EXPERIMENTAL ANALYSIS OF LOW ENERGY IMPACT IN FILAMENT WINDING CYLINDERS

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Abstract: Composite material is very attractive for structural applications due to its inherent mechanical properties and low weight. Also, because of many manufacture process, it is possible to apply composite materials even in parts with complex geometry. Among the manufacture process, filament winding is very suitable for automation and this process is used for several applications as pressure vessels, aircrafts fuselage, tubes, etc.During service life composite structures can be damaged by collisions with objects during operations, dropping tools during assembly or maintenance, etc. Despite the effects of impact are well known, the analysis can be very difficult. Several studies present failure analysis of impacted plates, but few for cylinders. This study presents the experimental test of low energy impact filament winding cylinders. Three different lay-up for the cylinders and two levels of energy were tested. Figure 1 shows the carbon fiber filament winding cylinder test set-up for impact test.For the first energy level (11 J), the cylinders were tested using a flat plate as a support. For the other energy level (30 J) a V support were used for the tests. Two bi-directional strain gages and one accelerometer plus the force and displacement sensors were used for data acquisition.Figure 2 shows the experimental results for force and displacement for three different layups. In this figure it is possible to observe that the force peak is not the first one. This tendency is observed for all cylinders layups and test energy level regardless the support used during the tests.Also, for the energy level of 11 J C-Scan does not indicate any sign of damaged. On the other hand, for 30 J impact test, the cylinders were damaged.

Keywords: *Impact, filament winding, composite, damage.*

1 Introduction

The uses of composite materials in aeronautical industry have been increasing in the last decades, even in large civil transportation aircrafts, mostly due to composite high stiffness and low weight [1]. Its intrinsic anisotropy, allows achieve an optimal material performance regarding the structure geometry and function. Composite materials, let design lighter structures without loss of airworthiness, which is a very attractive characteristic for aeronautical industry. Thus, using composite material makes possible save more weight decreasing the fuel consumption or increasing the payload.

However, despite few new designs as Airbus 380 and Boeing 787, the application of composite in structures is still limited by the difficulty in predicting their service life [2].

Advanced composites have been used as engineering materials for several years. Despite the static behaviour of composites are quite well established it is not possible to say the same for impact loads [24]. ASTM D7139 (2007) [3] guides the impact test for composite flat coupons.

Several studies of composite plates impacted were conducted by a number of researches ([4], [5], [1], etc), but only few studies were made regarding impact in curved geometry ([6], [7], etc).

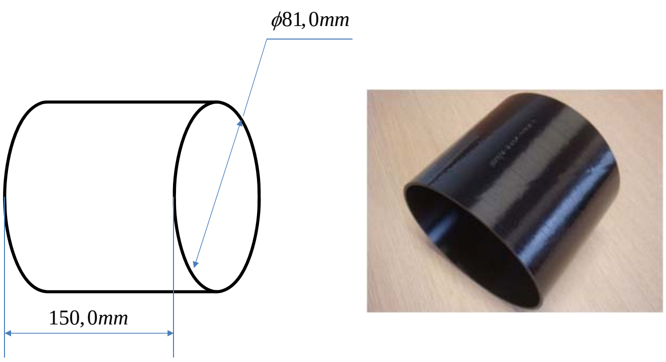
The guidelines for design composite vessels was establish more than 40 years ago and those guidelines recommend apply high safety factors in order to avoid failure, mostly for pressurized vessels [7].

Despite the high strength in fiber direction, out-of-plane loads, for example impact loads due to bird strike or dropping tool in a composite structure, could lead to severe dam-age. In a metallic structure this kind of damage is easier to detect, on the other hand for car-bon fiber structures this is not true [6].

The present work shows the results of a set of impact tests performed in filament winding cylinders with 3 different lay-ups.

2 Test coupons

There are several testing standards (tensile, compression, shear, bending, fatigue, impact tests) for composite flat coupons, but there is no standard for impact in composite cylinders. In order to overcome this limitation, in this work, the dimensions of the test machine as well as the available filament winding mandrel diameter were taken into account. Two dimensions of coupon are shown in Figure 1(a). It is important to notice that the cylinders (Figure 1(b)) were manufactured by CTM (Navy Technological Center- Brazil), using filament winding process for carbon fiber and epoxy resin.



