IMPACT DAMAGE AND SHEAR STRENGTH IN BONDED LAP JOINTS FOR REPAIR PURPOSES

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Abstract

In this study the impact damages and shear strength of pristine and impacted lap bonded joints for repair purposes are presented. Two different types of repair systems were submitted to testing in co-bonded specimens with a precured adherent: a repair pregreg in combination with two adhesive films and two wet lay-up systems with two different laminating resins. After a calibration phase to adjust the overlap size and the impact energy, the bonded specimens were impacted at three different locations and the damage pattern and damage dimensions analyzed. Single lap shear tests were performed on impacted and pristine specimens. The static strength and failure mode was determined and results analyzed as a function of the impact position. The behavior of the different repair systems tested is assessed.

1 Introduction

The capability to restore the damage tolerance at all operational conditions is one of the main requirements of bonded repairs for non-allowable damage sizes impacting the capability to sustain Ultimate Load and Limit Load in highly loaded primary and secondary CFRP components.

This capability relies in the use of a proper repair design [1, 2] and suitable repair materials and processes. The use of original production materials is usually prevented for field repairs, as they require autoclave curing to achieve their best performance, which is not suitable for wing, fuselage, stabilizers or other primary structures. Even for components that can be easily disassembled, like doors, access panels, fairings, etc., the use of original production materials is also not a common practice due again to the necessity of using autoclave with the appropriate tooling to avoid component deformation and due to the hazards associated to the heating of the component to high temperature.

Materials specially dedicated to repair purposes have in common the suitability to be cured at temperatures below 120ºC - 130ºC and to achieve good properties (low porosity) when cured only under vacuum pressure.

For years the most common repair materials for severe damages have comprised only prepregs, which in combination with compatible adhesive films, are used to restore the damaged skins. They offer the advantage of allowing large repairs and being clean and easy to use. On the contrary, they all are to be stored at low temperature (contributing to equipment and energy consumption) and have typically very short shelf lives leading to high waste rates. In addition, only those prepreg/adhesive combinations demonstrated to be compatible are allowed, what implies the maintenance of synchronized stocks. Laminating resins of improved performance can be also used for structural wet lay-up repairs. They can be stored at room temperature and have long shelf lives for which reason airlines prefer their use versus prepregs/adhesive films.

Studies performed on secondary bonded joints where the bonding agents were either neat laminating resins or adhesive films have shown that the mode I fracture toughness under static and cyclic loads of the laminating resins was significantly lower than the one of adhesive films [3, 4]. The same behavior has been also found in co-bonded specimens where the mode I fracture toughness of bonded joints with wet lay-up patches or adhesive film/prepreg patches was studied [5]. These results indicated the need of further investigation on the damage tolerance of wet lay-up versus adhesive film/prepreg repair patches.

A study of the impact damages and shear strength of pristine and impacted lap bonded joints for repair purposes was carried out and results are presented in this communication. Fresh wet lay-up and fresh adhesive films/repair pregreg patches were co-bonded to a precured adherent. The results presented here correspond to the feasibility phase, where the impact energies, the specimen damages and the results of tensile tests have been evaluated to be further completed with hot/wet and fatigue testing.

2 Experimental

2.1 Impact tests on calibration specimens and single lap bonded specimens

Repair prepreg and wet lay-up panels were manufactured with the following stacking sequence: $[45º/0º/-45º/90º/+45º/0º]_{2S}$ and a total nominal thickness of 5.1 mm for the repair prepreg and 4.8 mm for the wet lay-up laminates. To resemble the field repair conditions, the panels were cured under vacuum pressure only.

Specimens were impacted at several impact energies and the dent depth in each specimen was measured. The dimensions of the damaged zone were established by analysis of the C-scan image of each specimen and those of specimens with Barely Visible Impact Damage (BVID) or impacted with 35 J, whichever was reached first, were used to define the overlap width and length for the single lap shear specimens. Width and length were at least 2.5 times the longest damage length (D) to avoid edge interaction effects on the residual strength of the impacted joints [6].

