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Analysis of the impact location on damage tolerance of bonded-repaired composite laminates

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Abstract

In this work, the influence of impact point on the damage tolerance of repaired laminates was studied experimentally. Two configurations, thin carbon/epoxy laminates and the same laminate with a double patch repair, were impacted in two different locations, at the specimen centre and at the edge of the patch. Afterward, compression after impact (CAI) tests were performed, analysing the residual strength and failure progression. In repaired laminates, a significant influence of the point of impact on the impact resistance was observed, specifically for impact energies higher than 15 J. Both specimen configurations showed similar trends in all impact variables analysed when the impact was located at the centre. Related with damage tolerance, the CAI strength of repaired specimens impacted **at the centre is significantly higher** than the residual strength of those impacted at the patch edge. The latter have a similar trend that the non-repaired laminates in both impact locations.

Keywords: Compression after impact; Damage tolerance; Patch repair; Carbon fibre; Thin laminate.

1. Introduction

During service life, composite structures can be damaged due to different causes, being the two most common factors the degradation by environmental factors (e.g. change in temperature) and impact loading. Impact damage in composite laminates is of primary concern because it leads to large reduction in strength and compromises their structural integrity [1-3]. Main sources of impact damage in composite structures are dropping tools during maintenance operations, hailstone, and debris impacts on an aircraft in flight. Specifically, low-velocity impact produced by blunt objects is a foremost problem, as it results in barely visible impact damage (BVID) that usually goes unnoticed but can lead to catastrophic failure. Consequently, the demand of reliable inspection techniques is growing constantly.

When damage is detected in a structure, it must be assessed and several options are possible: replace the damaged component or repair it. In this context, when damage extension is small enough, a repair of the structure can be considered economically feasible [4]. The repair must restore the capabilities of the structure under all type of loads.

In composite structures, adhesive repairs present some advantages over mechanical fastening, such as higher corrosion strength, better external surface, lower weight increase, and less stress concentration associated with the drill [5-7]. Specifically, the stress concentration phenomenon is more critical in composite laminates than in metallic materials due to its fragility and anisotropy [8].

Since the analysis of damage tolerance in composite laminates is a relevant topic, the study must be extended to ensure the operational safety of structures with composite repairs. As a result, several works are focused in the study of the impact behaviour and damage tolerance of repaired laminates [9-15].

The point of impact is a relevant factor in the impact resistance and damage tolerance of a repaired structure [7, 10]. Most studies dealing with the influence of the point of impact focus on scarf repairs, which are more difficult to undertake in real structures than other types of repairs [16]. Scarf and stepped repairs require the removal of large amounts of undamaged material; therefore in very thin laminates, bonded-patch repairs are the only type than can be considered [17]. Findings about scarf repairs cannot be extended to external bonded-patch repairs, as their geometries are different and can modify the stress distribution in the transition zone between the patch and the parent laminate.

Harman et al [10] analysed the influence of impact location on the residual strength of scarf-repaired laminates. They studied the tension after impact (TAI) behaviour of laminates with thicknesses of 2.6 and 3.9 mm. Only one impact energy was tested at different points of impact. They found that the impact location has relevant effect in the TAI strength of scarf-repaired laminates, which increases when the point of impact moves away from the edge of the patch. Shufeng et al [7] studied the CAI strength of scarf-repaired laminates, impacting in four points: centre of the specimen, edge of the patch and two additional points, one inside the patch and another outside. Laminates of 20 plies (2.6 mm thick) and two impact energies, 11.6 J and 17.3 J and, were tested. They observed that the maximum impact load and the lowest CAI strength were given for specimens impacted at the edge of the patch. Therefore, it is necessary to study the influence of the impact point on the damage tolerance of patch-repaired laminates, in order to verify and complement the conclusions obtained in the studies performed on scarf repairs.

Studies dealing with CAI strength of repaired laminates are centered on relatively high thicknesses, around 4 mm [10, 16, 18]. The estimation of CAI strength in thin laminates (thicknesses below 4 mm), can not be carried out according to the standards [19-22] since

the experimental devices do not restrict the global buckling of the specimen, results lead to a lower value of compressive strength [23, 24]. Despite this, the device of the ASTM standard or similar has been used even for repaired laminates less than 3 mm in thickness [7]. In a previous work, the authors developed a CAI device that allows testing thin laminates (around 2 mm in thickness) at different temperatures and impact energies [23, 25].