(a) (b)

Figure 1: (a) Coupon dimensions; (b) Cylinder manufactured by filament winding process

Three different lay-ups were manufactured (Table 1): type A with 3,49 mm thick; type B with 3,25 mm thick and type C with 3,54 mm thick (average). Those lay ups allow to assess how different levels of anisotropy affect the structure response under impact loads.

Table 1: Cylinders lay-up

Identification	Lay-up
Type A	$[90/60/-60/90/60/-60/90]_S$
Type B	$[90/30/-30/90/30/-30/90]_S$
Type C	$[90/30/-30/60/-60/30/-30]_S$

Besides, according to the coupons manufacturer, the plies thickness was function of the orientation. Hence, the plies with fiber orientation equal 30^o are 31% thicker than 90^o plies, and 60^o plies are 15% thicker than 90^o. One important remark is that the material properties are classified data, thus the properties are not present in this study.

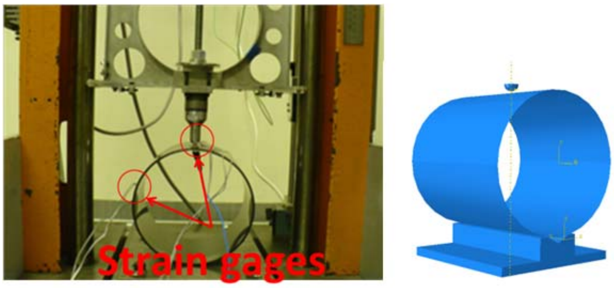
3 Drop tower apparatus

The impact test equipment provides the data of force and displacement when the impactor interacts to the coupon during an impact event (Figure 2(a)). It is also measured the strains in two different points of the cylinders using a bidirectional strain gages (Figure 2(b)). The impact tests were conducted in laboratories at Katholieke Universiteit Leuven (Belgium).

The principle of impact test is very simple, because this test consists on a certain mass dropped from a certain height, and this mass hits the test coupon. So, the force and displacement are measured when the impactor and the coupon are in contact.

The impact apparatus (Figure 2(a)) consist on two guiding bars to drive the falling weight during the test. Regarding the used equipment, these guiding bars limit the impact height to 1.8 m. The test coupons are placed at the bottom of the machine (Figure 2(a)).

Several types of impactor head can be fixed onto the impactor frame allowing test different types of materials. For harder material, a more pointed impactor head is used, for the case for softer material a more blunted impactor head is used. The tests were performed using a round impactor head with 16 mm of diameter. The round head avoid, in certain level, penetration of the coupon caused by the use of sharp head.



(a) (b)

Figure 2: (a) Test coupon placed in drop tower (10 J tests); (b) Test schema using V-block in the base (30 J tests)

A piezoeletric crystal, placed between the impactor head and impactor frame, is used as load cell in order to acquire the impact force. The displacement data was acquire using a light detector placed at the bottom of the apparatus, which measures the intensity of a Light Emit-ting Diode (LED) mounted on the impactor frame. Once the LED has a constant intensity, the distance measured is proportional to $\sim 1/d^2$, where d is the distance between the LED and the light detector.

The displacement measurement system is simple, reliable and stable, once the light detector integrates the light intensity. Despite that, the measurements should be done in the most sensitive area of the calibrated displacement range.

At the bottom of the drop tower is the local to place the coupons to be tested. In this work, the cylindrical coupons are positioned in a flat surface for the 10 J impact tests (Figure 2(a)) and in a "V" base for the 30 J impact test (Figure 2(b)).

4 Results and discussions

The experimental test results for 30 J impact energy, there is no data from the strain gages. Regarding experimental tests for 10 J impact energy, it can be seen the results for strain gages. However using C-Scan method, it was not detected any damage in the structure for all cylinders type impacted under 10 J (Figure 4(b)).

In general, the damage initiation is detected in impact test force vs. time history with a sudden force drop due to stiffness reduction caused by unstable damage growth [8]. Also, observing the force vs. time graphics, it is possible to identify the delamination threshold by the first force sudden drop. During the damage process, matrix cracking is the first type of damage, which happens in a structure due to impact loading. As commented by the literature, this type of damage does not affect the laminate stiffness during impact [8].

