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INVESTIGATIONS ON THE INFLUENCE OF DESIGN PARAMETERS ON THE STRENGTH OF CFRP REPAIRS

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Abstract

Traditional repair methods involving riveted joints necessitate the creation of numerous holes in still-intact material, thereby compromising the structural integrity of the area. Load transmission between the adherents occurs within this weakened zone. This disadvantage can be avoided through adhesive-based repairs. Presently, aviation authorities only certify the use of bonded repairs for very small areas of damage. For the experimental investigation of bonded repairs, a standardized specimen at the coupon level, the EN6066 specimen, is available. However, this specimen represents a considerable simplification compared to actual repairs. Therefore, effects that have a significant influence may no longer occur, or only to a small extent, when they are analysed on more realistic specimens.

In this study, "Cupped" and "Straight" repair configurations, differing in the arrangement of repair plies, were experimentally tested at both coupon and element levels under quasi-static loading. Significant variations were observed, strength differences between Cupped and Straight at the coupon level vary by about 27%, whereas the configurations exhibited only a 2% strength difference when tested at the element level. These disparities primarily are caused by the distinct detailing of the represented repair geometry, illustrating the challenges associated with designing specimens for investigating repair methods.

1. Introduction

The FightPath2050 objectives set by the European Commission demand a significant reduction in CO₂ and NO_x emissions, as well as improved fuel efficiency, from the commercial aviation sector. Innovations aimed at achieving these goals will inevitably entail an increased utilization of composite materials to reduce aircraft weight. These composites typically exhibit a 20-25% reduction in mass compared to aluminium while serving the same function. Therefore, AIRBUS embarked early on establishing these materials in aviation [1]. As early as 1963, Airbus introduced initial components made of carbon fibre-reinforced plastic (CFRP) on the A310-200. Three years later, the A310-300 saw the first deployment of a CFRP component, within the primary structure of an aircraft. This trend continued

with the Eurofighter, whose external structure consists of 82% Fiber-Reinforced Polymer Composite (FRPC) components [1]. The increasing size of global aircraft fleets, both military and civilian, necessitates reliable repair methods for these materials. The standard aviation method of bolted patching, or "Bolted Patch" is disadvantageous for Carbon Fiber Reinforced Polymer (CFRP) in several respects. Rivets not only add weight but also locally disrupt the fibre structure due to drilling, leading to significant material weakening. Moreover, stresses resulting from the force-transmitting mechanism of rivets are introduced into these weakened zones of CFRP. The localized stress concentration associated with riveted connections results in inadequate fatigue behaviour of such repairs [2]. In contrast, adhesive bonding offers numerous advantages in this context. It allows for better material utilization through uniform stress distribution. While adhesive bonds also exhibit stress concentrations, these are structurally minimized through scarfing, eliminating the need for material doubling. This saves weight, maintains radar signature, and notably reduces fuel consumption in supersonic flight by preserving aerodynamic properties. This is visible in the following Figure 1, showing a sketch of both types of repair, bolted and bonded.

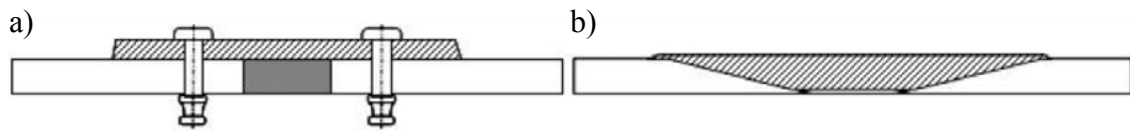


Figure 1: a) Bolted patch repair, b) straight scarf adhesively bonded repair [3]

Consequently, AIRBUS, in collaboration with other aviation stakeholders, is engaged in several projects aimed at certifying bonded repair methods for damages exceeding the current "Bonding Repair Size Limit." For instance, the Rapid Repair project developed suitable methods for removing damaged areas and creating the scarf. Subsequent efforts in the CAIRE project further refined these methods. Concurrently, initial investigations into design parameters and process variables, such as milling parameters, surface pretreatment, and repair layer configurations (layup), were conducted. These investigations are being intensified in the FACTOR project, to obtain certification from both the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) for this repair method, even for damages surpassing the current "Bonding Repair Size Limit" [1, 3 - 6].