In addition, many studies focus on a very small range of impact energies, or even just a relatively low single impact energy [10-12, 26]. However, to study the impact resistance and damage tolerance of laminates, it is necessary to consider a broad range of impact energy, since failure modes in laminates depend on the impact energy [27].

In this work, an experimental study of the influence of impact location on the damage tolerance of repaired laminates was carried out. Laminates without damage were also tested as reference. Thin carbon/epoxy laminates with double-patch repair impacted at two locations, at the centre and at the edge of the patch, were analysed. A broad range of impact energies, from 5 to 27.5 J, was tested. Firstly, the effect of impact location on the impact resistance of both specimen configurations was studied; and peak load, absorbed energy and damage extension in baseline and repaired laminates were compared. Finally, compression after impact strength and failure modes were also compared in both types of laminates and impact locations.

2. Experimental procedure

2.1. Material

Quasi-isotropic laminates $[45/0/-45/90]_{2s}$ were manufactured in a specialised centre from pre-pregs of carbon fibre and epoxy matrix (IM7/MTM-45-1). The material was supplied by Solvay (formerly Cytec), and the fibre volume fraction was around 59%.

The manufacturing process was in agreement with the material supplier recommendations, resulting in an appropriate curing process that ensures low void content. Square specimens of 120 mm x 120 mm x 2 mm were cut to get the intact specimens (baseline specimens). Double-patch repaired specimens were obtained from intact specimens with a centre circular drilled hole ($\varnothing = 20$ mm) and two circular patches ($\varnothing = 60$ mm). The patches ($[45/0/-45/90]_2$ carbon/epoxy laminate) were bonded to the open-hole specimen surfaces using MTA240 adhesive (0.13 mm thick).

2.2. Low-velocity impact tests

Low-velocity impact tests were conducted on an instrumented drop-weight tower CEAST Fractovis 6785. The impactor consisted of a hemispherical head of 12.7 mm diameter with 3.873 kg of mass. The specimens were clamped using a support with four toggle clamps according to ASTM D7136 [28]. The impacts were performed normal to the specimen and at room temperature. Each specimen received a single impact and rebound was prevented by an antirebound system.

Two different impact locations were considered: point A at the centre of the specimen, and point B at the edge of the patch along the diagonal of the specimen. The dimension of the cut-out is 90 x 90 mm (Fig.1).

Twenty seven specimens of each configuration (baseline and repaired) were tested at different impact energies, in a range of values between those that generate barely visible damage and those that are close to specimen penetration (from 5 J to 27.5 J).

The impactor head was instrumented with a load cell, so the load applied by the impactor on the specimen was recorded, as well as the initial velocity at the impact time. From the load-time record, assuming permanent contact between the impactor and the specimen, the displacement of the contact point and the absorbed energy were estimated by successive integrations [28].

After the impact tests, to analyse damage area, the specimens were inspected by an air-coupled ultrasounds C-Scan technique, preventing the specimens from getting wet. More details of the used technique are described in [29].

2.3. Compression after impact (CAI) tests

CAI tests were performed on a servohydraulic Instron machine, model 8802, with constant velocity of 0.5 mm/min and at room temperature.

Since the thickness of the tested laminates is thinner than 4 mm (about 2mm), standard devices [19-22] were not used. A CAI device developed in a previous work [23] was used to carry out the tests (Fig. 2).

The CAI device has an alignment system to ensure accurate orientation of direction of load application. The tests were carried out by placing the device between compression plates installed in the testing machine.

Three non-impacted specimens of both configurations, baseline and repaired, were also tested to estimate the residual strength variation due to the impact damage.

On each test, the record of load-time was obtained. The CAI strength was determined by dividing the ultimate load and the cross-section of the specimen.

To obtain a better estimation of the residual strength variation, the normalised residual strenght was determined, as the relation between the strength of damaged specimens and the non-impacted baseline specimen strength.

3. Results and discussion

In this section, an analysis of the results obtained for the low-velocity impact tests performed on baseline and repaired laminates is performed. The impact was carried out in the points A and B (Fig. 1). From each test, peak load, absorbed energy and damaged area of the specimens were estimated. After the analysis of the impact behaviour of all

the studied configurations, CAI tests were carried out in order to evaluate the effect of the impact location on the residual strength of both, baseline and repaired laminates.