The bonded panels for the single lap shear specimens were composed of a precured prepreg laminate on which the adhesive film and the repair prepreg fresh lay-up was co-bonded. Panels with adhesive films A1 and A2 were manufactured (further referred to as P1 and P2). In a similar way, for the wet lay-up materials, bonded panels were composed of a precured wet lay-up laminate on which fresh wet lay-up plies were co-bonded (further referred to as W1 and W2). The lay-up of each semi-specimen was $[45/0/-45/90/45/0]_S$ providing a total thickness equal to the one of the specimens used in the impact calibration tests.

The bonded specimens were impacted in three positions along the overlap as shown in Figure 1. Impact machine, clamping device and impact conditions were as the ones used for the calibration tests (refer to Figure 2). After the impacts, the specimens were analyzed by automatic through transmission and pulse echo US inspections to measure the damaged area. One specimen of each type and each impact position was sectioned for inspection of the type and extent of damages.

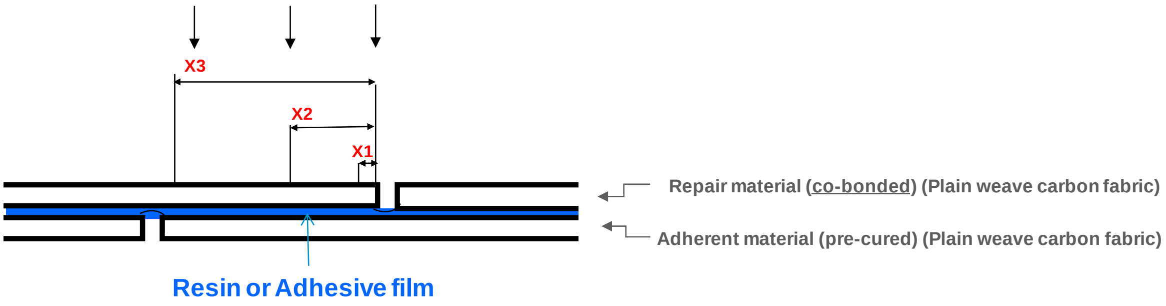


Figure 1. Impact positions on the bonded overlap

3.2 Lap shear test results

Mechanical tests were performed using a 500kN MTS universal testing machine. The tests were done in displacement control at a velocity of 2 mm/min until failure of the specimen. Impacted and pristine single lap shear specimens were tested with an anti-bending fixture measuring both the load and displacement (refer to Figure 2). The failure mode of the specimens was analyzed and pictures taken.

