Mechanical Analysis of Step-Step Wet Lay-Up Repairs: Experimental Approach

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Abstract: This study investigates the tensile performance of step-step bonded repairs manufactured using a wet lay-up process and applied to monolithic composite laminates. Nine repair configurations were evaluated experimentally to quantify the influence of three key parameters: the resin system, the step length, and the addition of an over-ply. Three epoxy systems were compared, two aerospace-grade wet lay-up resins (Loctite® EA 9390 and EA 9396) and a low-cost marine-grade epoxy (West System 105/206). Tensile tests were performed on repaired and pristine references to determine ultimate strength and repair efficiency. Results show that EA 9390 provides the highest tensile performance across all configurations, achieving up to 85% strength restoration. Increasing the step length improves joint strength, although the trend is not linear, with diminishing gains at larger step lengths. The addition of an over-ply significantly enhances repair efficiency, particularly for EA 9396. Overall, the study provides a systematic experimental assessment of the mechanical behavior of step-step wet lay-up repairs and highlights the parameters that most strongly influence their tensile performance.

1. Introduction

With the growing use of composite materials across many industries, including aerospace, the need for structural repairs has become increasingly important. When components are too complex or costly to replace, repair becomes essential. Bonded repairs are gaining prominence due to several advantages over bolted or riveted repairs. Among these advantages are improved stress distribution in the joint, preservation of aerodynamic surface continuity, and superior corrosion resistance [1-3].

Since the introduction of aerospace-grade prepreg composites, extensive research has been conducted on prepreg-based repairs, most often using adhesive films to bond the patch to the parent structure [4, 5]. This method generally provides excellent performance, with strength-restoration levels ranging from 80% to 100% depending on the configuration [4, 5]. However, prepregs also present several challenges: they require refrigerated storage, have limited shelf life, are sensitive to moisture, need to be purchased in large quantity and often require autoclave curing. These constraints make them less suitable for in service repair scenarios. This study therefore focuses on a more accessible and logistically flexible process: wet lay-up repair.

Several joint geometries are used in structural bonded composite repairs. The two most common are scarf joints and step joints [1], which respectively involve machining a taper or sanding successive plies to create a stepped profile. Both aim to transfer load as evenly as possible from the parent laminate to the patch, thereby minimizing adhesive stress concentrations. Step joints offer better control during surface preparation, as each ply can be removed individually [6]. For these reasons, the present study focuses on step-type repair geometries.

The aim of this study is to experimentally evaluate the tensile performance of step-step wet lay-up repairs and to identify the key parameters that govern their effectiveness. By examining several repair configurations and comparing them with pristine references, the work provides a clearer understanding of the strength restoration of wet lay-up repairs for composite structures.

2. Parametric analysis

2.1 Geometry and configuration

This study focuses on the repair of monolithic laminated plates. The configuration of the selected parent laminate and the manufactured patch is shown in Figure 1. This configuration consists of two distinct laminates. The first is the parent laminate, representing the damaged component to be repaired, whose layup is composed of three woven plies with orientations [(±45)/(0/90)/(±45)]. The second is the patch, applied on top of the parent material to reproduce the orientations of the damaged parent laminate.

It is well established that load is transferred from the parent to the patch along the step region due to the contact surface within the overlap area [7, 8]. Consequently, the ply orientations in the patch must match those of the parent material. A first ±45° lower ply is used in the patch as a filler layer, serving primarily as a support for the subsequent plies ±45°, 0/90° and ±45°.