3.1 Low-velocity impact analysis

Load-displacement curves are displayed in order to highlight the impact response of both laminate configurations (Fig. 3). For the sake of brevity, only representative curves of three impact energy levels are shown: 5 J, 15 J, and 25 J. From these curves, peak load and absorbed energy were calculated, Table 1 and Table 2. The slope of the curves represents the bending stiffness of the specimen.

At low impact energies (5 J) repaired laminates present slightly higher peak load values than baseline laminates (Fig. 3a and 3b): 10.5% at point A, and 5.8% at point B (Table 1). At this impact energy, the main damage mechanism is matrix cracking [30]. In specimens impacted at point B, the peak load and bending stiffness are slightly higher than in specimens impacted at point A. In baseline specimens, peak load in laminates impacted at point B is 8.0% greater than in laminates impacted at point A. In repaired specimens, this difference is lower (3.3%).

For impact energies above 15 J, differences between results for repaired and baseline specimens are more noticeable (18.7% at point A, and 5.5% at point B). The curves for the latter present a sudden decrease of load followed by oscillations (Fig. 3c and Fig. 3e), which is related with damage growth and the appearance of fibre breakage [31-33]. In repaired specimens impacted at point B, oscillations appear for impact energy equal to 25 J (Fig. 3f); whereas in repaired laminates impacted in point A, significantly less oscillations were observed at any impact energy.

In terms of bending stiffness (for all impact energies), baseline specimens show that the stiffness of specimens impacted in the centre (point A) is lower than that obtained for baseline specimens impacted at point B (around 19%). This is due to the boundary

conditions that surround the impact point: point A is further away from the edge and the displacement produced in the specimen is higher, which leads to smaller values of bending stiffness. However, the impact location does not present noticeable effect on the stiffness of repaired specimens (around 7.4%).

Results of the peak load measured in the low-velocity impact tests carried out on both baseline and repaired laminates are shown in Fig. 4.

In baseline laminates, the location of the impact point does not produce significant differences on the peak load as a function of the impact energy. In addition, the trend of the results for both impact locations is very similar: first, there is an increase in the peak load until an impact energy level of 15 J is reached. At this point, peak load values remain almost constant: around 5400 N and 5900 N for baseline laminates impacted at point A and B, respectively. This behaviour is usually presented in intact laminates subjected to low-velocity impacts applied on their centre [33-34].

Peak load values for impact energies below 15 J are almost coincident in repaired specimens impacted in both locations; furthermore, peak load results of repaired laminates impacted at the edge of the patch-repair (point B) are found to be similar to that observed in baseline laminates; that is: peak load increases almost linearly with impact energy, until a level of 15 J is reached. At this point, the peak load stabilises around a value of 6300 N, which is slightly higher than the one obtained in baseline specimens. This is probably because of their higher thickness, which results in higher bending stiffness.

The stabilisation in the peak load can be related to the results of absorbed energy presented in Fig. 5. When a certain impact energy level is reached, there is a noticeable increase of absorbed energy due to the activation of the characteristic damage mechanisms in laminates. As the damage increases, the bending stiffness of the

specimens is reduced, avoiding the increasing of the peak load. This phenomenon is observed at both baseline and repaired laminates.

On the other hand, in repaired laminates impacted at point A, peak load augmented almost linearly until 25 J, from this value of impact energy the stabilisation of the peak load is observed (around 8800 N). The delay in the stabilisation of the peak load suggests that failure mechanisms occur in a delayed fashion due to higher stiffness of the impacted area.

The maximum peak load in repaired specimens impacted at point A is about 34% higher than the maximum peak load when impact location is at point B. Consequently, differences in behaviour are noticeable between repaired laminates impacted at point A and B, which suggests that the location of the impact point has significant influence on the behaviour of patch-repaired laminates.

As observed in the peak load case, absorbed energy for baseline laminates (Fig. 5a) do not present visible differences with impact location for impact energies above 12.5 J. For impact energies below this impact energy, results of absorbed energy of baseline specimens impacted at point A are lower than results given for laminates impacted at point B (35.2% at 5 J, and 12.5% at 10 J). From this impact energy level, there is a sudden rise in the results and both curves overlap.

