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Experimental study of the impact behaviour of repaired thin laminates with double composite patch.

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Abstract

The aim of this paper is to present a study of the behaviour of double patch-repaired laminates subjected to low-velocity impacts. Experimental impact tests were conducted using a drop-weight tower at different impact energies. A broad range of impact energies was selected: from barely visible impact damage energy up to energies close to perforation. Results for repaired laminates in terms of contact load, damage and absorbed energy were compared to those obtained from intact specimens. At impact energies below 10 J, energy absorption in repaired specimens was higher than the one given in intact laminates, although the measured damage area was found to be greater in the former configuration. For higher impact energies, both damage area and energy absorption in intact specimens were greater than in repaired laminates.

Keywords: patch-repaired plate, thin laminate, low-velocity impact, damage threshold load

1. Introduction

Laminates are widely used in aircraft structures because of their excellent mechanical and specific properties. The use of laminates leads to measurable reduction of the structural weight as well as lower fuel consumption, increasing the efficiency of aircrafts and reducing pollution emissions. However, composite structures can be damaged in many ways, such as manufacturing defects (porosity), residual stresses, thermal effects, etc.

Complete replacement of damaged components is not always feasible, due to the big size and the high level of integration of structural elements. Therefore, repair and subsequent put into operation of composite structures, can be cost-effective and less time-consuming [1].

Bonded-adhesive repairs can produce a greater increment of the strength of damaged composite structures, without increasing their weight. In addition, they are the most indicated to repair thin laminates [2]. External bonded patches are a suitable solution to repair thin composite laminates with thicknesses around 2 mm, as other techniques (scarf and step repairs) are recommended only for laminates exceeding 3 mm in thickness [3-6].

Several works study the response of adhesive repairs with external patches taking into account the influence of the manufacturing factors (properties of surface, curing and adhesion conditions, etc.) [7-9], the behaviour of the adhesive [10-12], the effect of temperature and humidity [13, 14], and the geometry of the repair (overlap length, thickness, etc.) [15-16].

Repaired structures of aircrafts are susceptible to impact damage during service life, such as tool-drop, bird strike or hail [17]. In this regard, the structural response of adhesive repairs needs to be analysed with precision, since it is necessary to demonstrate that the repaired component has recovered the properties of the intact component.

A few studies can be found on the behaviour of composite repairs under impact loads at low-velocity [18-20], at high-velocity [21], and in compression after impact [6,22,23]. However,

most of these studies are focused in scarf repair of laminates with thickness greater than 2 mm.

Low-velocity impact is a potentially very dangerous situation for a composite laminate because it can produce a significant reduction in the structural strength of laminates without the damage generated being visually observable [24].

Cheng et al. [19] studied the impact behaviour of scarf-repaired carbon/epoxy laminates of 2.5 mm in thickness, analysing the effect of adhesive thickness and patch orientation on the peak load. Two impact energies, 4.45 J/mm and 6.67 J/mm, were considered. In a following work, Cheng et al. [20] analysed the influence of the stacking sequence on a different carbon/epoxy scarf-repaired laminate subjected to an impact of 6.67 J/mm. The authors that perform compression after impact of repaired laminates consider only one or two impact energy levels: 8.14 J [22], 4.32 J [6], and 4.45 J/mm and 6.67 J/mm [23], focusing their results in the residual strength of the specimens.

Since the damage mechanisms that appear near the barely visible impact damage energy (E_{BVID}) are different from those that appear near the perforation, a wide range of impact energies needs to be considered in order to analyse the overall impact response [18].

Therefore, the need to gain knowledge about the impact resistance of patch-repaired composite structures under service loading is readily apparent.

As a result, in this work the impact response of patch-repaired composite plates subjected to a broad range of low-velocity impact energies is analysed. In order to study the impact capabilities of composite bonded repairs, a comparison between intact laminates (without repair) and double-sided patch repairs is presented in terms of contact load, absorbed energy and damage. This comparison is referred to a series of experimental tests carried out in a drop-weight tower.

2. Material and experimental procedure

The composite panels used in this study were manufactured in autoclave by INTA (Spain) from carbon/epoxy pre-peg (IM7/MTM-45-1) supplied by Hexcel Composite Materials.

These panels presented a quasi-isotropic stacking sequence $[45/0/-45/90]_{2s}$ for a total thickness of 2 mm. The lamina properties are shown in Table 1.

Plates with a square size of 120 mm x 120 mm were cut to obtain the intact specimens (reference specimens). A circular hole of 10 mm in radius was drilled at the centre of the intact plates, representing the damaged region that is removed before the repair procedure.

After, external circular patches of 60 mm in diameter and 1 mm thick ($[45/0/-45/90]_2$ carbon/epoxy laminate) were bonded to the upper and lower surface of the open-hole specimens by using MTA-240 adhesive (0.13 mm thick). Fig. 1 shows the repair geometry and configuration used in this study.

