REWORK SIGNATURE: ASSESSING QUALITY OF REWORKED DEFECTS IN AUTOMATED FIBRE PLACEMENT COMPOSITES

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Abstract

This paper examines the assessment of reworking techniques in the realm of composite materials, going beyond conventional cosmetic pass-fail criteria commonly employed by practitioners. The findings of this study indicate that these criteria are not sufficient in ensuring the quality of reworked laminates. An ultrasonic Non-Destructive Testing (NDT) method was employed to investigate the laminates after curing. Our study utilised a linear ultrasonic phased array roller probe to capture through-thickness, depth-wise images (known as B-scans) perpendicular to the orientation of the top ply surface. This provided insights into the volumetric structure of the samples. Comparisons were drawn between pristine samples, samples with embedded defects, and those subjected to the reworking process in terms of their out-of-plane ply waviness on the internal plies. Despite the successful completion of the rework process, a discernible difference between pristine and reworked samples, termed the "novel rework signature" was identified in some samples. This observation underscores the critical need for optimising reworking activities from a quality perspective. Our experimental approach utilises a novel Benchtop-Automated Fibre Placement (AFP) setup which establishes a robust research environment for simulating real-world conditions. The successful generation of laminates using this method demonstrates its potential as a democratised research environment free of the high capital costs traditionally associated with AFP research and development. This research contributes not only to the understanding of rework effectiveness but also emphasises the importance of a comprehensive approach to quality assessment in composite material manufacturing. Additionally, the quantitative method demonstrates an effective acceptance measure for rework analysis. The findings pave the way for future optimisation strategies, emphasising the necessity of considering both internal and surface characteristics in evaluating the integrity of composite materials.

1. Introduction

Automated Fibre Placement (AFP) is an additive method of manufacturing large composite structures which combines the techniques of Automated Tape Laying (ATL) and Fibre Winding (FW)[1]. In AFP, long thin strips of composite material, called tows, are laid up sequentially on a mould at pre-determined fibre angles [2]. AFP manufacturing is especially suited to the manufacture of very large parts with low geometrical complexity such as wind turbine blades, composite pressure vessels, and aircraft wing components [3], [4].

A predominant area of research in the AFP field is defect studies, focused on ensuring the quality of structures produced through AFP [5]. Defects refer to irregularities or imperfections in the layup of composite materials. Defects range in their classification, however, a common type, and one which has received a large amount of attention in the literature, is gap/overlap defects [5]. Gap defects refer to spaces between tows within a ply where no material is present. Conversely, overlap defect refer to where tows overlap within a ply and additional material is present. Gap/Overlap defects typically occur in triangular geometry at tow boundaries, or with rectangular geometry when occurring in a sequence of tows with the same fibre direction [6].

Gaps have been found to cause a significant knockdown in mechanical strength, whereas overlaps conversely have been found to increase the strength of laminates at these points [7]. The effect of gap/overlap defects is increased over multiple layers where these defects are seen to “stack” i.e., defects align in the x and y direction through the z direction of the laminate [7]. Defect stacking over multiple layers induces increased out-of-plane ply waviness. This ply waviness is induced primarily through undulations at the ply level. Potter, et al. [8] found out-of-plane waviness accounted for a reduction in strength of 50% in compression, and 70% in tension. Woigk et al. [9] note that the severity of knockdown effect of a defect correlate to the degree of ply waviness induced by the defect.

Where these defects occur, it is necessary to rework them, to mitigate the effect they will have on the mechanical performance of the laminate and reduce the scrap waste generated [10]. Currently, the state-of-the-art practice is manual rework, performed by skilled practitioners [11], [12]. This is not widely reported in the literature, and hence remains as a craft known within industry but lacking any scientific study, or standardisation across industry. In the case of gap/overlap defects, the accepted method of the reworking of the defect is first to remove the defective tows, for example the misaligned tow and the overlapping subsequent tow; following this, new tows are placed in a corrected position. This practice has been examined to some extent in existing works and attempts at describing a best practice have been made [12].