In repaired laminates (Fig. 5b), differences are more noticeable for impact energies above 12.5 J. Generally, the absorbed energy increases with impact energy, but two different behaviours can be clearly distinguished depending on the point of impact. Repaired specimens impacted at point B behave very similarly to baseline specimens, although in repair laminates the energy for which the sudden rise is observed is 15 J (Table 2). Below this value, the energy absorbed by both baseline and repaired

specimens is similar; and when exceeding this impact energy level, the absorbed energy augments almost linearly with impact energy.

In general, at impact energies below 15 J, similar results for both impact locations in repaired laminates are found, as differences are about 10%. However, for impact energy levels above 15 J, the absorbed energy for repaired specimens impacted at point B augments more rapidly than in repaired specimens impacted on the centre of the patch-repair. Repaired laminates impacted at point A show a sudden increase in the energy absorption at impact energy of 20 J (Table 2). The difference in the value of impact energy in which the sudden rise is presented is related to the delay of the stabilisation of the peak load presented above, and reveals that the onset of the damage mechanisms is activated differently and depends on the impact point location.

Fig. 6 shows representative images of the C-Scan inspections. For simplicity, the images present results for baseline and repaired laminates, impacted at point A and B, and for impact energies of 5, 20 and 27.5 J.

For an impact energy of 5 J, the C-Scan images of baseline laminates impacted at point A show only matrix cracking damage mechanism, located at the centre of the specimen. At this impact energy level, baseline laminates impacted at point B show matrix cracking and the onset of delamination from these cracks.

Baseline specimens impacted at point A and B (at 10, 15, 20, 25, and 27.5 J impact energy levels), presented the aforementioned damage mechanisms along with fibre breakage at the bottom plies, which extends to the edges of the laminates. Moreover, the intact laminates impacted at 27.5 J were extensively damaged.

In all cases, the C-Scan images of the repaired laminates showed an outer ring located along the bond-line, corresponding to the change in the cross-section due to the bonding of the repair patch. The images of the repaired laminates impacted at point A showed

damage in the shape of a circle, without being extended to the edges of the repaired laminate.

Fig. 7 presents the percentage of damaged area, which is determined as the ratio of the measured damaged area to the total C-Scan inspected area. Unlike the results obtained for absorbed energy, in which results for baseline specimens at both impact locations almost overlapped in the whole range of studied impact energies, Fig. 7a shows that the extension of damaged area presents slight differences depending on the location of the point of impact.

At impact energies below 15 J, baseline specimens impacted at point B have an extension of damaged area slightly higher than the one obtained for baseline laminates impacted at point A. However, for impact energy values above 15 J, this tendency is quite the opposite: baseline specimens impacted at the centre of the patch-repair present higher extent of damaged area. This is due to the boundary conditions of the impact test, which prevent the damaged area from growing as the impact gets closer to the edge of the specimen. As a result, the point of impact has specific influence on the extent of damage developed in baseline specimens.

As for repaired laminates, differences are more noticeable than in baseline specimens, and the location of the impact strongly affects the results of damaged area (Fig. 7b).

Cheng et al [35] obtained similar results in thicker scarf-repaired laminates impacted at two impact energies, 1.45 J and 4.61 J. Therefore, the most critical point of impact is located at the edge of the patch: not only at low-impact energies (around 5 J), where the damage is mainly due to matrix cracking, but also at higher impact energies (27.5 J) in which the damage area is more extensive, and includes matrix cracking, delamination and fibre breakage.

Comparison between baseline and repaired specimens shows that damage extension is completely different. In all cases, repaired laminates impacted at point A present the smallest percentage of damaged area. This time the boundary conditions have less effect on the growth of the damaged area than the configuration of the repaired specimen itself. When the impact is given in the centre of the patch-repair, all the elements that are under the impact area contain the extent of the damage: the highest stiffness of the impacted area beneath point A results in less bending, which contributes specifically to delamination and failure. If the impact is located on the edge of the repair patch, the damage extends more easily along the adhesive bond-line on which the patch-repair overlaps with the repaired plate.

As a result, the extent of the impact damage is the most affected parameter by the location of the impact point, both on baseline and repaired specimens. As impact damage is one of the main parameters that affect the structural integrity of composite laminates, the study of the mechanical behaviour after low-velocity impact for both specimen configurations is necessary.