Low-velocity impact tests according to ASTM D7136M [25] were carried out using a CEAST Fractovis 6785 drop-weight tower with computer data acquisition system DAS4000. The instrumented impactor provided force-time curves, from which the maximum displacement and energy variation can be estimated. To obtain a more accurate estimation of the impact and rebound velocities, a high-speed camera APX PHOTRON FASTCAM was used to record the experimental tests. The complete procedure is described in more detail elsewhere [17].

In order to study the impact resistance of composite bonded repairs, two configurations were compared: intact specimens (reference specimens) and repaired specimens (double-sided patch repair specimens). All specimens were impacted in the centre, point A in Fig. 1. The constraints used for all tests were identical, with the plate being fully constrained around the edges.

A total of twenty-six specimens (intact and repaired) were tested with six impact energy levels (ranging between 5 J and 27.5 J). The selected impact range is between energies that

produce barely visible damage and close to perforation. The impactor mass was 3.873 kg, and its hemispherical nose had a diameter of 12.7 mm. Excelent reproducibility was obtained for each configuration and each impact energy level.

To analyse the damage caused by the impact, all specimens were inspected by C-Scan technique, using air-coupled ultrasounds to prevent the specimens from getting wet. The complete experimental device is described in [26].

3. Experimental results

In order to study the impact resistance of double-patch repaired plates, a comparison between the low-velocity impact behaviour of repaired specimens and intact laminates has been carried out. The obtained results have been analysed for a broad range of impact energy, evaluating differences in contact load in terms of: load-time curves, peak load and delamination threshold load. The damage has been estudied as a function of the damaged area, and the impact indentation. Finally, the absorbed energy is appropriately studied.

3.1. Contact load

3.1.1. Load-time curves

Comparison of typical contact load-time histories obtained in the performed low-velocity impacts of intact and repaired laminates is shown in Fig. 2. For the sake of simplicity, only a representative curve for repaired and intact laminates at each impact energy level is shown. Contact load-time curves of repaired and intact specimens tested at 5 J show similar trend, but repaired specimens have slightly higher peak force and smaller contact times (Fig. 2.a). The loading and unloading part of the curve in both structures is smooth, and they present a sinusoidal shape, which is typical for these kind of tests.

At impact energy level of 10 J, contact load histories of both specimens are almost coincident; however, the intact laminate shows an increasing level of noise and oscillations on its signal,

which suggest damage initiation due to loss of stiffness from unpredictable damage propagation [27, 28]. This damage was not visible in the tested specimens but it was supported by ultrasonic data (results will be presented in section 3.2.1.).

At impact energy of 15 J, repaired specimens present contact load-time curves clearly different from the curves obtained for intact specimens. Repaired laminates still show a sinusoidal shape for the loading and unloading part of the curve, whereas intact specimens present a sudden drop when the force reaches a certain value. This is clearly related with the activation of different damage mechanisms and the onset of delamination. At this point, differences between peak load and maximum contact time on intact and repaired specimens are more noticeable, about 25% and 31% respectively.

For impacts of 20 J, 25 J and 27.5 J, the noise in both curves increases strongly, but repaired specimens still show the typical sinusoidal shape, with increasing peak load in each impact level. Intact laminates peak load remains almost constant at this impact energy range. No damage on the lower patch repair was observed at this stage; however, perforation was given for an impact energy higher than 25 J in intact laminates.

3.1.2. Peak load and delamination threshold load

The peak load and the delamination threshold load (DTL) were estimated from load-displacement curves (Fig. 3). The peak load was calculated as the maximum value of the load registered during the test, and the DTL was defined as the load level at which a first sudden drop in the load occurs as a result of the onset of delamination [28]. In thin laminates, as those analysed in this work, the estimation of DTL is difficult in some cases because the drop in the load record is smaller than the one observed in thick laminates [27, 28].

The evolution of peak load with impact energy is showed in Fig. 4. At lower impact energies (5 J and 10 J), the value of the peak load is similar for both intact and repaired specimens, whereas for impact energy levels above 10 J, peak load is greater in repaired specimens. For

contact load-time curves at impact energies above 10 J (Fig. 2c-2f), intact specimens present a sudden drop of the load after reaching the peak load. This drop is followed by large amplitude oscillations. In repaired specimens, oscillations around the peak load value are softer and no abrupt load drop is evident.

Above an impact energy of 15 J, peak load in intact specimens remains almost constant and it does not vary with the increase in impact energy; however, the peak load value in repaired specimens showed an almost linear trend up to impact energy of 25 J, from which it tends to a constant value.

Fig. 5 presents the DTL as a function of the impact energy. For both specimens (intact and repaired), no sudden drop of the load was given at impact energy of 5 J, and DTL could not be estimated.