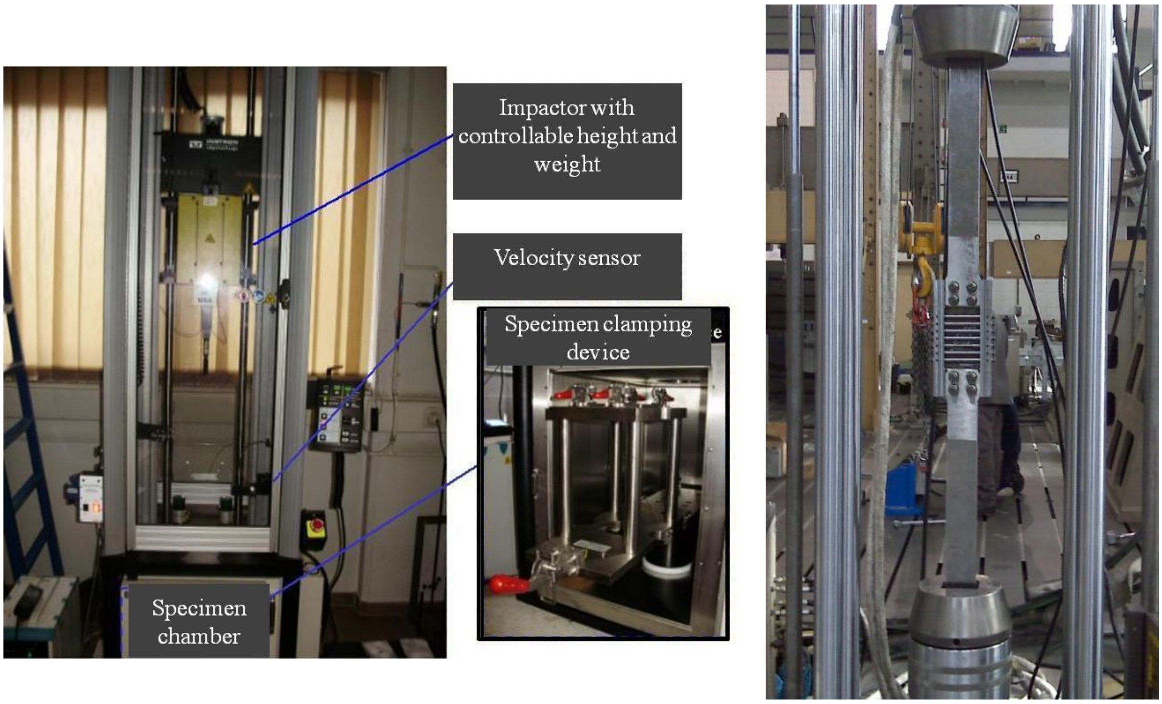


Figure 2. Test set-up: left hand side: Impact tests. Right hand side: Single lap shear tests.

3 Results

3.1 Impact tests on calibration specimens and single lap bonded specimens

Figure 3 shows the calibration test results for the repair prepreg R and the two wet lay-up materials W1 and W2, in terms of the dent depth as a function of the impact energy.

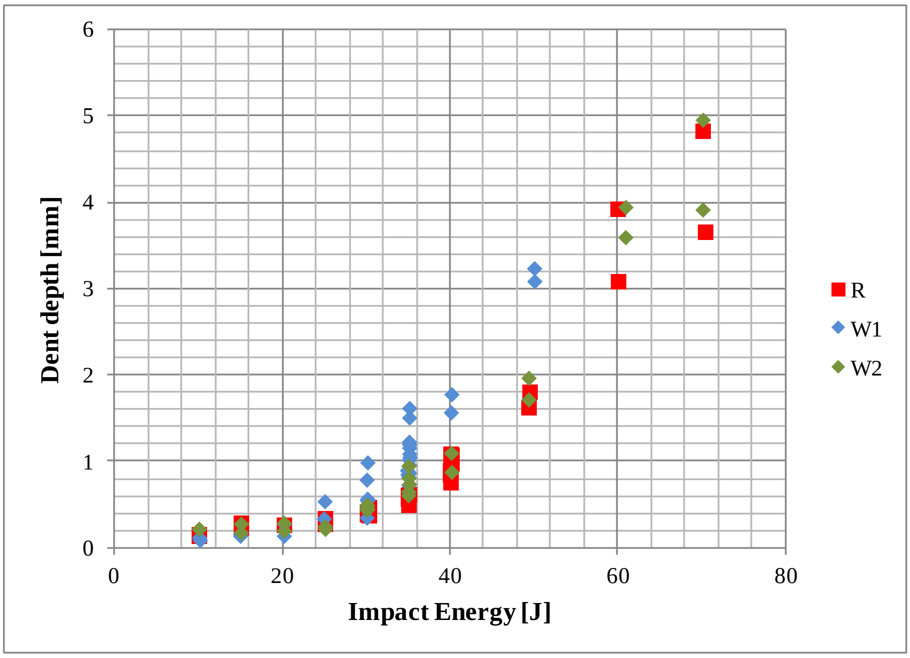


Figure 3. Calibration test results: Dent depth as a function of the impact energy.

The average values of the longest damage length (D) and the damaged area on those specimens impacted at 35 J were used to determine the suitable overlap width and length for the single lap shear specimens. The three repair materials investigated presented very similar damaged areas and in order to accommodate the damage into the overlap length and width, an overlap of 120 mm x 120 mm was selected, being the total length of the specimens of 320 mm.