3.2. Compression after impact analysis

Fig. 8 shows the normalised residual strength as a function of impact energy for repaired and baseline specimens, both configurations impacted in the centre of the specimen (point A) and on the edge of the patch (point B). The normalisation is calculated as the ratio of the measured strength of the impacted specimens to the strength obtained from non-impacted CAI tests.

The normalised residual strength shows a drop with the increase of impact energy, for both baseline and repaired specimens. Baseline specimens present a relevant loss of residual strength, and even for impact energies as low as 5 J (**Fig. 8a**) the reduction is around 30-40%. The baseline specimens impacted in point A and B showed a similar

reduction in strength for the whole range of impact energies studied, being the specimens impacted at point A slightly lower. For impact energies greater than 15 J, the loss of residual strength is approximately constant (around 55-60%) in both cases, as reported by other authors in intact laminates subjected to centred low-velocity impacts [36].

The impact location has a relevant influence in the normalised residual strength in the repaired laminates. Similar trend of residual strength to that described for the baseline specimens was found in repaired specimens impacted in point B. By contrast, significantly lower residual strength reduction was observed in repaired laminates impacted at point A due to its lower level of damage, as can be seen in Fig. 8b. This behaviour is observed for the entire range of impact energies tested in this study. While in baseline laminates impacted at 10 J, the reduction is around 30%, in the repaired laminates impacted at point A the reduction is only 10%. For impact energies higher than 15 J, in repaired laminates impacted at point A the loss of residual strength stabilises around 20%.

These results differ from that obtained for scarf-repaired laminates [7, 10]. Differences in behaviour can be related to differences in geometry of the repair: in a patch-repaired laminate there is an increment of thickness in the repaired area; whereas in a scarf-repair, the laminate thickness is not modified.

Images and sketches of the failure progression of CAI specimens are displayed in Figs. 9-14. Each figure shows the front and rear view of a representative specimen. Complete failure of the laminate and patch-debonding are represented by a dotted line.

Baseline laminates impacted at the centre of the patch (point A) are presented in Fig. 9, in which the same behaviour was observed for all impact energies. The failure under uniaxial compression is caused by the local buckling of sublaminates, represented by a

broken line (Fig. 9b). The local buckling was originated around the point of impact, but it did not cause complete failure at the back side of the laminate. Sublaminates that have been impacted directly (front-face sublaminates) are more susceptible to local buckling and lower failure loads, as their bending stiffness is lower than in non-impacted laminates. As a result, complete failure on the front side is produced by both local buckling and the delamination propagation, mainly perpendicularly to the load direction (Fig. 9a, dotted line).

CAI behaviour of baseline specimens impacted at point B varies on the impact energy level (Figs. 10 and 11). For impact energies below 12.5 J, the failure progression is similar to the previously described for baseline specimens impacted at the centre, this is: local buckling and complete failure at back and front-side, respectively. However, in this case the failure is not initiated on the impact point (Fig. 10). In contrast, for impact energies above 12.5 J (Fig. 11), the CAI failure is originated at the point of impact, leading to a failure progression similar to the previously described.

Failure progression of repaired laminates impacted at point A presents some similarities when compared to baseline laminates (Fig. 12); however, the local buckling of the sublaminate is now presented at the back-side patch-repair, and half of the patch is completely debonded. Patch debonding is considered as complete failure, thus it is represented with a dotted line. As observed in baseline laminates impacted at point A, this behaviour is shared for repair laminates impacted at the centre at all impact energies.

As it happened in baseline laminates, repaired laminates failure progression depends on the impact energy level when specimens are impacted at point B.

At impact energies below 12.5 J, the failure initiation of repaired laminates is located at the point of impact, progressing along the border-line of the patch-repair until the

middle of the laminate (Fig. 13). In this case, same behaviour was observed at both front- and back-side of the specimens.

Fig. 14 shows repaired laminates impacted at point B for impact energies above 12.5 J.

The initiation of the failure on these specimens is similar to the one described previously. Additionally, the progression of the failure is extended from the point of impact not only along the border-line of the patch repair, but also in other two directions, perpendicular to the applied load.