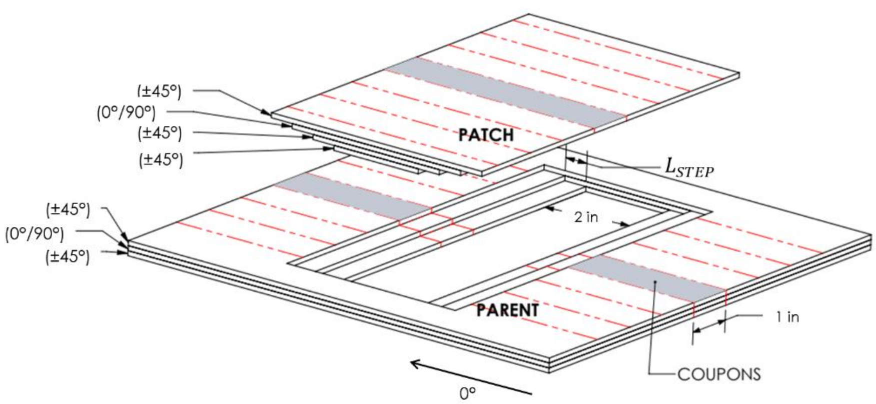

Figure 1. Configuration of the manufactured plates and the cutting of the specimens from the plates.

A rectangular patch was selected for this study. In practice, repairs performed on aeronautical components are typically circular, due to the multidirectional nature of mechanical loading. However, since the specimens in this study are tested solely under tensile loading, the rectangular configuration represents a more severe case, as 100% of the load is transferred through the adhesive joint. This is not the case for circular repairs, where part of the load bypasses the repaired area due to the generally higher stiffness of the parent material [6, 9].

2.2 Materials and manufacturing process

The parent plates were manufactured using the out-of-autoclave prepreg CYCOM® 5320-1 T650-35 3K 8HS, following the bagging arrangement and the cure cycle recommended by the manufacturer [10]. The prepreg plies were cut so that the step was already included in the laminate. This approach provided greater accuracy on the L_{STEP} length compared to producing it afterward by sanding. The step surfaces were then hand-sanded using 180-grit abrasive paper and carefully cleaned with isopropyl alcohol and lint-free wipes.

The patch material was manufactured using a wet lay-up process. The fabric used was a carbon plain-weave PW T650-35-3K. This fabric is approximately twice as thin as the parent-material prepreg which has a nominal thickness of 0.37 mm. Therefore, for each parent-material ply, two plies of the repair fabric were applied. Two Loctite® epoxies were used: EA 9390 (Resin A) and EA 9396 (Resin B). These two resins were specifically developed for wet lay-up repair applications and are commonly used in the limited research available on wet lay-up repairs [11]. In addition, a third resin was evaluated: West System 105 (Resin C) combined with the slow 206 hardener. This resin is significantly less expensive and is primarily used in the marine industry. It is also an epoxy resin that can serve as an adhesive, a matrix reinforcement, or a coating [12].

For the repair process, the parent plate with the sanded and cleaned steps was fixed onto an aluminum base on top of a release film. In parallel, the fiber fabric was placed on a plastic film, then the resin was poured over it, and another plastic film was placed on top. A roller was then used to evenly distribute the resin throughout the fabric, saturating the fibers without excess. The plastic films helped support the fibers to prevent distortion during resin application and allowed for more precise cutting of the impregnated fabric, with careful attention to fiber orientation.

A layer of resin was applied to the step surface, after which the repair plies were stacked onto the plate. A P3 perforated release film with 0.14% nominal open area was placed on top, followed by several layers of breather, and the assembly was then sealed under a vacuum bag. Repairs performed with EA 9390 resin were debulk for 120 minutes and then cured in an oven at 93 °C for 220 minutes with a nominal ramp rate of 2 °C/min, while those using EA 9396 and West System 105 resin were cured at room temperature for 5 days, with the first 24 hours under full vacuum.

2.3 Investigated parameters

Several parameters influence the mechanical strength of step-step bonded joints. The different configurations tested in this study are presented in Table 1. The first parameter evaluated is the resin used for impregnation. The three resins introduced in the previous section are compared here. According to Found et al. [11], EA 9396 performs better than EA 9390 in double-lap shear and picture-frame tests for wet lay-up repairs. West Systems 105&206 is included to assess how much better aerospace-grade resins perform compared to low-cost, standard-grade alternatives.