Single lap bonded specimens were impacted at 35 J on their co-bonded side at the three impact positions, X1, X2 and X3, shown in Figure 1. Figure 4 shows the pulse-echo inspection results of two specimens P1 and of two specimens W2, as well as a representative C-scan, for each impact position. The four repair systems, P1 and P2 with adhesive films and repair prepreg and W1 and W2 with wet lay-up composites, presented the same typical impact damages for the different impact positions, which can be described as inversed champignon, round and half-moon for the impact positions X1, X2 and X3, respectively.

Specimens of each type were sectioned and submitted to microscopic inspection. In case of the impact position X2 the damage concentrated around the impact. For the impact position X3, two characteristic damage zones were distinguished: the center of the damaged area, which concentrated the damage in the laminates (red spot in the C-scan shown in figure 4), and the zone around it which corresponded mainly to debonding between the two laminates. Impacts in X1 also produced damages in the laminates around the impact position, while beyond the central overlap, the damage corresponded to debonding between the laminates.

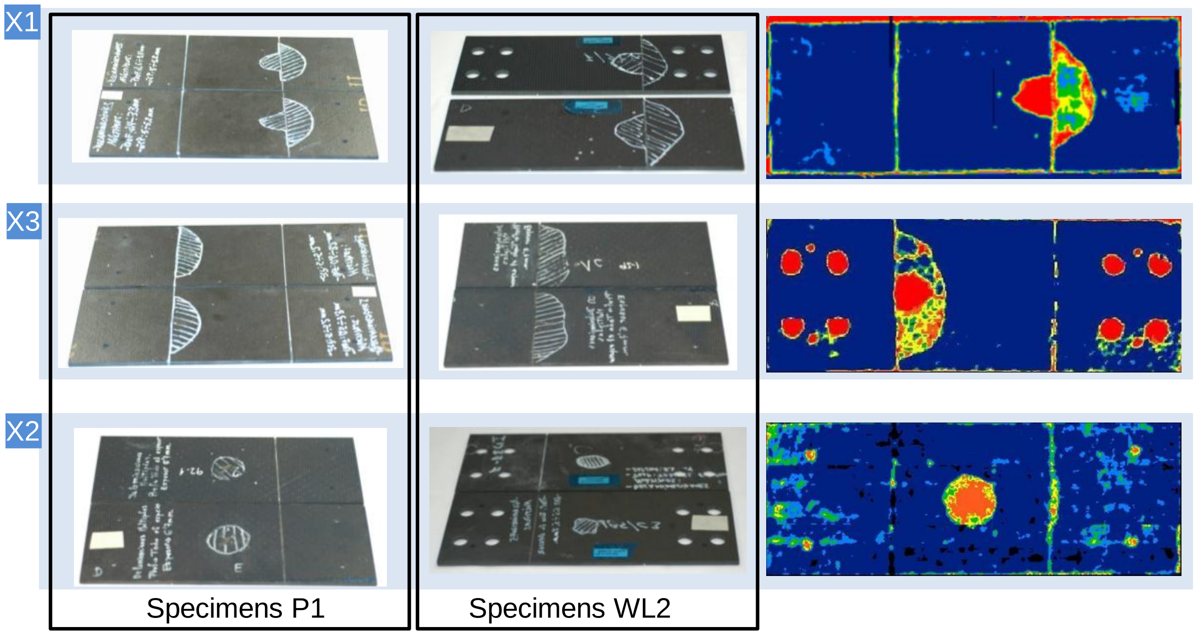


Figure 4. Impact damages in the bonded specimens for the three impact positions X1, X2 and X3.

Figure 5 shows the average values of the dent depth for the three impact positions. For the four repair systems investigated, average dent depth values in positions X1 and X2 were comparable and also comparable to the ones in the calibration specimens with no bonded joint but the same total thickness (refer to Figure 3). However, the dent depth in position X3 was notably higher than the ones in positions X1 and X2.

The average values of the damaged area, obtained from the C-scan analysis of the impacted specimens, are shown in Figure 6 as a function of the impact position for the four repair systems. For the impacts in position X1, only the damaged area on the central overlap region was measured. Again, the damaged areas in the bonded specimens produced by the impacts in positions X1 and X2 were similar and comparable to the ones in the calibration specimens. In position X3, the damaged area was much bigger for the four types of bonded specimens, because this included not only the area where the laminates are damaged by also the debonded area in the overlap (refer to Figure 4).