2. Materials and methods

A bonded repair that does not require material doubling necessitates scarfing of the repair area. This study exclusively considers straight-scarfed repair areas. Based on this, two basic variants of a repair configuration can be defined. On the one hand, repair plies with decreasing diameters can be sequentially applied to the repair area. This configuration is referred to as "Cupped." On the other hand, repair plies with increasing diameters can be introduced into the repair area. In this configuration, the repair plies remain straight in the lateral cross-section, hence this configuration is termed as "Straight."

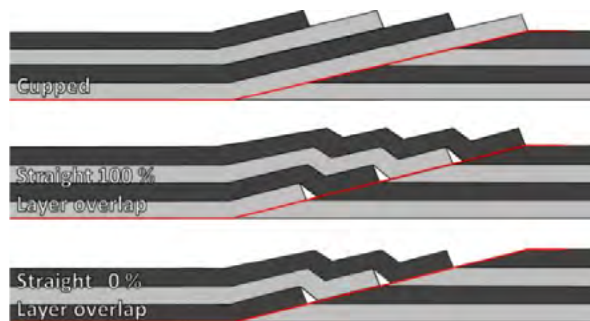


Figure 2: Sketch of repair configurations Cupped, Straight 100% and Straight 0% overlap according to [7]

In the Straight configuration, depending on the accuracy of the ply cutting and the positioning precision, the attachment of a repair ply to the parent material can occur with a ply of the same fibre orientation or one with a different fibre orientation. Depending on this, the Straight repair configuration is additionally defined with a percentage indicating the degree of overlap.

These repair configurations were examined at the coupon level using the EN6066 test specimen. This specimen represents a simplified geometry of a real repair, where the repair area is simplified to a straight scarfing over the width of the specimen, resulting in a skewed 2-dimensional surface for the adhesive area. Additionally, this specimen does not include the use of so-called "cover plies," which are required for repairs according to the Structural Repair Manual (SRM) [8]. At the next level of the testing pyramid, the repair configurations were examined using Airbus's own 2,5D specimen geometry. This specimen features a circular straight scarf of the repair area, resulting in a 3-dimensional curved surface for the adhesive area. However, the parent laminate remains a flat plate, thus not accounting for the typically curved shape of an aircraft's outer skin structure. Nevertheless, this specimen includes the cover plies required by the SRM, making it a significantly more realistic representation of a real repair. The following figure depicts the EN6066 specimens in the top view and a side view on the left side, while the 2,5D specimen is shown in the top view on the right side.