Table 1 : Sample nomenclature and configuration

Config. No.	Resin System	L_{STEP} [mm]	Over ply
A0.25	EA 9390	6.35	0
A0.50		12.7	0
A0.75		19.05	0
A1.00		25.4	0
A0.50+2OP		12.7	2
B0.50	EA 9396	12.7	0
B0.75		19.05	0
B0.50+2OP		12.7	2
C0.50	West System 105&206	12.7	0

The step length is a second parameter with a significant influence [13]. Some studies have even shown that performance can be optimized by using different step lengths within the same joint, depending on the ply orientations [14]. However, in real applications where components are subjected to multiple and multidirectional loads, using uniform step lengths is more practical. For this reason, identical step lengths are used in the present study.

The last parameter examined is the effect of adding additional plies on top of the patch. Those over-plies extend beyond the patch by a length equal to L_{STEP} on each side to provide a bonded overlap surface, as illustrated in Figure 2. To maintain consistency with the previous stacking approach, two plies of the repair material are added, corresponding to the thickness of one parent-material ply. The added plies are oriented at ±45° relative to the loading direction.

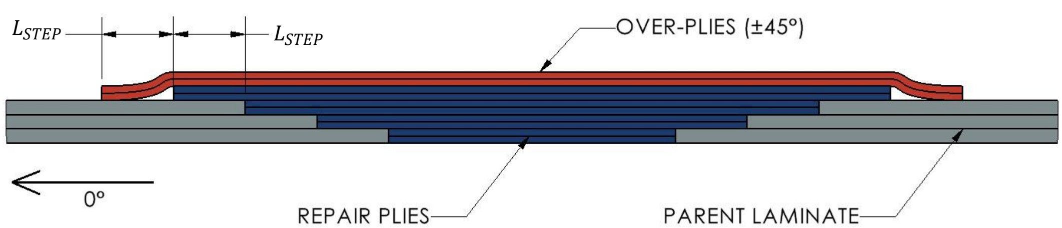

Figure 2. Cross-section of the repaired region illustrating the over-plies.

3. Experimental Work

3.1 Experimental setup

The specimens were cut from the repaired plates (see Figure 1) using a water-cooled diamond circular saw. After cutting, the specimens were carefully blotted and dried. They were then tested in tension at ambient temperature using an MTS Insight electromechanical testing system equipped with a 100 kN load cell. The test setup is shown in Figure 3. Self-tightening grips were used, meaning that the clamping force increased automatically as the applied load increased. A small mechanical stop on each grip ensured that the specimen was positioned centrally and aligned with the loading direction. All tests were performed at a constant crosshead displacement rate of

1 mm/min. No tabs were used, as failure consistently occurred within the gauge section. All remaining procedures followed the ASTM D8131 standard [15].

Figure 3. Photograph of the mechanical testing setup.

3.2 Experimental results

The different configurations were tested, and the ultimate failure load was measured. The ultimate tensile stress can be calculated either using the thickness of the parent laminate or the thickness of the patch. As shown in Figure 2, the thickness varies along the specimen because the filler ply allows the patch plies to match the parent plies and ensures proper load transfer along the step. The stress based on the parent-laminate thickness is therefore calculated using:

$$F_p^{tu} = \frac{P_f}{h_p \times w} \quad (1)$$

where P_f is the maximum force carried by the specimen at failure, h_p the real specimen parent laminate thickness and w the specimen width.

To compare the performance of the repairs, six pristine specimens of the parent laminate were also tested under the same conditions. These specimens were manufactured from the same material batch and under the same processing conditions as the parent panels. Table 2 presents the results obtained for the pristine laminate.

Table 2 . Average tensile tests results for the pristine material.