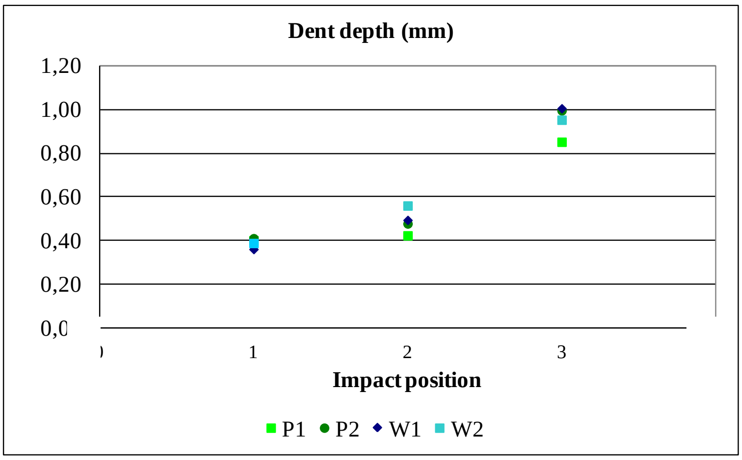


Figure 5. Dent depth as a function of the impact position in the single lap shear specimens.

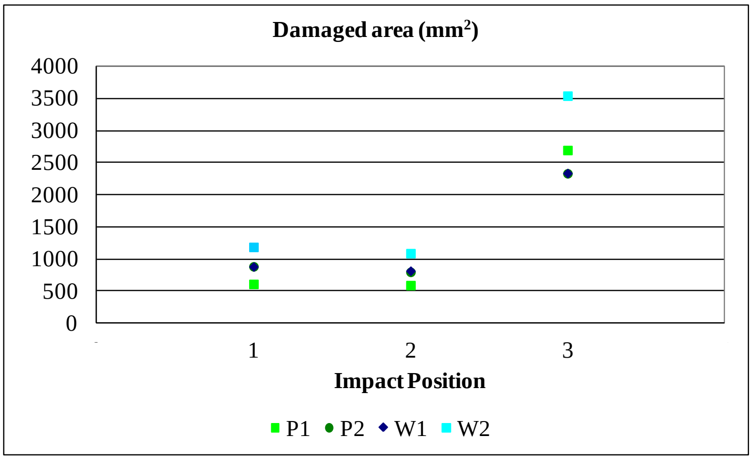


Figure 6. Damaged area as a function of the impact position in the single lap shear specimens.

3.2 Lap shear test results

Reference non-impacted lap shear specimens and specimens impacted in positions X1, X2 and X3 were subjected to tensile loading at room temperature up to failure. Specimens were tested with a fixture designed to prevent bending in tension and buckling in compression for subsequent test phases where cyclic loading including tension/compression loads is foreseen.

Figure 7 shows the individual values of the ultimate shear strength for the four repair systems investigated and the three impact positions, together with the reference values from pristine specimens. Regardless of the impact position, the strength values in all specimens were similar and also similar to the ones of the reference specimens. A summary of the failure modes is presented in Table 1 together with representative photographs of failed specimens of type repair prepreg and adhesive film (either P1 or P2) and of type wet lay-up (either W1 or W2). Reference non-impacted specimens presented substrate failure by delamination between the plies combined in some cases with tensile ply failure. Specimens impacted on positions X1 and X3 presented net section tensile failure at the impact position in the load-carrying plates (precured semi-specimen for X1 and co-bonded semi-specimen for X3). Finally, specimens impacted on position X2 (the center of the overlap area) presented substrate failure by delamination between the plies combined in some cases with tensile ply failure.