4. Conclusions

This experimental work analyses the influence of the impact location on the damage tolerance of repaired laminates, comparing the obtained results to those given by non-repaired laminates. The analysis is conducted in terms of load, absorbed energy, damage area, residual strength, and CAI failure progression.

Regarding to the impact resistance, the peak load, absorbed energy and damage area are significantly modified by the impact point in repaired specimens. Peak load results in repaired laminates impacted at the patch edge present a similar trend when compared to results of non-repaired laminates. Due to the higher stiffness associated with the presence of the double-patch, peak load increases when the impact is located at the centre of the specimen. Similar behaviour was observed in absorbed energy results. In repaired laminates impacted at the centre, the lower growth of absorbed energy with increasing impact energy is related with the smaller extent of damaged area shown by these specimens.

The higher stiffness and the smaller extent of damaged area in repaired laminates have significant effect on the CAI strength. Repaired specimens impacted at the centre present more damage tolerance than repaired laminates impacted at the patch edge,

showing a reduction in CAI strength of 20% and 55% respectively. On the other hand, the impact location has negligible effect on the CAI strength of non-repaired laminates. The impact point modifies the CAI failure progression in all laminate configurations; additionally, in the case of repaired specimens, failure is also related with patch-debonding. Both baseline and repaired laminates impacted at the centre present the same failure progression at all impact energies (developing from the middle of the specimen); however, failure progression varies with impact energy when the impact is located at point B. At impact energies below 12.5 J, the failure progresses in the middle of the specimen; whereas at impact energies above 12.5 J, failure initiates at the impact point. This behaviour is related with the extent of impact-induced damage, which represents more than 10% of the area of specimens.

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References

1. W.J. Cantwell, J. Morton, The significance of damage and defects and their detection in composite materials: a review, *J. Strain Anal. Eng. Des.* 27 (1992) 29–42.
2. A.T. Rhead, S. Hua, R. Butler, Damage resistance and damage tolerance of hybrid carbon-glass laminates, *Compos. Part A Appl. S.* 76 (2015) 224-232.
3. M.A. Caminero, I. García-Moreno, G.P. Rodríguez, Experimental study of the influence of thickness and ply-stacking sequence on the compression after impact strength of carbon fibre reinforced epoxy laminates, *Polym. Test.* 66 (2018) 360-370.

4. R. Garcia, M. Linke, S. Neßlinger, J.A. García-Manrique, An infiltration strategy to repair Carbon Fiber Reinforced Polymer (CFRP) parts, *Procedia Manuf.* 13 (2017) 380-387.
5. G.S. Bhatia, J.J. Andrew, G. Balaganesan, A. Arockiarajan, The role of patch-parent configurations on the tensile response of patch repaired carbon/epoxy laminates, *Polym. Test.* 70 (2018) 413–425.
6. K.B. Katnam, L.F.M. Da Silva, T.M. Young, Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities, *Prog. Aerosp. Sci.* 61 (2013) 26–42.
7. L. Shufeng, C. Xiaoquan, X. Yunyan, B. Jianwen, G. Xin, Study on impact performances of scarf-repaired carbon fiber reinforced polymer laminates, *J. Reinf. Plast. Comp.* 34 (2015) 60–71.
8. M.M. Moure, F. Otero, S.K. García-Castillo, S. Sánchez-Sáez, E. Barbero, Damage evolution in open-hole laminated composite plates subjected to in-plane loads, *Compos. Struct.* 133 (2015) 1048-1057.
9. H.C.H. Li, T. Mitrevski, I. Herszberg, Impact on bonded repairs to cfrp laminates under load, in: *25th International Congress of the Aeronautical Sciences*, 2006.
10. A.B. Harman, A.N. Rider, Impact damage tolerance of composite repairs to highly-loaded, high temperature composite structures. *Compos. Part A Appl. S.* 42 (2011) 1321–1334.
11. C. Xiaoquan, Z. Wenyi, L. Shufeng, X. Yunyan, B. Jianwen, Damage of scarf-repaired composite laminates subjected to low-velocity impacts, *Steel Compos. Struct.* 17 (2014) 199-213.

