WET LAY-UP PATCH REPAIR OF COMPOSITE STRUCTURES

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Keywords: Composite Structures, Bonded Patch Repair, Optimisation

ABSTRACT

This study assessed stepped and overlap wet lay-up composite patch repair methods. The stepped repair design exhibits many desirable features such as high strength recovery and flush installation, however typically results in excessively large repair sizes, making them unsuitable for many repair areas. Furthermore, the stepped repair application requires removal of large areas of pristine composite material and is time and resource intensive. The coupon test and numerical modelling program detailed herein demonstrates that the use of an optimally designed overlap patch repair provides equivalent mechanical performance, but with reduced patch size, repair application time and repair complexity. It also significantly improves future part repairability through preservation of pristine structure. An investigation into the repair application methodology was also conducted and recommendations for improvements made.

1 INTRODUCTION

Wet lay-up material systems utilising two-part epoxy resin and dry reinforcement fabric has the merits of a long shelf life, ease of storage and the ability to be processed using minimal infrastructure and thus has seen wide use throughout aerospace composite structures [1-2]. Despite these merits, quality control associated with this type of repair is more difficult when compared with typical pre-impregnated composite systems due to a variety of factors including variable fibre-to-resin ratio, non-uniform resin distribution and variable fibre distribution uniformity. In addition, the resultant bond lines in wet lay-up repairs are generally much thinner than required for optimal bond line strength. As a result, repairs produced by the wet lay-up methodology generally exhibit lower strengths when compared with repairs fabricated using pre-impregnated composite materials. These characteristics of wet lay-up repairs necessitate the generation of improved, specific repair designs and tailored application methodologies for successful repair implementation.

The Defence Science and Technology Group (DST Group) has conducted experimental and analytical investigations to further develop wet lay-up repair methodologies. These investigations include:

- Exploration of the wet lay-up repair process and controlling variables.
- Assessment of a common stepped patch repair approach.
- A critical comparison between the stepped patch repair and a typical overlap repair design.
- Development of a practical optimal overlap repair design.

These investigations have yielded significant, useful and practical outcomes that can be used to guide design and application of future wet lay-up patch repairs.

2 EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS

The parent material system considered for the investigation was manufactured from autoclave cured carbon fibre reinforced epoxy of approximately 2 mm thickness. The parent epoxy system was M18/1 from Hexcel [3] which was used in combination with two different carbon fabric types, a bi-directional carbon fabric, G939 and a unidirectional carbon fabric, G947. Typically these were used in a ply stacking sequence of [0/90, 0, -45/45, 0/90, -45/45, 0, 0/90] for both parent and repair structures, with the repair resin system being Hysol EA9396 [4].

2.1 Assessment of a Stepped Patch Repair

The stepped patch repair, although requiring a higher level of operator skill and time to implement, has many advantages over the overlap patch repair design. They may transfer significantly higher loads when compared to overlap patch repairs, in the case when the load transferred through a single overlap is insufficient [5-6]. Furthermore, the methodology can achieve a flush surface repair, which is often a critical requirement, particularly for aerodynamic considerations or around actuated control surfaces or doors where protrusions may inhibit movement or door closure. One significant disadvantage of the stepped repair design is the often excessively large repair sizes for comparably small damage sizes, resulting from the many long steps in the repair, thus restricting application to very large planar areas of a platform.

Two repaired panels were considered in the investigation from which specimens were excised in 20 mm wide strips. The first panel (panel X) was a circular repair as would typically be implemented on a platform as shown in Fig. 1 and Fig. 2(d) and the second (panel Y) was formed as a one-dimensional repair laminate as shown in Fig. 2(a)-(c). In both cases the same repair materials were utilised.