For type A cylinders under 30 J impact energy, the force vs. time and displacement vs. time results are shown in Figure 3. The graphics show that the results for each coupon are nearly identical.

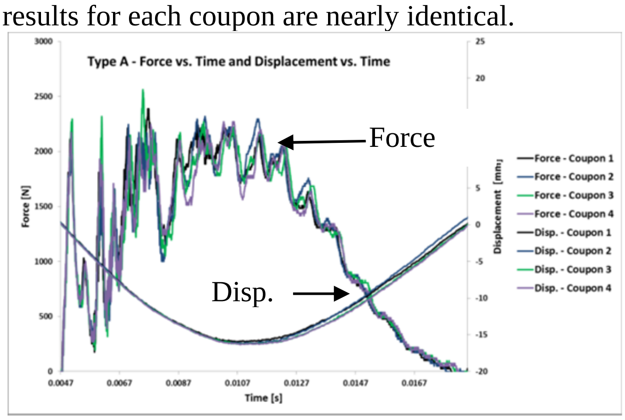


Figure 3: Force vs. time and displacement vs. time for type A cylinders (30 J impact energy).

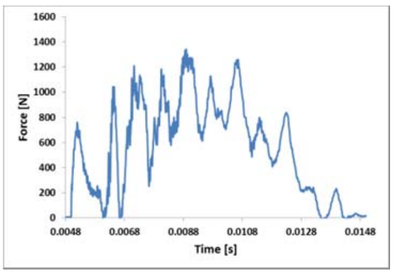
Table **2** shows the maximum peak force value for each coupon as well as the maximum displacement (absolute value). For displacements measurements, the standard deviation is only 1.23% of the average displacement. For force, the standard deviation is 5.23% of the average force. Also, there is no correlation between the maximum measured forces with the maximum displacement.

Table 2: Results summary for type A cylinders

Coupon	Maximum force peak [N]	Maximum displacement [mm] (absolute value)
1	2388.9	16.0
2	2319.3	16.2
3	2563.5	16.3
4	2270.5	16.3
Avarage	2385.6	16.2
Standard deviation	128.2	0.2

Figure 3 shows that the force increases rapidly close to 0.0052 s and then a sudden force drop occurs. After that, the force increases again and a new sudden drop occurs. This trend repeats for close to 0.0087 s of the impact event. A similar behavior was presented by Minak et al. [9]. This part of peaks and valleys could indicate the initialization of delaminations in several layers. After this first time, the unstable delamination propagation can cause the further oscillations in the force vs. time history, as observed by Schoeppner and Abrate [8]. Also, Figure 3 shows that the maximum force level does not occur in the first peak and the maximum force value does not occur in the same time of the maximum displacement.

On the other hand, as mention before, the cylinders impacted under 10 J did not show any damage (Figure 4(a)) as observed by the C-Scan images. However, the force vs. time history shows a similar trend as shown by specimens impacted under 30 J (Figure 4(b)).



(a) (b)

Figure 4: Type B cylinders (10 J impact energy): (a) C-Scan image; (b) force vs. time.

This trend indicates that the peaks and valleys are not only caused by delaminations and the further unstable propagation also. The boundary conditions and the cylindrical geometry can affect very strongly the cylinder impact behavior. Furthermore, it is well known that the force vs. time history has many oscillations, which could be introduced by two sources: the impactor can load the structure in a natural frequency (impactor ringing) and the coupon can show flexural vibrations [3]. Despite delaminations, this oscillatory behavior also could be explained by the wave propagation across the cylindrical structure and the cylinder natural frequency. Further finite element simulations showed that the delay in the basis reaction force possess an interesting correlation with the impactor force and the support reaction force (Figure 5).

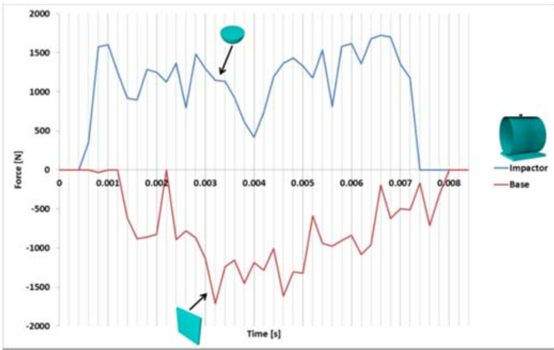


Figure 5: Force vs. time history for impactor and base for type B.