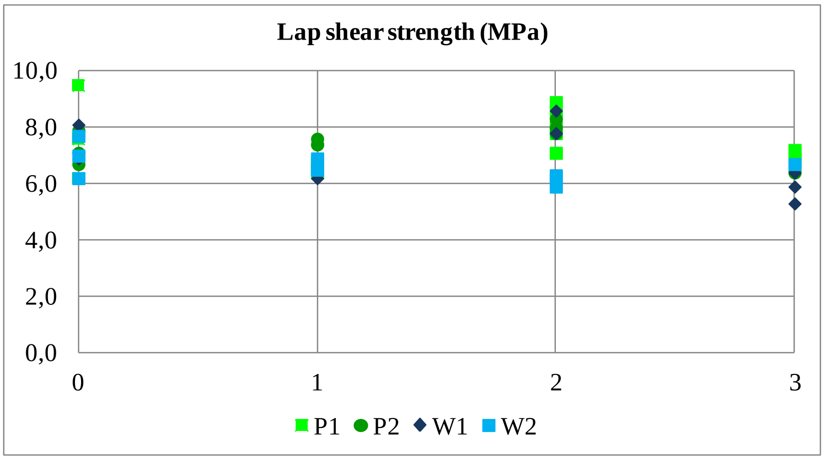


Figure 7. Lap shear strength as a function of the impact position. Reference samples with no impact are indicated as 0 in the graph.

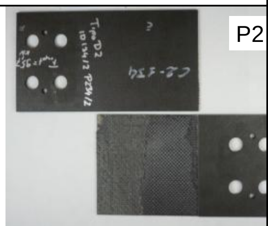
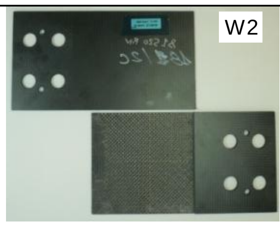
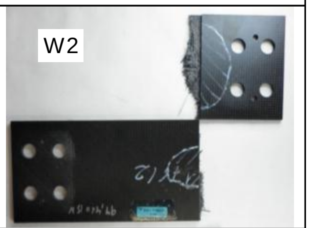
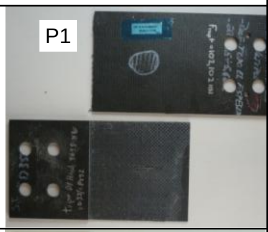
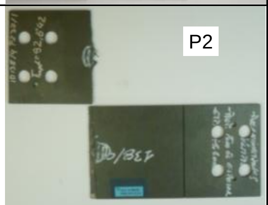
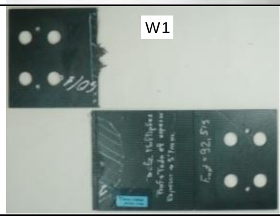
Impact position	**Failure mode**		
No impact	Substrate failure by delamination and tensile ply failure in the overlap area		
X1	Net section tensile failure in the load-carrying plate (precured semi-specimen, opposite to the impacted side)		
X2	Substrate failure by delamination and tensile ply failure in the overlap area		
X3	Net section tensile failure in the load-carrying plate (co-bonded semi-specimen, impacted side)		

Table 1. Failure modes in the single lap shear specimens

4 Conclusions

Repair prepreg and wet lay-up laminates presented a very similar response to the impacts in the calibration specimens. When impact damages in the co-bonded specimens were analyzed, a uniform behavior was also observed for the four types of repair systems investigated, repair prepreg and adhesive film (either P1 or P2) and wet lay-up (either W1 or W2). On one hand the same damage pattern was found as a function of the impact position and in the other hand similar values of the dent depth and the damaged area were also observed in all the systems for each impact position.

No significant differences were found in the ultimate strength of the single lap shear specimens impacted at 35 J with regards to the one of pristine specimens. Neither the impact position nor the type of repair system involved in the co-bonded specimens had an significant effect on the ultimate strength.

However, the analysis of the failure modes showed relevant differences among the specimens as a function of the impact position. Failure was influenced by the shear response of the bonded joint but also by the tensile strength of the adherents damaged by the impacts. The four repair materials investigated presented again a consistent failure mode with no remarkable difference among them.

This feasibility phase is to be completed with hot/wet and fatigue tests and with complementary studies on the fracture toughness under mode II and mixed mode of co-bonded joints of the type investigated here but the results found so far encourage the use of wet lay-up materials as much as the use of adhesive film/prepreg for bonded repairs.

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