12. J.J. Andrew, V. Arumugam, K. Saravanakumar, H.N. Dhakal, C. Santulli, Compression after impact strength of repaired GFRP composite laminates under repeated impact loading, *Compos. Struct.* 133 (2015) 911–920.
13. S.R.M. Coelho, P.N.B. Reis, J.A.M. Ferreira, A.M. Pereira, Effects of external patch configuration on repaired composite laminates subjected to multi-impacts, *Compos. Struct.* 168 (2017) 259–265.
14. Y. Tie, Y. Hou, C. Li, X. Zhou, T. Sapanathanb, M. Rachik, An insight into the low-velocity impact behavior of patch-repaired CFRP laminates using numerical and experimental approaches, *Compos. Struct.* 2018; 190: 179–188.
15. J.J. Andrew, S.M. Srinivasan, A. Arockiarajan, Influence of patch lay-up configuration and hybridization on low velocity impact and post-impact tensile response of repaired glass fiber reinforced plastic composites, *J. Compos. Mater.* 53 (2019) 3–17.
16. B. Liu, Q. Han, X. Zhong, Z. Lu, The impact damage and residual load capacity of composite stepped bonding repairs and joints, *Compos. Part B Eng.* 158 (2019) 339–351.
17. I. Ivañez, S.K. Garcia-Castillo, S. Sanchez-Saez, E. Barbero, Experimental study of the impact behaviour of repaired thin laminates with double composite patch, *Mech. Adv. Matl. Struct.*, 2018. <http://dx.doi.org/10.1080/15376494.2018.1524952>.
18. H. Park, C. Kong, A study on low velocity impact damage evaluation and repair technique of small aircraft composite structure, *Compos. Part A Appl. S.* 42 (2011) 1179–1188.
19. NASA. Standard test for toughened resin composites. NASA Reference Publication 1092; 1983.
20. Boeing. Advanced composite compression test. Boeing Specification Support Standard BSS 7260, 1988.

21. SACMA Recommended Methods SRM 2 94. Suppliers of Advanced Composites Materials Association, 1994.
22. ASTM D7137 / D7137M – 17. Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates, 2017.
23. S. Sanchez-Saez, E. Barbero, R. Zaera, C. Navarro, Compression after impact of thin composite laminates, *Compos. Sci. Technol.* 65(2005) 1911-1919.
24. M. Remacha, S. Sánchez-Sáez, B. López-Romano, E. Barbero, A new device for determining the compression after impact strength in thin laminates, *Compos. Struct.* 127 (2015) 99-107.
25. S. Sanchez-Saez, E. Barbero, C. Navarro, Compressive residual strength at low temperatures of composite laminates subjected to low-velocity impacts, *Compos. Struct.* 85 (2008) 226-232.
26. P.G. Slattery, C.T. McCarthy, R.M. O'Higgins. Assessment of residual strength of repaired solid laminate composite materials through mechanical testing. *Compos. Struct.* 147 (2016) 122-130.
27. K. Saravanakumar, H. Subramanian, V. Arumugam, H.N. Dhakal, Influence of milled glass fillers on the impact and compression after impact behavior of glass/epoxy composite laminates, *Polym. Test.* 75 (2019) 133–141.
28. ASTM D7136/D 7136M-07, Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. ASTM International, West Conshohocken, PA; 2007.
29. I. Ivañez, M.M. Moure, S.K. Garcia-Castillo, S. Sanchez- Saez, The oblique impact response of composite sandwich plates, *Compos. Struct.* 133 (2015) 1127–1136.
30. M.O.W. Richardson, M.J. Wisheart, Review of low-velocity impact properties of composite materials, *Compos Part A-Appl S 27A* (1996) 1123–1131.

31. L. Yang, Y. Yan, N. Kuang. Experimental and numerical investigation of aramid fibre reinforced laminates subjected to low velocity impact. *Polym Test* 32 (2013) 1163–1173.
32. H. Tuo, Z. Lu, X. Ma, J. Xing, C. Zhang, Damage and failure mechanism of thin composite laminates under low-velocity impact and compression-after-impact loading conditions, *Compos Part B-Eng* 163 (2019) 642–654.
33. A. Sasikumar, D. Trias, J. Costa, N. Blanco, J. Orr, P. Linde, Impact and compression after impact response in thin laminates of spread-tow woven and non-crimp fabrics. *Compos. Struct.* 215 (2019) 432–445.
34. E. Panettieri, D. Fanteria, M. Montemurro, C. Froustey, Low-velocity impact tests on carbon/epoxy composite laminates: A benchmark study *Compos Part B-Eng* 107 (2016) 9–21.
35. X. Cheng; W. Zhao; S. Liu; Y. Xu; J. Bao, Damage of scarf-repaired composite laminates subjected to low-velocity impacts, *Steel Compos Struct* 17(2) (2014) 199–213.
36. G. Zhou, The use of experimentally-determined impact force as a damage measure in impact damage resistance and tolerance of composite structures. *Compos. Struct.* 42 (1998) 375–382.