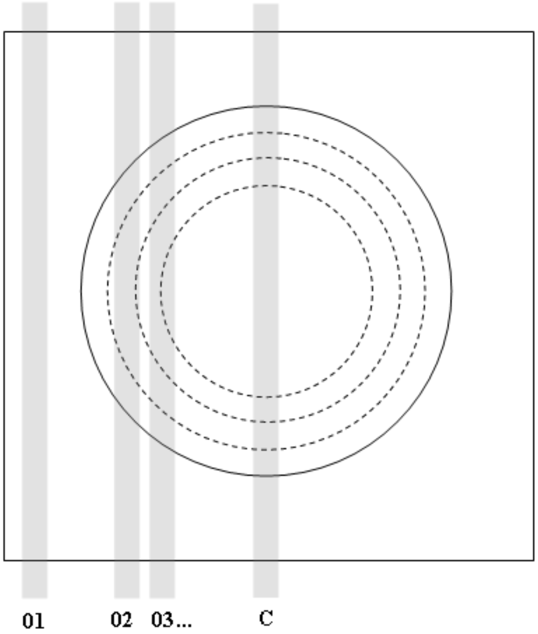


Figure 1: Illustration of large stepped patch repair panel (panel X) with excised strip specimen locations shown in grey.

Tensile mechanical testing was performed on specimens excised from both types of panels per ASTM D3039M-00 [7]. The results of the testing indicated specimen failure in excess of 8,000 $\mu\varepsilon$ remote strain, sufficiently high for typical aerospace composite repairs. Comparing the different specimen results from panel X, the full repair diameter specimen (specimen C of Fig. 1) exhibited a strength reduction of approximately 30% when compared with the pristine structure (specimen 01 of Fig. 1), resulting in a reduction in safety margin in these areas. The tensile testing results also confirmed the consistence between those specimens excised from panel Y (Fig. 2(c)) and those specimens cut from the centre of panel X (specimen C of Fig. 1). Thus the specimen configuration shown in Fig. 2(c) may be used to estimate the patch repair strength conservatively in the two dimensional strip specimens, as used within this test and analysis program.

2.2 Overlap Patch Repair

A conventional overlap repair design, as shown in Fig. 2(a), was considered for the investigation, exhibiting uniform ply-drops of 3 mm and manufactured using the same repair materials as utilised for the stepped repair design. Tensile mechanical testing of specimens excised from repair panels manufactured (Fig. 2(a)) demonstrated specimen failures in excess of 5,000με, lower than those of the stepped repair design however acceptable for typical aerospace composite repairs.