Figure 5 shows a finite element simulation results for force vs. time history for a cylinder under 10 J impact energy. In fact, the oscillatory behavior is not due to any kind of damage. When the impactor just hit the cylinder, the force increases, but there is no reaction in the support yet. After 0.0006 s, the reaction force in the support increases, but the force in the impactor decreases. The next peak in the impactor force corresponds to decrease of the support reaction force. This trend repeats until 0.003 s of the impact event, after this time, there are not clear correlations. It could indicate that the existence of an interference between the support reaction and the impactor leading to harmonic resonance in the force vs. time history.

It is possible to observe that all type A cylinders present matrix cracking and delaminations between several layers, also a small indentation mark (dent) is also observed. Despite the several damage detected, fiber breakages for all coupons are not observed.

For type B cylinders, the force vs. time and displacement vs. time results are shown in Figure 6. The graphics show that the results for each coupon do not possess a considerable dispersion.
The same observations made for type A cylinders still valid for type B coupons, but the force peak intensity is higher for this cylinder type, due to the differences in thickness and lay-up. Delaminations, matrix damage and indentation marks are detected for type B cylinders, too.

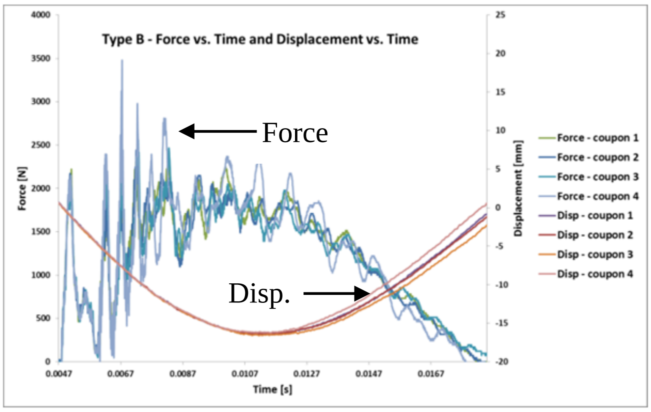


Figure 6: Force vs. time and displacement vs. time for type B cylinders (30 J impact energy).

For type B coupons, Table **3** shows that the standard deviation is only 0.61% of the average, showing almost no dispersion in the maximum measured displacement, but form 0.0127 s, it is observed that the displacement measurements starts to diverge. For force the standard deviation is 19.1% of the average value, thus there are some considerable dispersion in the maximum peak value measurement, but regarding all the force history for all coupons, they are rather close. Again, there is no correlation between the maximum measured force and displacement.

Table 3: Results summary for type B cylinders

Coupon	Maximum force peak [N]	Maximum displacement [mm] (absolute value)
1	2319.3	16.4
2	2441.4	16.4
3	2612.3	16.6
4	3466.8	16.2
Avarage	2710.0	16.4
Standard deviation	518.7	0.1

Figure 7 shows the force vs. time and displacement vs. time results for type C cylinders. In this case, the dispersion in the displacement is more pronounced than for previous results. For example, the coupon 4 displacement results diverge even before the impactor reaches the maximum displacement.

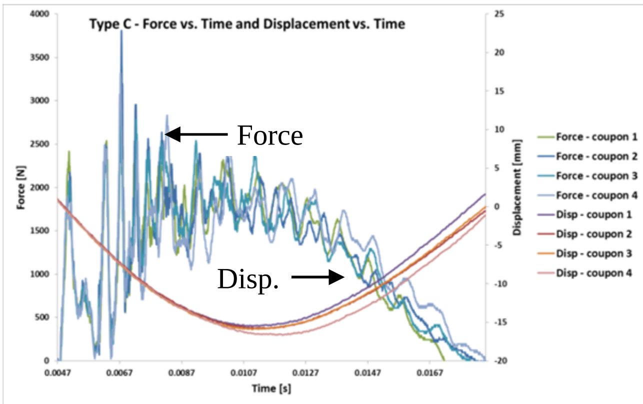


Figure 7: Force vs. time and displacement vs. time for type C cylinders (30 J impact energy).