While a best practice can be determined based on a cosmetic approval/disapproval basis, the implications of rework on the quality of a part has not been studied yet. In this work, we investigate this aspect of defect rework in more detail. The study determined whether there is a discernible difference between pristine parts with zero placement induced defects, and those which had defects but were subsequently reworked to as-close-as pristine condition as possible. A discernible difference in quality indicates, firstly, that the current state-of-the-art processes of manually reworking defects cannot be a fully effective guarantee of part quality, and hence that these processes remain poorly optimised for the application.

2. Experimental setup

This study showcases a “Benchtop-AFP” experimental setup, as described in [13]. This low-cost, low-tech setup was used to create parts with characteristics similar to those produced through traditional AFP. We present this setup as a viable experimental test bed for AFP research. Hexcel M91/34%/UD194/T700GC ¼ inch prepreg tows were used to layup 120x120mm laminates with a [90, 0, 0, 0, 90] structure. Artificial 2.5mm gap/overlap defect were inserted at 3 places within the defective laminates to allow for three different data sources per laminate. Figure 1. shows the laminate structure and defect configuration.

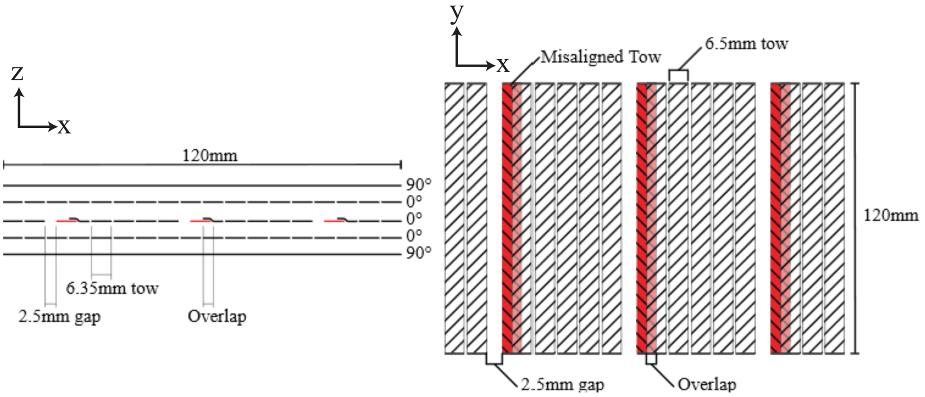

Figure 1. Laminate structure (left); and defect configuration in ply 3 (0°), Defective and Reworked samples only (right)

The samples were manufactured as above with a tooling temperature of 60°C and using a consolidation force of 100N using a hard silicon roller. Following the completion of layup these were cured as per manufacturers instructions.

Three classes of samples were manufactured. These were: **(P)** Pristine, where all tows were placed in alignment and the resulting laminate was therefore free of defects; **(D)** Defective, where on the innermost 0° ply (ply 3) a 2.5mm misalignment was artificially induced in specific tows, as described in Figure 1. The subsequent tow was placed in the original alignment, such that a dual Gap/Overlap defect was created. Finally, **(R)** Reworked samples, where the same process was followed as for **(D)** samples however these defects were manually reworked following the existing best practices as described in more detail in [11] [12], following which the following plies were laid up in the correct alignment. The reworking technique involved the removal of the misaligned tow and the subsequent overlapping tow using hand tools, taking care to not damage the surrounding and underlying tows in the process. Thus **(R)** laminates should cosmetically appear similarly to the **(P)** samples.

Two samples were generated for each of the sample classes, each containing three distinct defect instances in classes **(D)** and **(R)**. In the subsequent NDT scans, each of these defects were scanned individually, or in the case of **(P)** three different regions were scanned corresponding to the locations of the defects in the other defect classes. We henceforth use the following nomenclature to discuss the scans. Xn_N, where X refers to the class, n refers to the class number (1 or 2) and N refers to the defect where each defect in a given sample is numbered from left to right 1-3. For example, P2_2 is the scan of region 2 of pristine sample number 2.