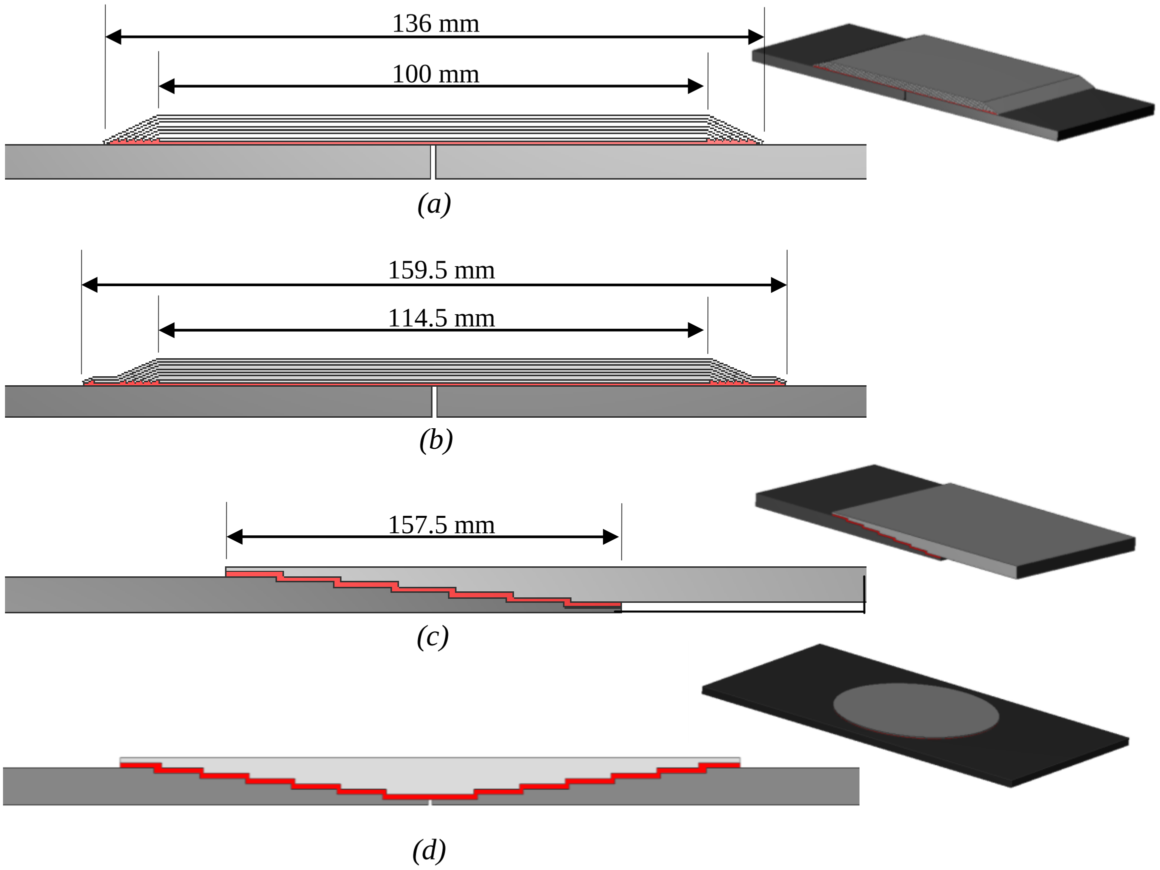


Figure 2: Specimen configurations considered: (a) overlap repair, (b) optimised overlap repair, (c) stepped repair and (d) representative platform repair. Three dimensional representations of the overlap, stepped and representative repair designs are shown to the right, from which specimen strips were cut.

A practical, simplified optimisation design was considered (Fig. 2(b)) in which the overall patch length and first ply drop-off length were adjusted in a two phase optimisation to minimise the maximum bond line shear stress at the patch edges. A comparison of the resulting overlap repair strengths for the standard overlap design and optimised overlap design are shown in Fig. 3, with a comparison made to the stepped repair configuration. These results indicate the failure strength of the optimised overlap design exceeds that of the stepped patch repair design. In this context, utilisation of the overlap patch repair has a number of advantages over the stepped repair design, namely the improved ease by which the repair can be enacted and the smaller repair sizes for equivalent strength (as indicated by the results in Fig. 3). The use of the overlap repair also mitigates the need to remove large amounts of the parent structure, as would be required for the stepped repair (to form the steps), thus enhancing the future repairability of the damaged region. Although overlap repairs present higher repair thicknesses when compared with the stepped repair approach, for thin-skinned structure as considered here, this thickness increase is insignificant.

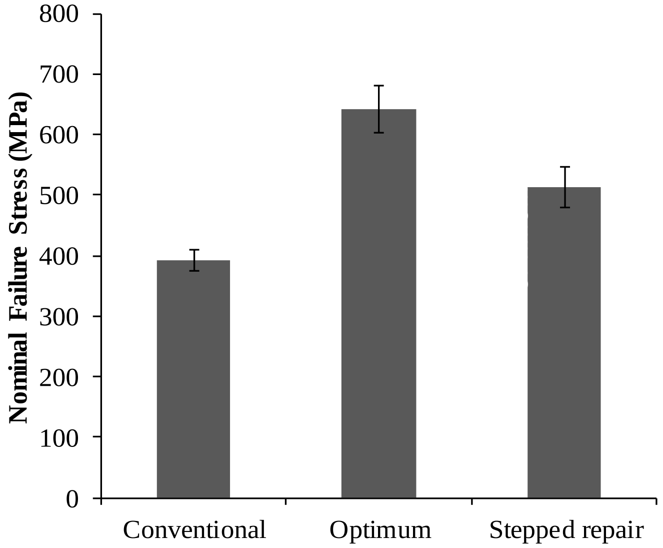


Figure 3: Tensile test results from conventional overlap, optimised overlap and stepped repair designs.