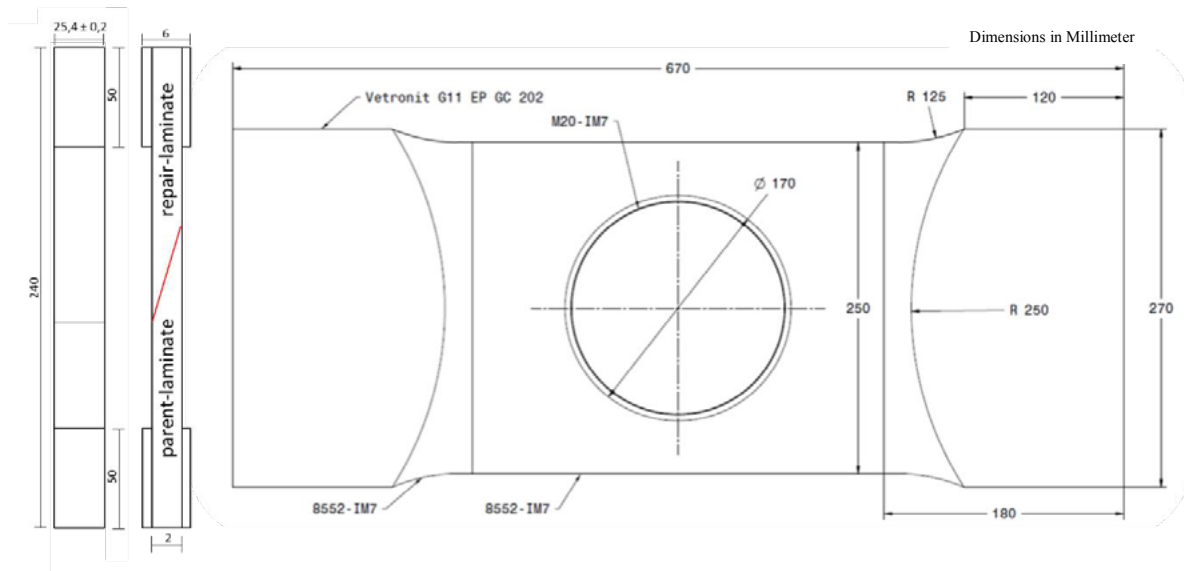


Figure 3: l. to r. sketch of specimen EN6066 top view, EN6066 side view and 2,5D top view

Both types of specimens feature fibreglass-reinforced plastic (GFRP) tabs in the clamping area. The parent laminate consists of unidirectional (UD) prepreg Hexply 8552-IM7 from Hexcel (Hexcel Corporation, Stamford, Connecticut, United States). The repair laminate utilizes UD prepreg Hexcel M20-IM7 from Hexcel (Hexcel Corporation, Stamford, Connecticut, United States). The adhesive used is Hysol® EA 9695™ 050K AERO with a 240 g/m² area weight, including a knit supporting carrier (Henkel AG & Co. KGaA in Duesseldorf, Germany).

In the context of this study, EN6066 specimens are tested under quasi-static tensile loading in the configurations of Cupped, Straight 0%, Straight 100%, and a Straight configuration where the repair plies are applied in the geometrically nominal position (S-Nom). The 2,5D specimen is examined in the configurations of Cupped, Straight 0%, Straight 100% with circular scarfing, and Straight 100% with oval scarfing. Both types of specimens are tested quasi-statically and 2,5D is also subjected to quasi-static loading until failure under tension after prior fatigue loading.

2.1. Manufacturing

Since the manufacturing process of the different specimen types largely follows the same steps, the fabrication process of the 2,5D specimens is described below. Firstly, the CFK plates of the parent laminate are produced using hand lay-up techniques. Curing takes place in an autoclave according to the manufacturer's specifications [9]. Subsequently, a GFRP reinforcement plate is applied to the backside of the repair area. This serves to support the fibres during the milling process, reducing fraying of the bottom fibre layers. Next, the scarf is milled. The surface is initially measured using a distance laser and then milled using a 6-arm articulated robot. Following this, an analysis of the scarf pattern is conducted (see Chapter 2.2 Specimen analysis: Overlap), based on which the repair ply cutouts are generated. Before the actual repair begins, the parent laminate is dried to ensure a comparable initial state of the parent laminates. After drying, the repair area is cleaned with isopropanol and then pretreated with a 3M Scotch-Brite +7447 abrasive pad. Subsequently, the repair area is cleaned again with isopropanol and allowed to air-dry for at least 30 minutes. This is followed by the application of the film adhesive and repair plies, with a "debuckling process" occurring for 5 minutes after every 4 plies. After the application of all repair plies and cover plies, the repair is cured in an autoclave process. To assess the repair quality and ensure that the bonding is not affected by pores or other defects, an ultrasound scan is performed. If the repair quality is sufficient, the tabs are attached, and the specimen is trimmed to have a narrower width in the test area to ensure targeted fracture in the repair area. Shortly before testing the specimen in the testing machine, a black and white speckle pattern is painted on the specimen, which is required for the generation of digital image correlation (DIC) data. Lastly, strain gauges are applied to the backside of the specimen, and an alignment tool is attached by screws. The described manufacturing process and the test-ready specimen are shown in the following figure 4.