An ultrasonic Non-Destructive Testing (NDT) method was employed to investigate the laminates post-cure. Ultrasonic Testing (UT) is widely adopted for volumetric inspections of composite components. Unfocused, bulk wave inspection was chosen to inspect the samples. In this inspection method, sound waves are excited on the surface of a component, and the reflected/scattered wave from internal scatterers provides valuable information about the volumetric discontinuities of the component. UT allows for the detection of a diverse range of defects or discontinuities. A manually deployed 64-element, 5 MHz Olympus RollerFORM [14] was used to collect the ultrasonic data. The use of a linear phased array probe, allowed for the capture of through-thickness, depth-wise images (known as B-scans). The component was scanned parallel to the orientation of the top ply surface. Water was used as an acoustic couplant to ensure effective acoustic transmission between the roller probe and the sample. For more in depth discussion on the method, readers are directed to [15]. Within each of these B-scans the internal 0-degree layers could be seen running horizontally through the scan, at a specific step (henceforth referred to as 'Slice') along the y-axis (Figure 1.). From this perspective, undulations in the plies can be seen. Undulations in the plies are indicative of the magnitude of the defect within the laminate and have been linked to knockdowns in mechanical performance in composite laminates. Internal ply undulations propagate through the layers of the laminate, due to the sequential, additive nature of AFP, new plies are lied directly on top of existing plies. In the case where there are undulations in the underlying ply, the surface of the subsequent ply will follow the contours of the underlying ply during compaction. Further, during curing, resin flow will occur and fill internal pockets between ply surfaces and tow edges in a gap. In a perfectly pristine sample, we would expect minimal internal ply undulations, as there is no negative space for the plies to fall into when compacted and then subsequently during curing. Conversely, in a defective sample, maximum ply undulations are expected. The outcomes of this study are on the level of undulations seen in reworked samples.

3. Results

The voltage response at each pixel was recorded as three-dimensional NumPy arrays. This data underwent processing to extract the internal ply topography using the following method:

Firstly, a two-dimensional data slice was obtained from the three-dimensional array where the signal was most pronounced, facilitating data processing and minimising the impact of noise on the signal. Next, to enhance the signal-to-noise ratio, a thresholding approach was employed. The mean and standard deviation of the data slice was calculated, excluding values below a predefined static threshold. A thresholding operation was then applied, setting values below (mean - standard deviation) to zero, thereby reducing noise. The noise-reduced data slice was then smoothed using a Gaussian filter. Subsequently, a local adaptive thresholding technique (Sauvola's method) was applied to binarise the smoothed data, creating a binary image representation. The binary image underwent further processing using morphological operations, such as closing and opening, to remove small holes and smooth the boundaries of the detected regions. Connected regions in the binary image were labelled using a labelling algorithm. The labelled regions were then assigned to a ply number based on their position in the sample. Unconnected regions within the same ply super-region could then be processed together to extract the topography of the entire ply rather than in sections. For each ply super-region, the middle line was extracted by finding the mean y-coordinate for each x-coordinate within the super-region. Linear interpolation was applied to fill any gaps in the middle line resulting from discontinuities in the ply super-region. A quadratic polynomial curve was then fitted to the middle line using a non-linear least-squares optimisation method. The waviness coefficient was calculated as the root mean square of the residuals between the middle line and the fitted polynomial curve. This coefficient served as a quantitative measure of waviness for each ply super-region, and thus as a quantitative measure of the out-of-plane waviness level of each ply in each sample.