2.3 Computational Modelling

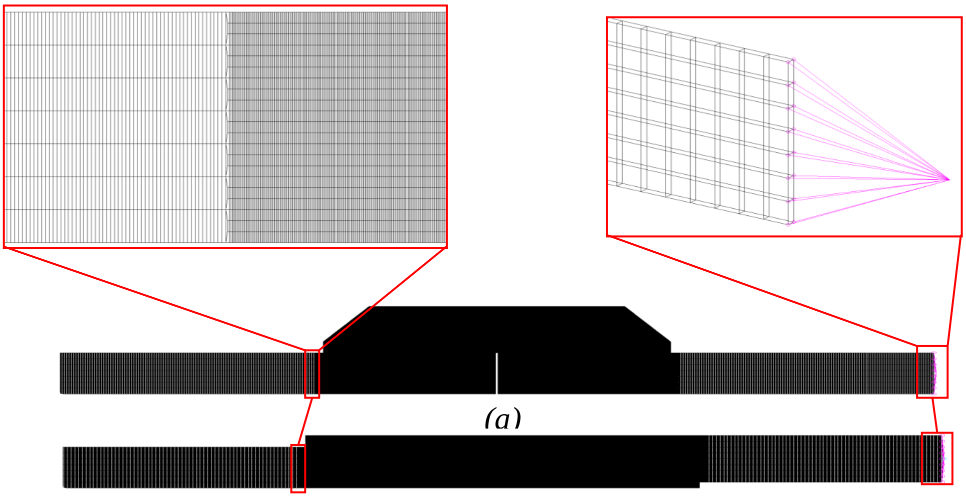
Linear static and non-linear static analyses of the stepped, overlap and optimised overlap repair designs were performed using MSC Patran for geometry, mesh definition and post-processing and MSC Nastran for analysis. For the model meshing, the model width was set to one unit mesh whilst the composite plies and bond line were all represented by 3 elements in height in the critical bond line joint region. Away from the bond line and toward the joint ends, the mesh density was reduced, with each ply represented by a single element in height. The model width was set to 0.076 units with a transverse displacement constraint applied to enforce a plane strain condition on the joint. This model width resulted in an element width : height : depth ratio of 3:3:1 away from the bond line region and 1:1:1 within it. Fig. 4 depicts the mesh considered for both overlap and stepped repair geometries and the transition from the joint region.

The material property data as used in the modelling are available in [3, 4]. For non-linear analysis, the adhesive bond line was modelled as an elastic-perfectly plastic material, with a Von Mises yield criterion. The bond line thickness was taken to be the same as the ply thickness for all configurations, to be practical for the finite element meshing.

For the optimised overlap repair model, a practical, simplified optimisation of patch design was performed. Given that the overall patch length and the first ply drop length have the most significant effect on the adhesive peak stress for this repair under tensile loading, optimization of these two lengths was considered. The optimization was conducted in two steps:

- The first ply (0/90) was adjusted in 6 mm increments and the effect of this on bond line shear stress interrogated to yield the optimum ply overlap length. This first ply adjustment had the effect of adjusting the overall patch length.
- Using the optimum ply overlap length from step 1 and modifying the ply overlap length of the second ply in 6 mm increments, the optimum repair configuration was determined. This has the effect of adjusting the first ply drop-off length.

For this optimisation, a symmetric half model of the joint was considered, with translational constraints placed on the mid-point of the model as shown in Fig. 5.


(a)

(b)

Figure 4: Schematic showing details of the mesh used in the analysis for (a) overlap repair and (b) stepped repair. The insert on the left details the transition region from the region of interest to the parent laminate plies whilst the insert on the right shows the single element width and a multipoint constraint (in pink) used to apply the joint load or displacement.

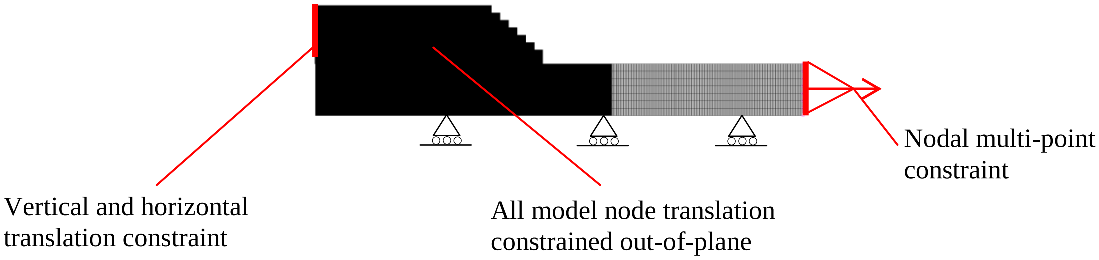


Figure 5: Schematic showing details of the mesh used in the optimization analysis.