Average strength ($F^{tu}_{pristine_{avg}}$) [MPa]	Standard deviation [MPa]
463.7	16.6

The performance of the repairs is evaluated by calculating a strength restitution coefficient (COR). This coefficient is obtained by comparing the average ultimate tensile stress of the repaired specimens, calculated using the parent-laminate thickness, to the average value measured on the pristine specimens, as defined in equation (2). The measurement uncertainty is calculated using standard error-propagation rules, as given in equation (3). The average results for the different repair configurations are presented in Figure 4.

$$COR\ [\%] = \frac{F^{tu}_{p\ avg}}{F^{tu}_{pristine_{avg}}} \times 100 \qquad (2)$$

$$\Delta COR = COR \cdot \sqrt{\left(\frac{\Delta F^{tu}_{p\ avg}}{F^{tu}_{p\ avg}}\right)^2 + \left(\frac{\Delta F^{tu}_{pristine_{avg}}}{F^{tu}_{pristine_{avg}}}\right)^2} \qquad (3)$$

In equation (3), $\Delta F^{tu}_{p\ avg}$ and $\Delta F^{tu}_{pristine_{avg}}$ are respectively the standard deviation of the repaired-specimen tests for the given configuration, and the standard deviation of the pristine specimens.

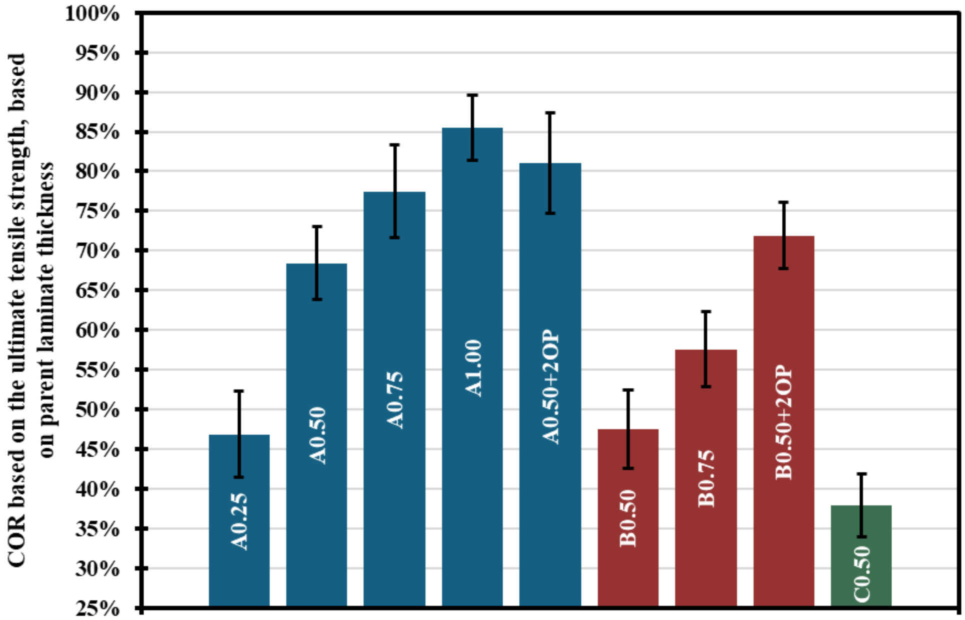

Figure 4. Diagram of the ultimate-strength restitution coefficient in tension, calculated using the parent laminate thickness, for all configurations tested in this study.

For resin A, the ultimate strength results are plotted as a function of the step length in Figure 5. The individual data points correspond to the results of each specimen, in contrast with Figure 4, which presents only the average values.