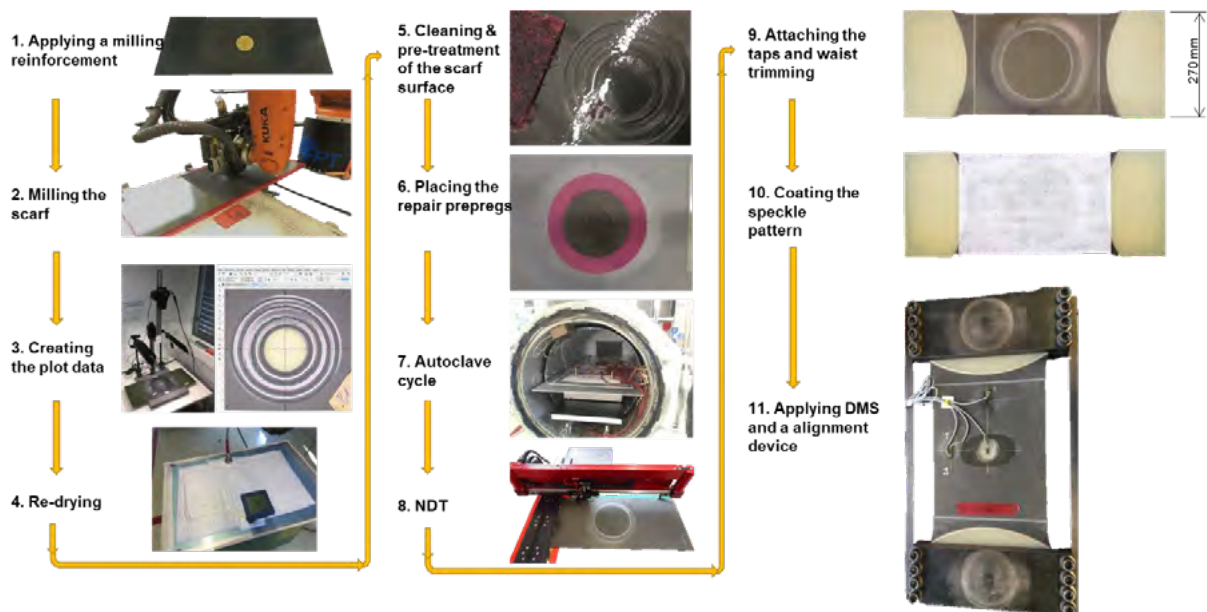


Figure 4: Manufacturing process of a 2,5D specimen

2.2. Specimen analysis

As described in Chapter 2.1, the specimen is analyzed for the first time after milling the scarf geometry. Additionally, an analysis of the specimen is conducted after the completion of manufacturing. The following presents the results of the analysis regarding the overlap degree of the Straight configurations.

Overlap

The degree of overlap depends not only on the accuracy of the repair ply cutouts and their positioning precision but also on the conditions in the repair area, known as the "scarfing pattern." Figure 5 depicts, on the left side, a schematic representation of the nominal positions of individual plies in the scarfing

pattern for an EN6066 specimen. The white lines represent the nominal positions extending into a photo of an EN6066 scarfing pattern, indicating significant deviations from the theoretically expected straight lines. This is magnified for an extreme range (green border). Similarly, in the analysis of the circular scarfing of a 2,5D specimen, as shown on the right side of Figure 5, the nominal positions of the ply rings are indicated by red lines, illustrating significant discrepancies between the theoretical scarfing pattern and the actual one. This necessitates an adjustment of the ply cutouts and layup positions of individual repair plies to achieve the desired overlap degrees of 0% and 100%. This adjustment constitutes step 3 in Figure 4. For the EN6066 specimens, an additional configuration was fabricated where no ply adjustment were made, and instead, the repair plies were applied according to the theoretical nominal positions.