The modelling results are plotted in Fig. 6, indicating that at higher loads (and thus parent strains), the conventional overlap repair would exhibit significantly higher maximum bond line shear strains whilst the optimised overlap presents the lowest maximum bond line shear strains of the three joints tested. For the perfect elastic-plastic behaviour considered, the predicted maximum shear strain is a measure of the failure of the joint. Consequently, the results suggest that the stepped joint would have a higher load capacity than that of the conventional overlap joint whilst the optimised overlap would exhibit the highest load capacity of the three joints considered. These results were consistent with the mechanical testing results (Fig. 3).

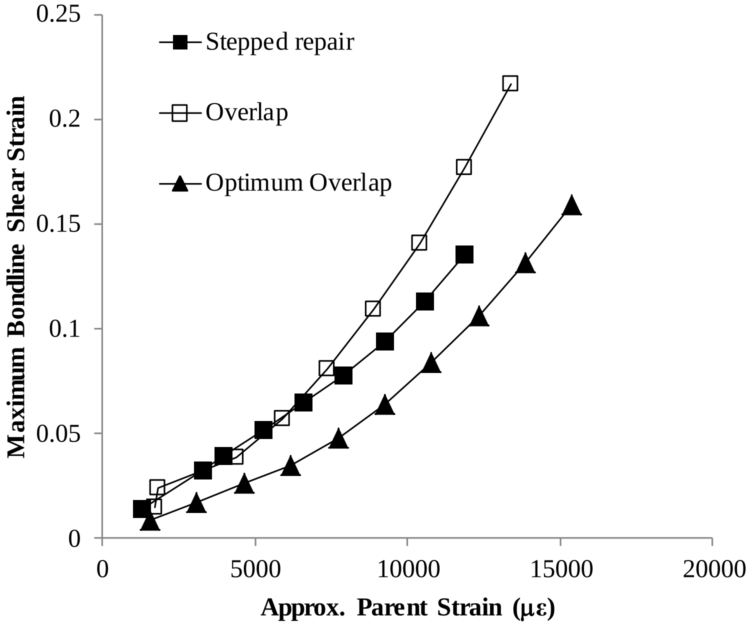


Figure 6: Comparison of maximum bond line shear strain results achieved for the stepped repair, overlap repair and optimised overlap repair configurations.

3 EFFECT OF BAGGING METHOD AND BOND LINE THICKNESS CONTROL

For the repairs manufactured, vacuum bagging was utilised to consolidate the lay-up during cure. The initially used, standard (ST) bagging regime is illustrated in Fig. 7(a), which allowed for resin flow from the repair region during consolidation and cure.

To investigate typical bond line thicknesses achieved with this bagging regime, a small section was excised from the centre of the panel shown in Fig. 1 (location C). The section was removed using a water lubricated pneumatic diamond saw and the region of interest was hand-polished to an angle of 5.74°. This 5.74° angle was chosen so that the polished face features were amplified by 10 times in the polished face long direction, as can be seen in the schematic of Fig. 8. A local enlarged micrograph view of this specimen is given in Fig. 9. As can be seen, the bond line between the parent panel lay-up and the repair lay-up is very thin. For bonded joint using epoxy adhesive, an extremely thin bond line thickness would not be able to yield high bond strengths. In an attempt to address this and explore the effect of bond line thickness on the repair performance, a bond line control tape was incorporated into the bond line. The tape used, Tac-Strip V820 (Airtech), is a 3 mm square mesh fiberglass tape of 25.4 mm width and approximately 0.2 mm thickness.