The section below displays and discusses the data recorded through the ultrasonic scanning method detailed above. Indicative example scans for the **(P)** and **(D)** samples are shown in Figure 2. Since **(R)** scans are of more interest to the outcome of this study, these are show in full in Figure 3. ‘Slice’ in the figure title refers to the y-position of the cross-section where slice 0 is the top of the sample with reference to Figure 1. For the full data set, readers are directed to Pure portal [16]. It should be noted that, due to the warping of the samples during curing, all sample scans show a curvature. The waviness coefficient calculations are normalised to the shape of the plies, thus negating this curvature. Additionally, for the edge samples i.e., Xn_1 and Xn_3, the probe runs over the edge of the sample, hence the signal includes data from beyond the laminate, in the relevant cases, the data slice size in the x-dimension was adjusted to exclude this outside data. This is indicated in the figures by the reduced x-axis scale.

Figures 2 and 3 show the binary colour map of the data slice before processing, overlaid with the middle lines of each of the ply super-regions (blue-solid) and the best fit polynomial (yellow-dashed).

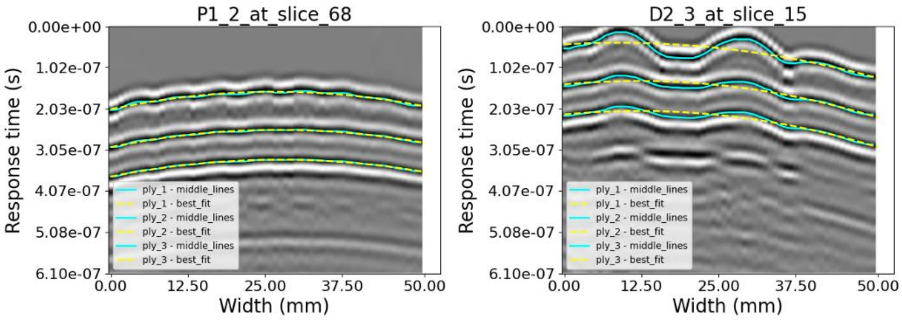

Figure 2. Pristine sample example scans

3.1 Pristine and Defective

Figure 2. shows indicative examples of the recorded B-scans for the Pristine **(P)** and Defective **(D)** samples. For the **(P)** samples, clear and distinct signal responses are seen for each of the three internal 0° plies. These plies have little to no undulations, and as such the middle lines and the polynomial best fit lines are in close agreement. In Table 1 the waviness coefficient for the **(P)** samples is low, and thus there are little to no voids or out-of-plane waviness within these samples.

In contrast to the **(P)** examples, the scans for the **(D)** samples returned a clear and obvious indication of undulation in the three internal 0° plies. This signal represents the actual topography of the internal plies, and thus these undulations and breakages show resin rich areas (voids). These have been attributed as the cause for significant knockdowns in mechanical performance in composite laminates. There are situated in alignment with the defect regions, signalling the defects inducing out-of-plane ply waviness. The degree of undulation is indicated by the waviness coefficients for these scans (Table 1), which are much higher than those recorded for the **(P)** samples.

3.2 Reworked

For the reworked, **(R)**, samples a more varied result is seen. Figure 3. Shows the full set of scans for this class of samples. In some scans (R1_2, R1_3) moderate to large undulations are seen. Here the samples resemble more closely the defective samples in their ply waviness; this level of nascent defect we call the rework signature. Samples R1_1, and R2_3 show a limited but still noticeable undulation, the severity of this undulation being far less extreme than those in the **(D)** samples, or in other **(R)** samples but still greater than any seen in the **(P)** samples. R2_1, and R2_2 show minimal or no signs of ply undulations and resemble the **(P)** samples in their topography and waviness coefficients.

