminated area of the PVC. What the results show is that a low impact energies Cork cores are preferred since the cork cores absorb more energy than the DivinyCell Cores resulting in smaller impact areas which are simpler/cheaper to repair, although at higher potential energy levels there is significant lower penetration in the DivinyCell core specimens.

4 CONCLUSIONS

All of the specimens impacted at 100%, 50% and 33% impact energy show damage on the lower face with the first two impact energies showing complete perforation of the sandwich structure.

The amount of energy the specimens can absorb is in the vicinity of 11.5 J as can be seen in the impact energy tables, since the absorbed impact energy from full Specific Energy to 50% Specific Energy is negligible.

The NL10 specimens have a high degree of variability. This variability has been observed in other tests and it is maybe due to the cork itself and the method of fabrication, since the NL10 Sandwiches rely on natural materials separated by granule size and that epoxy has to completely permeate the Core in the manufacturing process.

Another remark is that there is no statistical difference between the absorbed energy of the two cores, mostly due to the high standard deviation presented in the cork tests. This can mean that the cores have similar behavior when subject to impact or, more likely, that the thickness of the cores is too small to have any influence on the impact characteristics.

Although the fact remains that there is more visible damage on the cork core specimens than on the Divinycell specimens in the lower faces from 100% down to, and including, 33% potential energy, it does not seem to have much effect on the resistance of the specimens to other solicitations, which will be studied in another series of tests.

Below 33% the visible damage is only present on the faces impacted on both core types.

For potential impact energies of 16 and 25%, Cork cores suffer a higher maximum stress, although becoming statistically insignificant the lower the impact energy, and about the same energy is absorbed. Cork cores have less delaminated area after impact which means that the cork cores are able to absorb more impact energy than the Divinycell cores.

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