Although there is some scattering in the results, DTL shows a significant variation with impact energy. For the selected impact energy range, DTL value is greater in repaired specimens than in intact specimens, possibly due to the fact that repaired specimens present higher stiffness than intact laminates due to the size of the patch, increasing the value of load needed to produce the onset of delamination. For intact specimens an increase of approximately 35% is observed when the impact energy varies between 10 J (E_{BVID}) and 27.5 J (perforation energy), while for repaired specimens the increase of DTL in this energy range is around 80%.

In intact specimens, DTL remains almost constant for impact energies between 15 J and 25 J, when perforation has not occurred. In repaired specimens, and for the studied range of impact energies, DTL augments with impact energy.

In Fig. 5b, the DTL/peak load ratio is presented as a function of the impact energy for intact and repaired specimens. For impact energies above 10 J, this ratio is barely affected by the increase in impact energy, and values are similar for both specimen configurations. As a

conclusion, DTL is around 80% of the measured peak load for intact and repaired specimens.

3.2. Damage

3.2.1. Damaged area

The damaged area of both specimen configurations was estimated from C-Scan images, that provide a plan-type view of the specimen features. Fig. 6 shows the C-Scan images of different specimens studied (intact and repaired).

The C-Scan image of the intact specimen impacted at 5 J shows only matrix cracking damage, located at the centre of the specimen. At impact energy of 10 J, the intact specimen shows not only matrix cracking but the onset of delamination. Intact specimens impacted at 15 J, 20 J, 25 J and 27.5 J presented the aforementioned damage mechanisms and fiber breakage at the bottom plies, which extends to the edges of the specimen. Intact specimens impacted at 27.5 J were perforated.

For repaired specimens, the shape of damage is completely different: damage is much more localised than in the case of intact specimens and its shape can be approximated to a circle, without being extended to the edges of the specimen. At impact energy of 5 J, this localised damage cannot be directly related to the onset of delamination, as the DTL determined from the load-displacement curves for repaired specimens could only be measured for impact energies above 10 J.

In all cases, repaired specimens C-Scan images showed two concentric rings: the outer ring is located along the bondline and corresponds to the change in the cross-section of the specimen due to the bonding of the repair patch. The inner ring could be related to the manufacturing process, although its extension increases with increasing impact energy.

Fig. 7 shows the results the damaged area (in percentage) versus impact energy for intact and repaired specimens. At low impact energies (E_{BVID}), the percentage of damaged area is similar in both configurations (differences of 0.9% and 1.7% for 5J and 10J, respectively), although

the shape of the damage is completely different (see Fig. 6). From an impact energy value of 15 J, damaged area of repaired specimens increases slightly, the difference between 10 J and 27.5 J being 4.8%. However, in intact specimens there is a strong increase in damaged area between 10 J and 20 J (13.3%) that becomes gradual for 25 J, as perforation was given at 27.5 J.

3.2.2. Impact indentation

The indentation depth can be used as indication of the damage induced by low-velocity impacts. In this work, the instantaneous impact indentation depth was measured as the recorded displacement when the load values zero (Fig.3).

In Fig. 8, the impact indentation depth as a function of impact energy was shown, for both intact and repaired specimens. For low-impact energies, 5 J and 10 J, impact indentation depth was similar for both configurations: no difference was observed for impact energy of 5 J, and a difference of 8% was measured for 10 J.

At higher impact energies the indentation depth increases more sharply for intact specimens, being 0.7 mm and 6.34 mm for impact energy of 10 J and 27.5 J respectively. In repaired specimens, indentation depth augments almost linearly and less than in the intact specimens (0.76 mm for 10 J and 2.25 mm for 27.5 J). Same tendencies are observed in the measured damage area (Fig. 7).

In addition, it can be concluded that values of indentation depth greater than 4.5 mm produce perforation, as well as that for values below 0.76 mm it could be said that the damage is barely visible. Since the indentation depth is measured instantaneously, its value can decrease with the relaxation of the specimen. For example, Abi Abdallah et al. [29] give a value of permanent indentation depth for barely visible impact damage of 0.6 mm after 48 hours of relaxation.

3.3. Absorbed energy

Absorbed energy versus impact energy is presented in Fig. 9a. The evolution of the results (in both intact and repaired specimens) confirms that it is necessary to carry out enough experimental tests in order to cover a broad range of impact energy levels as tendencies can change due to the effects of the brittle nature of composite materials. Absorbed energy is found to increase almost linearly for impact energy levels ranging from 5 J to 10 J. However, this trend cannot be extended to results for impact energy levels above 15 J as there is a change in the slope of both absorbed energy curves (intact and repaired specimens).