In the ST bagging regime, resin starvation was observed in the final cured repair specimens. The use of vacuum bagging to consolidate the repair could compound this issue by enlarging any porosity in the wet lay-up. To mitigate this, a double bagging approach could be used in order to reduce vacuum pressure applied to the repair during initial stage of cure and minimise the occurrence and enlargement of porosity. However, in order to keep the repair process as simple as possible, in this study a zero bleeding (ZB) approach was trialled, with the bagging scheme detailed in Fig. 7(b).

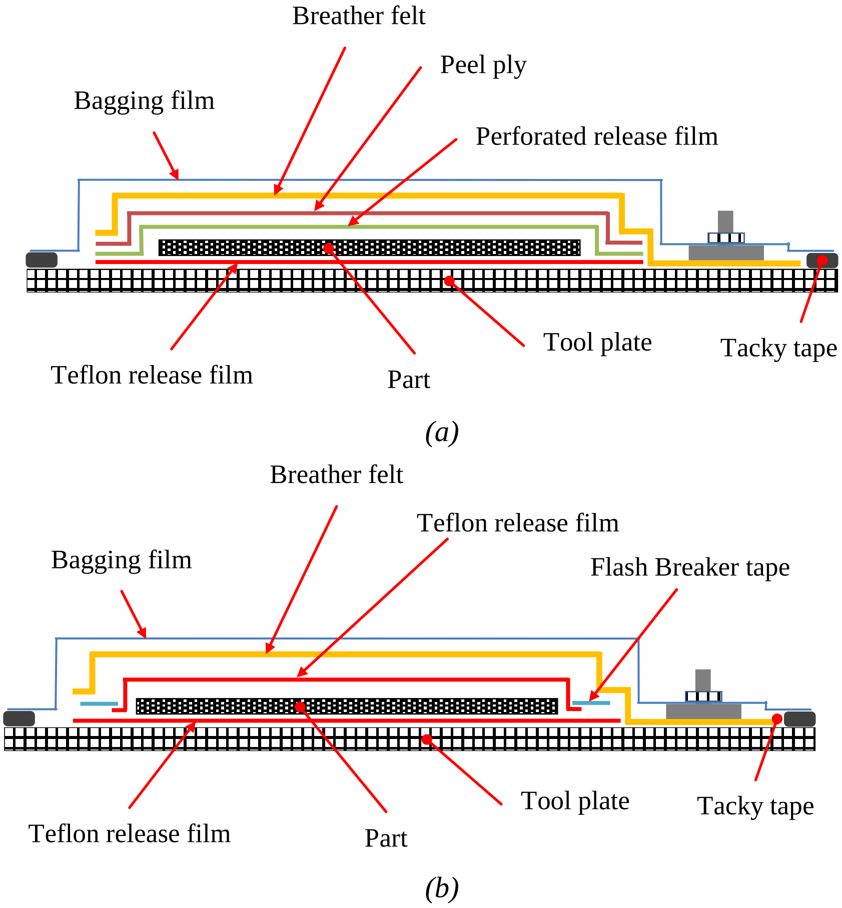


Figure 7: Composite bagging methods considered, (a) standard and (b) zero-bleed.

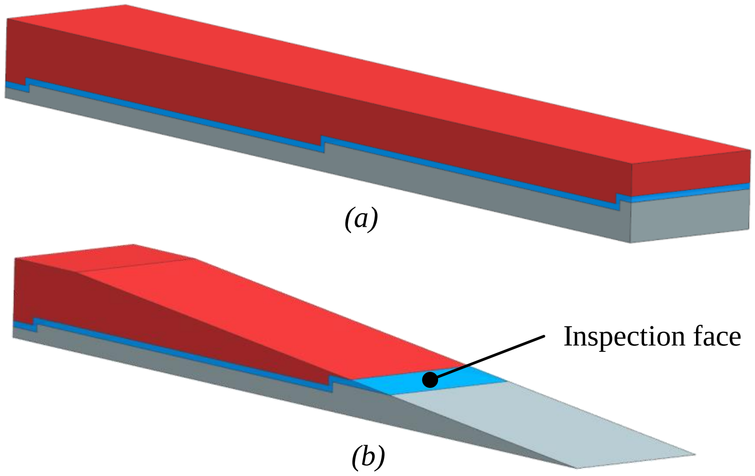


Figure 8: Schematic showing: (a) the extraction of a microscopy specimen from the test coupon, and (b) the angle to which this specimen is polished to achieve an amplified bond line thickness for measurement.