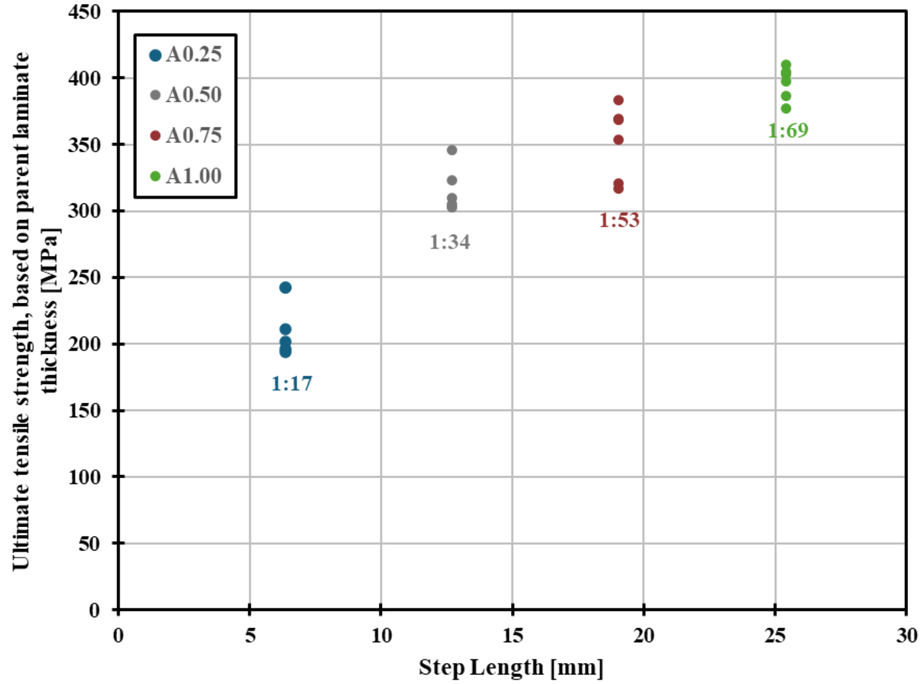

Figure 5. Ultimate strength as a function of the step length, and step height-to-length ratio annotated on the graph.

4. Discussion

None of the tests performed in this study achieve full restoration of the parent-material strength. However, configuration A1.00 reaches a restitution level of 85.5%. It should be noted that the configuration tested here corresponds to a rectangular repair spanning the full width of the specimen. In real applications, part of the load bypasses the repair, which increases the overall strength of the patch [9].

The results in Figure 4 show that repairs made with resin A exhibit higher tensile strength than those made with resin B. Other researchers have reported the opposite trend for double-lap shear tests, where resin EA 9396 (Resin B) performs 20% better at room temperature [11]. Regarding the influence of the resin, the relative strengths obtained with resins A, B and C (using the 0.50 configuration, 12.7mm step length) are 68.4%, 47.6% and 38,0% respectively. Overall, the two repair resins supplied by Loctite® outperform the West System's resin.

The influence of step length on the ultimate strength of the repairs is presented in Figure 5. Increasing the step length from 6.35 mm (A0.25) to 12.7 mm (A0.50) leads to a strength increase of about 100 MPa, corresponding to a 46% improvement of the strength. However, the trend is not linear: doubling the step length again from specimen A0.50 to specimen A1.00 results in a smaller gain of 79 MPa, which represents only a 25% increase of the strength despite the same proportional change in length.

Finally, the addition of two overplies has a significant positive impact on the ultimate strength of the repaired specimens. For configuration A0.50+2OP and B0.50+2OP, adding the overplies increases the strength restitution coefficient by 12.6% and 24.3% respectively compared to the same repairs without additional layers. The effect is therefore more pronounced for resin B. This improvement is attributed to the additional bonded surface to transfer the load and geometrical effect reducing the peel stress in the last step.

5. Conclusion

In this study, the mechanical performance of nine different step-step bonded-joint configurations manufactured using a wet lay-up process and representative of composite repairs was evaluated under tensile loading. Among the three epoxy resins investigated, resin A (EA 9390) consistently provides better performance than resin B (EA 9396) and resin C (West System 105). The different configurations also allowed assessing the effect of step length. Doubling the step length from 6.35 mm to 12.7 mm increases the strength of the joint by 46% for resin A. However, the trend is not linear: as the step becomes longer, the relative benefit of further increasing its length diminishes. Finally, the influence of the overplies was also examined. Overall, the repaired joints achieved strength restitution levels ranging from 38% to 85%, depending on the configuration. This study represents Phase 1 of a larger research project. In the subsequent phases, currently underway, the influence of environmental conditions at the time of repair as well as those encountered during aircraft operation on the repair strength will be evaluated. The ability to numerically simulate the behavior of these repairs will also be investigated.

6. Acknowledgments

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