FIGURE CAPTIONS

Fig.1. Impact point locations and cut-out dimensions (dashed line): a) baseline laminate, b) double-patch repaired laminate.

Fig. 2. Experimental configuration for CAI test.

Fig. 3. Load versus displacement curves for baseline specimens (left) and repaired specimens (right) at impact energies of 5 J, 15 J and 25 J.

Fig. 4. Peak load versus impact energy: a) baseline specimens, b) repaired specimens

Fig. 5. Absorbed energy percentage versus impact energy: a) baseline specimens, b) repaired specimens.

Fig. 6. C-Scan images of baseline and repaired specimens impacted at different energies

Fig. 7. Damage area extension versus impact energy: a) baseline specimens, b) repaired specimens.

Fig. 8. Normalised residual strength versus impact energy: a) baseline specimens, b) repaired specimens.

Fig. 9. Baseline laminates impacted at point A: a) front view, b) rear view.

Fig. 10. Baseline specimens impacted at point B (impact energy < 12.5 J): a) front view, b) rear view.

Fig. 11. Baseline specimens impacted at point B (impact energy ≥ 12.5 J): a) front view, b) rear view.

Fig. 12. Repaired specimens impacted at point A: a) front view, b) rear view.

Fig. 13. Repaired specimens impacted at point B (impact energy < 12.5 J): a) front view, b) rear view.

Fig. 14. Repaired specimens impacted at point B (impact energy ≥ 12.5 J): a) front view, b) rear view.

TABLE CAPTIONS

Table 1. Average values and standard deviation of the peak load

Table 2. Average values and the standard deviation of absorbed energy

Table 1. Average values and standard deviation of the peak load

Impact energies	Intact specimen		Repaired specimen	
	Point A	Point B	Point A	Point B
5 J	2992.42±13.48 N	3230.67±25.21 N	3306.91±80.86 N	3416.51±47.17 N
7.5 J	--	4288.50 N	--	--
10 J	4684.03±74.20 N	5179.55±6.74 N	4836.48±20.22 N	5260.56±53.91 N
12.5 J	--	5384.45±13.48 N	--	6022.96±161.73 N
15 J	5370.16±424.54 N	5894.31±249.33 N	6375.57±40.43 N	6218.33±20.22 N
20 J	5441.63±229.12 N	6022.96±409.79 N	7371.46±6.74 N	6245.33±282.92 N
25 J	5370.16±141.51 N	5413.04±202.16 N	8805.72±252.14 N	6566.17±256.07 N
27.5 J	5708.47 N	5718.00 N	8839.08±114.56 N	6232.62 N

Table 2. Average values and the standard deviation of absorbed energy

Impact energies	Intact specimen		Repaired specimen	
	Point A	Point B	Point A	Point B
5 J	1.25±0.18 J	1.69±0.19 J	1.70 ±0.10 J	1.50±0.04 J
7.5 J	--	2.46 J	--	--
10 J	3.18±0.28 J	3.58±0.06 J	3.87±0.16 J	3.47± 0.19 J
12.5 J	--	7.81±0.33 J	--	5.20±0.23 J
15 J	9.26±0.23 J	10.06±0.28 J	5.56±0.23 J	9.10±0.16 J
20 J	15.07±0.26 J	15.14±0.68 J	10.08±0.31 J	14.09±0.26 J
25 J	21.47±0.22 J	21.26±0.04 J	12.41±0.28 J	20.25±0.28 J
27.5 J	25.89 J	26.10 J	14.75±0.60 J	24.96 J

a)

b)

BASELINE LAMINATES

REPAIRED LAMINATES

5 J

15 J

25 J

Baseline specimens

Point A

Point B

Repaired specimens

Point A

Point B

a)

b)

a)

b)

a)

b)

a)

b)

a)

b)