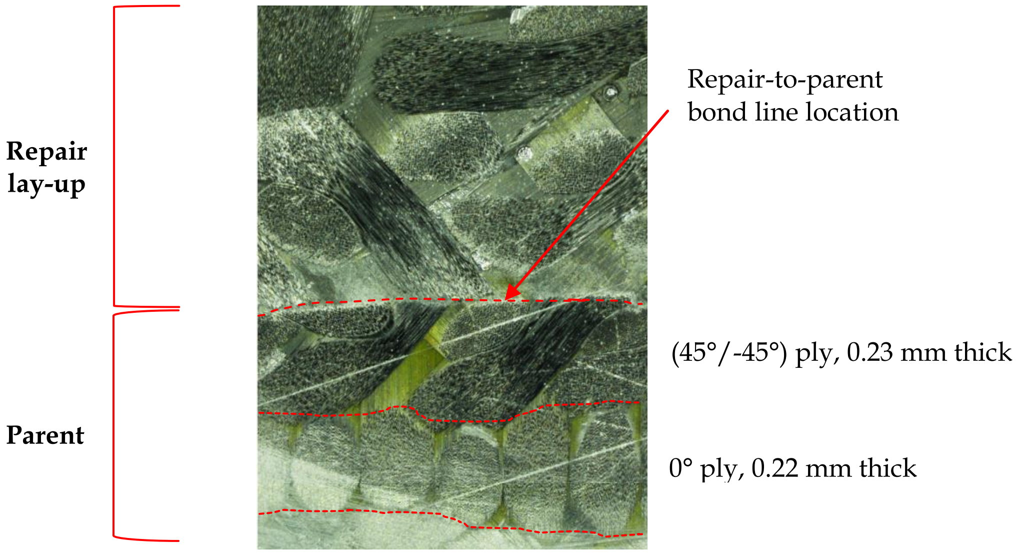


Figure 9: Optical micrograph of local enlarged view of angled specimen section.

The effect of the bagging method on resultant laminate strength was explored through the manufacture of a series of 9-ply unidirectional laminates using either the ST or ZB bagging procedures. These laminates were then machined into 20 mm wide coupons and tensile testing performed with loading applied perpendicular to the fibre toe direction. By loading the coupons in a direction perpendicular to the principal fibre direction, the principal load is experienced by the matrix, allowing any differences in strength as a result of the porosity between the two laminate manufacturing methods to be identified. The results from this testing are shown in Fig. 10, suggesting that the ST bagging technique yields failure strengths approximately 25% lower than that with the ZB bagging technique. However, since the thickness of the specimens with the ZB bagging technique was increased, which may introduce slightly higher peel stress in the bond line, the overall effect on bond joint strength needs further assessment.

The effect of bond line control can be seen in the failure stress results of Fig. 11, suggesting that the use of the bond line control tape decreases the mechanical performance of the repair. From the failure sections of the tested specimens, it was seen that significant air bubbles existed within the mesh regions of the bond line control tape. This air entrapment effectively decreases the bond line adhesion area, and thus the load bearing capacity of the joint. In addition, since the wet-layup laminate was soft prior to cure and would deform under vacuum pressure, the mesh structures of the bond line control tape would likely not be effective in maintaining a uniformly thick bond line. To mitigate this, an alternative bond line thickness control methodology should be considered, such as to apply a layer of higher viscous adhesive to the parent structure surface, which has successfully been used in a similar application [8]. In addition, recent developments in the use of Nano-particulate enhanced resins for improved adhesive bond strength [9] could be used for this application.