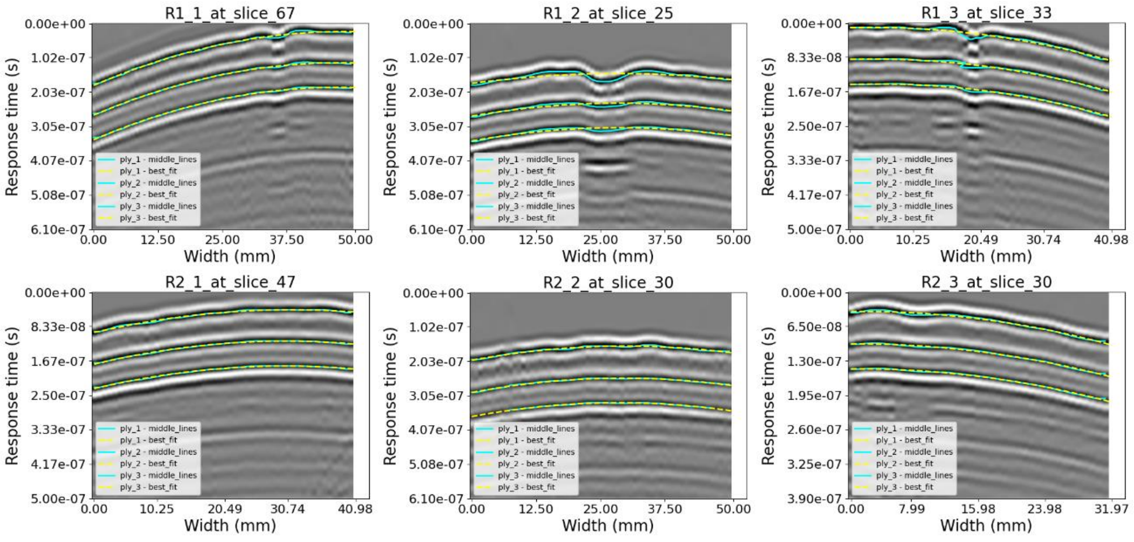

Figure 3. Reworked samples scans

Table 1: Waviness Coefficients of middle lines for all Samples vs Best fit polynomials

Scan ID	Ply 1	Ply 2	Ply 3	Average
P1_1	1.881699	1.513868	0.564231	1.319933
P1_2	1.578945	0.835563	0.629358	1.014622
P1_3	1.616815	1.092711	0.9855	1.231676
P2_1	1.435694	0.786178	0.774108	0.99866
P2_2	1.650169	0.836346	0.854921	1.113812
P2_3	1.221919	0.642916	0.609168	0.824668
Pristine mean	1.564207	0.951264	0.736214	1.083895
D1_1	5.400489	2.816963	2.213279	**3.476911**
D1_2	4.54694	2.312037	1.73089	**2.863289**
D1_3		4.643996	7.701194	**6.172595**
D2_1		2.501143	4.13452	**3.317832**
D2_2	4.894359	2.389081	1.979523	**3.087654**
D2_3	11.59642	5.493785	4.837369	**7.309192**
Defective mean	6.609552	3.359501	3.766129	**4.371245**
R1_1	1.941199	1.233893	1.045553	**1.406881**
R1_2	6.085114	2.912162	2.516425	**3.8379**
R1_3	3.399824	2.223273	1.549776	**2.390958**
R2_1	1.252168	0.6421	0.60343	0.832566
R2_2	1.253022	0.772279	0.559766	0.861689
R2_3	1.973872	1.191873	0.981563	1.382436
Reworked mean	2.650866	1.49593	1.209419	1.785405

Table 1 shows the waviness coefficients for each of the plies within each sample scan. The averages for each scan are shown to the right, along with a mean value for each sample class per ply and an average of this mean across all plies. Shown in bold are the values for the **(D)** samples, which are significantly higher than those recorded for the **(P)** samples, similarly, those **(R)** samples which are higher are bolded to indicate their closer similarity to the **(D)** samples rather than **(P)**.

4. Discussion

The ultrasonic scanning method employed in this study was able to effectively capture the internal ply topography of composite laminates with varying degrees of defects. The ability to detect and quantify defects in composite laminates through ultrasonic scanning has significant implications for quality control and performance optimisation in the aerospace and other industries that rely on composite materials. The clear distinction between the pristine and defective samples demonstrates the sensitivity of this method in identifying even minor defects, such as resin-rich areas or voids, which can substantially impact the mechanical properties and structural integrity of the composite material. Early detection of such defects during the manufacturing process can prevent the use of substandard materials, reducing the risk of premature failure and ensuring safety and reliability.