Table **4** summarize the results for coupons type C, in this case, the displacement standard deviation is 3.1%, the higher value for all cylinders type, Also, the force standard deviation is 11.0% of the average value. Once more, there is no correlation between maximum force and displacement.

Table 4: Results summary for type C cylinders

Coupon	Maximum force peak [N]	Maximum displacement [mm] (absolute value)
1	3393.6	15.5
2	3808.6	15.8
3	2905.3	15.9
4	3320.3	16.7
Avarage	3356.9	16.0
Standard deviation	370.0	0.5

Type C cylinders present a higher load peak than other cylinders type, and Type B cylinders present a higher displacement. All the comments for Type A cylinders are also valid for Type C cylinders. Delaminations, matrix damage and indentation marks are detected for type C cylinders, too.
Table 5 shows the values of the maximum load peak and the differences between type A and the other types. This table shows that for same impact energy, type C cylinders has an average force 40.7% higher

than type A, and type B has an average force 13.6% higher than type A.

Table 5: Maximum force peak

Cylinder Type	Maximum peak load [N]	Difference $\frac{V_{Type\,i} - V_{Type\,A}}{V_{Ttype\,A}} \cdot 100$
Type A	2385.6	-
Type B	2710.0	13.6%
Type C	3356.9	40.7%

Regarding the displacements, there are no considerable differences between the averages displacements.

Table 6: Maximum displacement (absolute values)

Cylinder Type	Maximum absolut displacement [mm]	Difference $\frac{V_{Type\,i} - V_{Type\,A}}{V_{Ttype\,A}} \cdot 100$
Type A	16.2	-
Type B	16.4	1.2%
Type C	16.0	-1.2%

Finally, regarding the damaged area, type A cylinders were more damaged than others type, mostly in the internal surface. The other cylinders type did not show damage in the internal face.

5 Conclusions

Cylinders lay-up with closer orientations (type A) had shown to be more susceptible to damage, and this damage absorbed part of impact energy which explains the lower peak force registered for type A cylinders.
The lay-up did not have an important effect in the maximum displacement and in the total impact time.

6 Acknowledgements

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7 References

[1] Kevin V. Williams, Reza Vaziri, and Anoush Poursartip, "A physically based continuum damage mechanics model for thin laminated composite structures," *International Journal of Solids and Structures*, vol. 40, no. 9, pp. 2267-2300, 2003.

[2] A. T. Travessa, "Simulation of delamination in composites under quasi-static and fatigue loading using cohesive zone models," Universitat de Girona, Ph.D. dissertation 2006.

[3] ASTM D7139, Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event, 2007.

[4] M.V. Donadon, L. Iannucci, B.G. Falzon, J.M. Hodgkinson, and S.F.M. de Almeida, "A progressive failure model for composite laminates subjected to low velocity impact damage," *Computers \& Structures*, vol. 86, no. 11-12, pp. 1232-1252, 2008.

[5] S.M.R. Khalili, M. Soroush, A. Davar, and O. Rahmani, "Finite element modeling of low-velocity impact on laminated composite plates and cylindrical shells," *Composite Structures*, vol. 93, no. 5, pp. 1363-1375, apr 2011.

[6] L. Ballère, P. Viot, J.-L. Lataillade, L. Guillaumat, and S. Cloutet, "Damage tolerance of impacted curved panels," *International Journal of Impact Engineering*, vol. 36, no. 2, pp. 243-253, 2009.

[7] Satoshi Kobayashi and Mari Kawahara, "Effects of stacking thickness on the damage behavior in CFRP composite cylinders subjected to out-of-plane loading," *Composites Part A: Applied Science and Manufacturing*, vol. 43, no. 1, pp. 231-237, 2012.

[8] G.A. Schoeppner and S. Abrate, "Delamination threshold loads for low velocity impact on composite laminates," *Composites Part A: Applied Science and Manufacturing*, vol. 31, no. 9, pp. 903-915, 2000.

[9] G. Minak, S. Abrate, D. Ghelli, R. Panciroli, and A. Zucchelli, "Residual torsional strength after impact of CFRP tubes," *Composites Part B: Engineering*, vol. 41, no. 8, pp. 637-645, 2010.