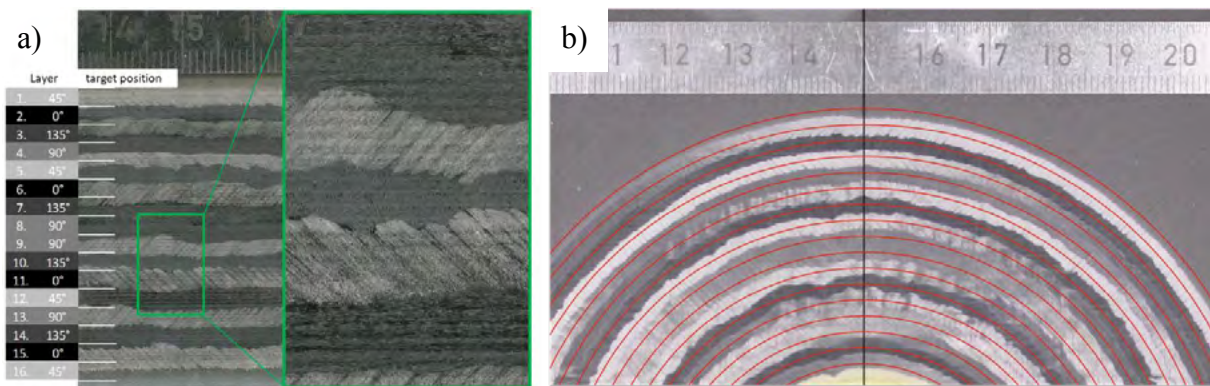


Figure 5: Deviations in scarfing pattern, a) EN6066, b) 2,5D specimen

The deviations in the scarfing pattern of the parent laminate can stem from various sources. Beginning with the possible waviness of the prepreg plies in the parent laminate. Additionally, gaps between two prepreg plies within a layer can exert influence. The relative height position of a ply within the laminate as well as variations in ply thickness itself are potential causes associated with the parent laminate. Furthermore, deviations in the milling process may result from elastic deflection of the mill or the laminate. Moreover, it cannot be ruled out that the robot may approach certain positions with higher repeatability than others.

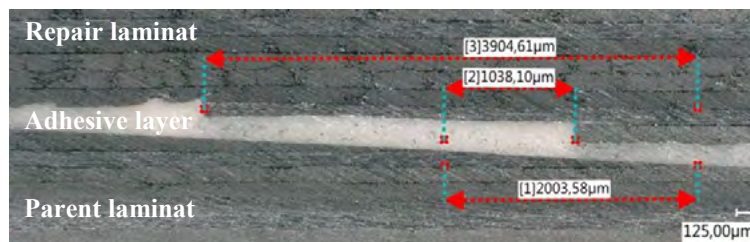


Figure 6: Method to determine the degree of overlap

Figure 6 illustrates the method used to determine the degree of overlap for the Straight configurations. Firstly, the projected length of the ply within the scarfing is measured (2003.58 μm). Subsequently, the length of the repair ply with the same fibre orientation is measured, specifically the portion that is in direct contact with the corresponding ply in the parent laminate and not influenced by another ply (1038.10 μm). The quotient yields the percentage overlap for this particular repair ply. Following this methodology, the following measurement results are obtained for the degree of ply overlap of the Straight configurations for the EN6066 specimens.

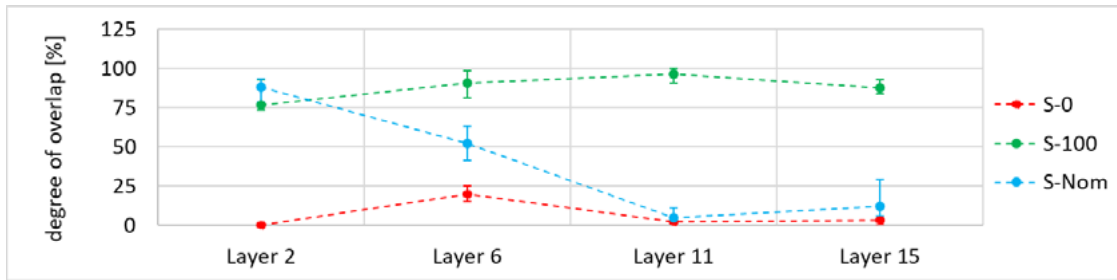


Figure 7: Result of analyzing the degree of overlap of the 0° Layers from EN6066 specimen

3. Experimental results EN6066

The results of the quasi-static tensile tests are presented below regarding the fracture strength. The measured maximum force is divided by the nominal cross-sectional area of the parent laminate, as prescribed by the standard [10]. The diagram in Figure 8 illustrates the fracture strength of the EN6066 specimens. The results of this study on 2mm laminates are shown. Additionally, the required strength is denoted as σ_{req} , is indicated. This required strength is achieved by all configurations. As expected, the highest strength is exhibited by the reference specimen, which consists only of parent laminate and does not involve bonding or repair. The Straight 0% and Cupped configurations barely achieve the required strength. The Straight 100% configuration averages 525 MPa, while the Straight variant with nominal dimensions (S-Nom) averages 565 MPa.