The variations observed in the reworked samples highlight the potential for this method to assess the effectiveness of rework procedures. The presence of the "rework signature" in some samples suggests that the rework process may not have fully addressed the defects, potentially leaving residual issues that could compromise the material's performance. On the other hand, samples that exhibited minimal undulations similar to pristine samples indicate successful rework, providing confidence in the integrity of the repaired material. The quantitative nature of the waviness coefficient provides a valuable metric for establishing acceptance criteria and quality standards for composite laminates. By defining threshold values for waviness coefficients, manufacturers can implement objective and consistent quality control measures, ensuring that only materials meeting the required specifications are used in critical applications.

5. Limitations

It is critical to acknowledge the limitations of this study for its generalisation. Firstly, the study focused on samples that underwent manual rework procedures. This approach may not fully represent the challenges and variability encountered in industrial-scale AFP processes, limiting the generalisability of the results to larger-scale production environments. Secondly, due to the benchtop-AFP setup used in this study, the sample size was limited. A larger sample size encompassing a wider range of defect types and severities could provide more comprehensive insights and improve the statistical significance of the findings. Next, the ultrasonic scanning method was designed for larger thickness parts (>10mm), which may have resulted in a loss of resolution when applied to the relatively thin composite laminates (1.25mm) used in this study. Higher resolution imaging techniques could potentially reveal finer details and defect characteristics that were not captured in the current analysis. Lastly, manual rework processes are inherently variable, as the defect characteristics and the skill level of the operator can introduce inconsistencies from one rework to another. This variability may contribute to the observed differences in the rework signature among the samples, potentially limiting the generalisability of the results to more controlled and automated rework processes.

6. Conclusions

The ultrasonic scanning method employed in this study has demonstrated its effectiveness in detecting and quantifying defects in composite laminates. By extracting the internal ply topography and calculating a quantitative waviness coefficient, this approach enabled the identification and out-of-plane waviness as a result of embedded gap/overlap defects. The results clearly distinguished pristine samples from defective ones, with the latter exhibiting higher waviness coefficients and pronounced undulations in the internal ply structure. Additionally, the study revealed a "rework signature" in some of the reworked samples, indicating the presence of residual defects or sub-optimal rework procedures.

The ability to quantify defect levels through the waviness coefficient offers valuable insights for quality control and performance optimisation in the composite industry. By establishing acceptance criteria based on this metric, manufacturers can implement objective and consistent quality standards to the reworking process. Furthermore, the detailed mapping of internal ply topography opens opportunities for advanced computational modelling and simulation, allowing researchers and engineers to incorporate actual ply geometry and defect distributions into numerical models for more accurate predictions of material behaviour under various loading conditions.

While the study demonstrated the potential of ultrasonic scanning for defect detection and characterisation, there are several limitations that should be acknowledged. These include the limited scope of manual rework processes, the small sample size due to the benchtop-AFP setup, resolution constraints for thinner laminates, and the inherent variability associated with manual rework procedures. Despite these limitations, the findings from this study represent a significant step forward in the development of non-destructive evaluation techniques for composite materials. By providing a quantitative measure of defect levels and enabling the visualisation of internal ply topography, this approach can contribute to improved quality control.

Future research efforts could address the limitations of this study by exploring larger sample sizes, incorporating automated rework processes, employing higher-resolution imaging techniques, and expanding the data set to include a wider range of composite materials and defect types. Additionally, further investigation into the correlation between rework signature and mechanical properties could enhance the qualitative study of the process, ultimately leading to increased efficiency, and cost-effectiveness in various applications of composite materials.

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[16] All data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase at https://doi.org/10.15129/0fd139f9-f2bd-463d-bad8-43a30c584f4c