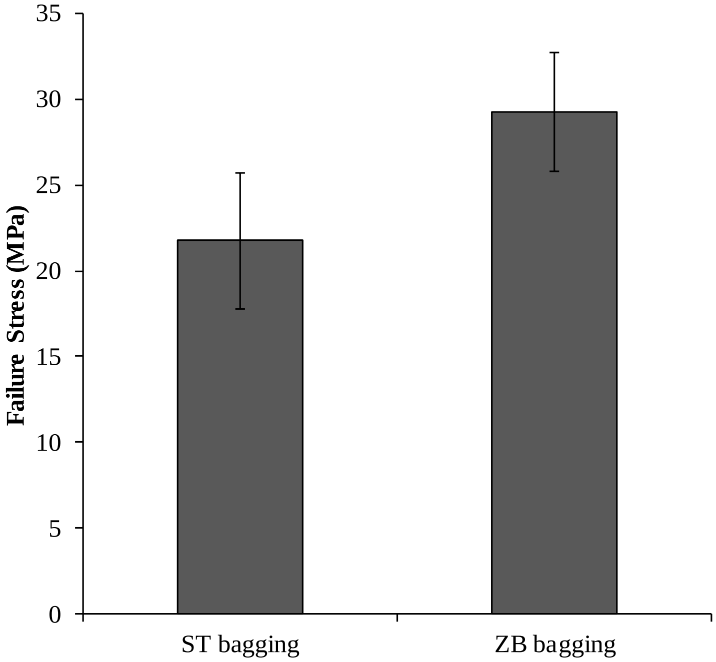


Figure 10: Effect of bagging technique on resultant laminate failure strength (loading perpendicular to fibre direction).

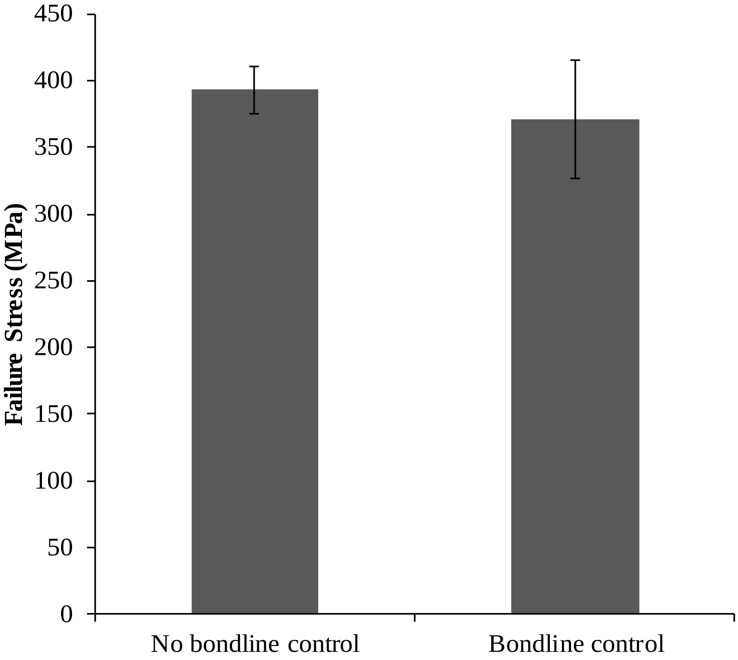


Figure 11: Effect of bond line control on the resultant repair failure stress.

9 CONCLUSIONS

A coupon level mechanical test and modelling program was successfully conducted to explore the suitability of a simplified overlap bond repair concepts in place of a stepped repair method for a wet-layup repair of thin-skinned composite structures. In this study the effect of bagging technique and bond line thickness controls were also explored. Through coupon testing, an optimised overlap repair design demonstrated improved strength when compared with a typical stepped repair design, with analytical modelling conducted aligning with the test results performed. The use of this overlap concept significantly improves repair simplicity, which would lead to reduced repair time and cost. Furthermore, as the repair patch size is significantly reduced, the repairability of the structure is significantly improved when compared with stepped repair designs.

ACKNOWLEDGEMENTS

The authors would like to thank WOFF David Sowden (Royal Australian Air Force), Mr Graeme Smith (Macro Recruitment) and Dr Jinan Cao (Macro Recruitment) for their support in technical advice, specimen manufacture and mechanical testing.

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