The energy absorption percentage as a function of the impact energy curve is presented in Fig. 9b. For intact laminates, two energy absorption regions can be considered: for impact energies below 10 J, absorbed energy increases slightly and its values vary a 10% (from 5 J to 10 J). Above impact energy of 15 J, the energy absorption percentage varies from 60% to 90%. For repaired specimens, variations on the energy absorption percentage between the lowest and the highest impact energy are around 20%. Although damage area results for lower impact energy levels were similar for both specimen configurations, comparison between the absorbed energy of intact and repaired specimens shows that repaired specimens absorb slightly more impact energy than intact specimens. This small difference (less than 5%) is due to the damage produced on the filler inserted into the drilled hole, that represented the removal of damage in the repaired specimen.

At higher impact energies the tendency changes, and intact specimens increase their energy absorption capabilities quite rapidly. In this region, the evaluated damage is clearly more extensive in intact specimens than the one given in repaired specimens (see Fig. 7), and damage mechanisms are likely to activate the energy absorption capabilities of the intact specimen. In the case of repaired specimens, damage tends to remain almost constant in the selected impact energy range; thus damage mechanisms, and the associated energy absorption in each case, are not activated so promptly.

4. Conclusions

Impact resistance of double-sided patch repaired composite plates was evaluated by carrying out a series of experimental tests in a drop-weight tower. A broad range of impact energies was selected and results were compared to the ones obtained for intact composite laminates. Contact load, damage and absorbed energy were evaluated, and the following conclusions can be drawn:

- At lower impact energies (5 J and 10 J), contact load histories of intact and repaired specimens are almost coincident; however, at impact energies above 15 J, intact specimens present a sudden drop, whereas repaired laminates still show a sinusoidal shape (although with increasing noise in its signal).
- At impact energy below 10 J, measured peak load is similar for both intact and repaired laminates, whereas for impact energy levels above 10 J, peak load is higher in repaired specimens.
- Above an impact energy of 15 J, peak load in intact specimens remains almost constant with increasing impact energy; however, in repaired specimens the peak load presented an almost linear trend up to impact energy of 25 J.
- For the studied impact energy range, DTL varies with the impact energy and its value is higher in repaired specimens than in intact laminates, due to the higher stiffness of the repaired configuration, which increases the load needed to produce the onset of delamination. DTL was around 80% of the measured peak load for both intact and repaired configurations.
- Damaged area of intact and repaired specimens was determined using C-Scan technique. The shape of the damage in repaired specimens was completely different for the given in intact specimens. In intact specimens for higher impact energies,

matrix cracking, delamination and fibre breakage were observed, whereas for repaired specimens the damage was located on the centre of the patch repair.

- In both specimen configurations, the damage area increases with impact energy; however, for impact energies above 10 J, intact specimens show an abruptly augmentation of the damaged area that was not observed in the repaired specimens, in which the damage area increases almost linearly for the studied impact energy range.
- The impact indentation depth was used as indication of the damage induced by low-velocity impacts and it was concluded that, for intact specimens, values above 4.5 mm produce perforation, while values of indentation depth below 0.76 mm give barely visible damage.
- Absorbed energy confirmed the need to carry out a broad range of impact tests to analyse the low-velocity impact behaviour of both studied configurations.
- For intact laminates, two energy absorption regions were observed: for impact energies below 10 J, absorbed energy increases slightly. Above impact energy of 15 J, the energy absorption in intact specimens increases quite rapidly. For repaired specimens, variations on the energy absorption percentage between the lowest and the highest impact energy are around 20%.
- At low impact energy levels, repaired specimens absorb slightly more impact energy than intact specimens, due to the damage produced on the filler inserted into the hole. At high impact energies, this tendency changes and intact specimens absorb more energy due to the activation of the different damage mechanisms.

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FIGURE CAPTION

Fig. 1. Double-patch repair configuration

Fig. 2. Load-time curves for different impact energies: a) 5 J, b) 10 J, c) 15 J, d) 20 J, e) 25 J and f) 27.5 J.

Fig. 3. Peak load and DTL from the force-displacement curve in a repaired specimen impacted at 20 J.

Fig. 4. Peak load vs. impact energy.

Fig. 5. a) DTL variation with impact energy, b) DTL/peak load ratio variation with impact energy.

Fig. 6. C-Scan images for impacted specimens

Fig. 7. Extension of damaged area vs. impact energy for all different specimens

Fig. 8. Impact indentation depth vs. impact energy.

Fig. 9. Absorbed energy vs. impact energy: a) absolute value, b) percentage.

TABLE CAPTION

Table 1. Lamina properties IM7/MTM-45-1

a)

b)

c)

d)

e)

f)

Intact specimens

Repaired specimens

Young's modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
$E_x=173$	$\nu_{xy}=0.32$	$G_{xy}=3.89$
$E_y=7.36$	$\nu_{xz}=0.5$	$G_{xz}=3.89$
$E_z=7.93$	$\nu_{yz}=0.5$	$G_{yz}=2.94$