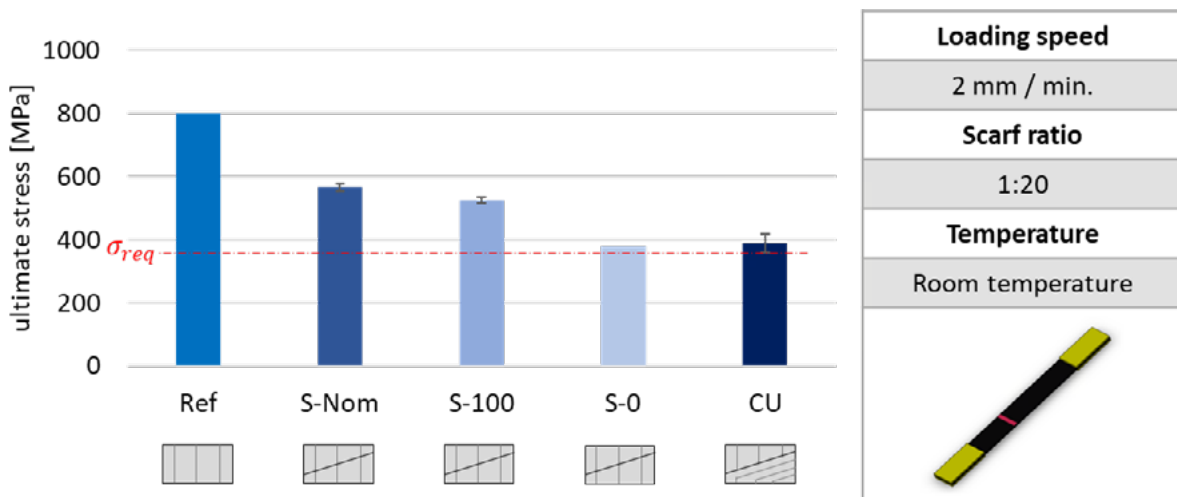


Figure 8: Ultimate stress of EN6066 specimen

It should be noted that the effective adhesive area also varies due to the different degrees of overlap and therefore the utilisation of the theoretical adhesive strength is not considered. If this is done, the configuration Straight 100% achieves the highest utilisation of the theoretical adhesive strength.

2,5D

The 2,5D specimens show a completely different result about the influence of the repair configurations. For example, the fracture strength for Straight 0% and 100% is the same, regardless of whether the

specimen was directly subjected to a quasi-static test or was subjected to a fatigue test with parent laminate strain of $4000\mu\text{m}/\text{m}$ for 54000 cycles prior to the quasi-static test. In addition, the cupped configuration exhibits only slightly lower fracture strengths. In addition, it is found that oval scarfing, where a higher scarf-ratio is used in the loading direction, leads to an increase in fracture strength. In the case of Straight 100%, the specimen labelled S-100-LAM2 also shows a higher fracture strength compared to S-100-LAM1b, indicating that the layout of the parent laminate is also a relevant parameter for the strength of a CFRP repair.

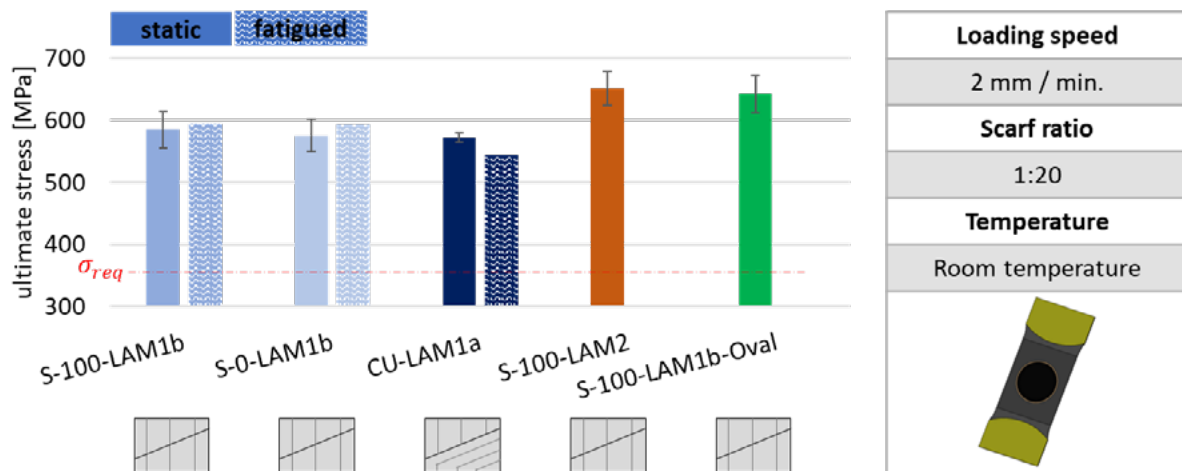


Figure 9: Ultimate stress of 2,5D specimen

A clear distinction in the influence of repair configurations between EN6066 and 2,5D specimens can be identified through DIC data. This data reveals that the 2,5D specimen bends in the laminate thickness direction under tensile loading. This bending leads to superimpose of tensile strain and bending-induced compression, creating a region within the repair area experiencing reduced tensile strain. Simultaneously, this bending generates a bending moment that increases towards the clamping region, subjecting the specimen to higher stress immediately before the grips than in the test region. As a result, some of the 2,5D specimens did not fracture in the repair area but rather near the clamping region. The cause of this phenomenon can be attributed to the presence of the cover plies, which create an asymmetric cross-section of the specimen along its longitudinal axis. Under tensile loading, the specimen attempts to align its centre of mass with the line of force flow, inducing bending in the thickness direction.

4. Interpretation

Manufacturing exact overlap is very challenging due to the numerous influencing factors that deviate the scarfing pattern from the theoretical one, coupled with the requirement for positioning accuracy to approach practically zero tolerance. Nevertheless, good accuracy for the overlap grades of the EN6066 specimens could be achieved. The results of the tensile tests demonstrate a significant influence of the repair configurations on the fracture strength. However, it is important to note that the overlap grade directly affects the size of the bonding area, and therefore, the influence of the varying bonding area must be considered alongside the overlap grade.

The 2,5D specimens show no significant influence of the repair configurations on the fracture strength. One explanation for this may be the parent laminate surrounding the repair, as this is so strong that the influence of the different repair configurations is not reflected in the ultimate stress. Additionally, it is likely due to the influence of the cover plies and the associated asymmetrical cross-section of the 2,5D specimen. As a result of this, the specimen bends in the thickness direction, causing unilateral compression of the specimen. This leads to a region of reduced tensile strain in the repair area due to the superposition of tensile strain and bending-induced compression. Furthermore, the bending of the

specimen generates a bending moment that peaks at the clamping region, resulting in some specimens fracturing outside the repair area. Thus, it can be concluded that an investigation into the influence of varying repair methods using 2,5D specimens without cover plies should be conducted. If the investigation aims to provide evidence that the repair is not a weak point in the laminate, the use of cover plies is advisable as it allows for a more realistic examination of the repair.

5. Conclusion

At Coupon level, the test result of the EN6066 specimen shows a significant influence of the repair configuration. Cupped and Straight 0% configuration just achieve the required strength. Straight with $\geq 100\%$ overlap degree reach a strength minimum 45% higher than required. If the variation of the adhesive area, due to varying repair configurations is considered, the configuration Straight 100% is the best one tested.

The 2,5D specimen, which is a more realistic representation of a real repair, shows no significant influence depending on the repair configuration. Here, the influence of the parent laminate surrounding the repair is probably so strong that the differences in the repair configuration are not significantly reflected in the ultimate stress. Additionally, this can be caused by the use of cover plies, which are required from SRM [10] for a convincing repair but influences the cross-section of the specimen in a manner, that an undesired bending of the specimen occurs. This results in a less high-stress level in the repair area of the specimen and caused some of the tested 2,5D specimens to fail near the clamping of the specimen rather than the desired fracture in the repair area. Future use of this specimen should rethink the shape of the taps (see Figure 3) since, the rounded shape led to partial failure of the bonding of the taps itself. The use of cover plies should only be considered if the behaviour of a real repair is wanted. If the influence of different repair configurations is to be analysed, no cover plies should be used since the resulting asymmetric cross-section of the specimen generates a disturbing bending of the specimen. Alternatively, the waist trimming could be done more strongly to ensure the breaking of the specimen in the desired area.

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