INNOVATIVE ROOT REPAIR STRATEGIES FOR WIND GENERATOR BLADES: FROM FAILURE ANALYSIS TO PRATICAL IMPLEMENTATION

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SUMMARY

The article explores repair solutions for defective wind turbine blade roots, identifying failure causes and manufacturing challenges. Three repair solutions are analyzed for uncertainties, modeled using Finite Element Analysis (FEA), and assessed for robustness. The best solution is then manufactured and structurally tested to validate the computational results.

Keywords: Blade root; Blade repair; Root replacement; Blade failure.

ABSTRACT

This article aims to analyze root repair solutions for wind turbine blades. It identifies the root causes of blade root failures and addresses the manufacturing and quality control challenges. Three types of repair solutions are mapped out and initially analyzed for the uncertainties involved in their processes. Feasible solutions, based on their level of uncertainty, are modeled using FEA (Finite Element Analysis), and their robustness is assessed through computational analyses. Finally, the most viable solution, also considering economic and environmental factors, is detailed, manufactured and subjected to structural tests, including coupon tests and full-scale blade tests according IEC 61400 series standard. Testing validates the repair project once the certification requirements are met. The root cause analysis and the project of root repair carried out for SGRE G97t wind generator blade. The results show beside a root replacement possibility, but it´s reliability as acceptable costs, saving wind farms from huge financial losses and avoiding blades premature scrap. The root replacement concept as a new root insert model were submit to Patent.

1. INTRODUCTION

Composite materials have been used in many industries, but their implementation in the wind energy sector is of particular interest. Since wind turbine blades are continuously exposed to fluctuating wind loads, understanding the mechanical behavior of fiberglass composites is crucial for improving durability and efficiency. In summary, both perfect impregnation and strong interfacial bond formation have to be guaranteed among layers.

According to [1] most of the failures modes that may occur for a composite blade are delamination, splitting of fibers and sometimes gelcoat crack. There are also instances where blades suffer damage due to harsh weather and extreme operational conditions, for example leading edge erosion produced by particles in the air. This reduces overall turbine efficiency or, even worst, lead to blade loss.

According to [2], there are several potential regions where a blade can fail. However, this study focuses on the blade root failure, whose length extend from 1 to 1.5 meters spanwise and connects to the hub via insert-type blade preloaded bolts. This region has a complex structural architecture because of the steel-composite interaction, which requires a strong interfacial bonding. It is also important to note that the layers around the insert are stressed prior to the operation due the compressive force produced by the preload applied to the stud. Parallel to this, [2] states that buckling of composites under compressive loading is the most common issue experienced in the root region, typically caused by interface debonding or thin layer degradation, hence turning this zone one of the most critical prone to failure.

To address this issue, uniaxially oriented roving has been widely utilized by major manufacturers due to its processing advantages, anisotropic properties, and ease of dispersion. However, paradoxically, it may present a significant risk of catastrophic failure (bushing detachment then blade loss, for instance) caused by either manufacturing flaws or inadequate structural design.

The design of a blade root, specifically the roving, may contain inherent weaknesses; however, in the field of composite materials, there is no single formula for a perfect solution. Nevertheless, there are best practices that can mitigate major problems:

- The fiber volume content and stiffness determine the composite’s stiffness and strength. However, fiber volume exceeding 65% may end-up into fiber dry-out.
- Interleaving unidirectional and biaxially oriented fibers can prevent wrinkles and waviness, allowing for the homogeneous dispersion of resin.
- Some thermosetting matrices generally exhibit superior fatigue behavior compared to thermoplastics [1] and offer straightforward curing processes.

On the other hand, according to survey results from blade service companies, premature structural failure of blades (within 1-5 years after installation) is most often caused by manufacturing defects [2]. The manufacturing flaws include insufficient resin, inadequate curing process and fiber misalignment, leading to fiber dry-out, bubbles, inclusion of foreign materials, waviness of fibers and so on. All of these factors are prone to happen during the roving manufacturing, significantly impacting the final mechanical properties and, when combined with elevated loads, leads to crack nucleation and propagation, debonding areas, and finally insert detachment.

From this comprehensive overview and considering the importance of sustainable energy, stopping a wind turbine is unacceptable due to the significant losses incurred by both the wind farm owner and the end-user. Within the scope of this article, this concern is exacerbated by the age of the wind turbine — fatigue-related issues have emerged, and the availability of older blade models is limited by manufacturers due to structural project obsolescence — as cracks likely propagate to a critical point, blade failure becomes imminent, necessitating replacement (the conventional approach). However, this approach is prohibitively expensive, due to the extended downtime of the turbine caused by the long lead times required to deliver that specific blade, unavailability of new blades for mid-life wind generators and, moreover, this alternative involves discarding the blade, leading to significant environmental concerns.

In order to overcome this, the present article investigates the root causes of bushing detachment in several 47.6m long wind turbine blades, that belongs to AES-Brasil wind Farm, and examines three potential solutions aimed at extending its blade lifespan:

- Replacement of damaged inserts concept.
- Root replacement without joint bevel concept;
- Root replacement with joint bevel concept.

The reduction in costs and downtime compared to replacing the blades, highlights the advantages of the aforementioned solutions. They will be discussed further in this article, along with a feasibility study covering manufacturing and design considerations.

2. G97T BLADE ROOT FAILURE CASE: A ROOT-CAUSE ANALYSIS

Despite manufacturers not anticipating bushing detachment during the operational lifetime of wind turbines, several factors can lead to such premature failures. Most of them probably take place due to the degradation of the best-practices, which produces unnecessary omissions in quality control procedures ending up rushed production and poorly manufactured composites.

This section delves into a root cause analysis (RCA) of a particular 47.6m blade root failure produced by bushing detachment. The study involves a series of post-failure processes, where parts of the blade, particularly the root region, are extracted to examine “under the skin” the origins of the failure. The blades, located at a wind farm in Ceará-Brasil owned by AES-Brasil, and their technical details are strictly confidential then reserved for the scope of this article. Detailed and strategic information were avoided in order to comply with customer NDA.

A sample from the root region, as shown in Figure 1, was the subject of the study and the initial step involved a visual inspection to check for evidence of fractures.

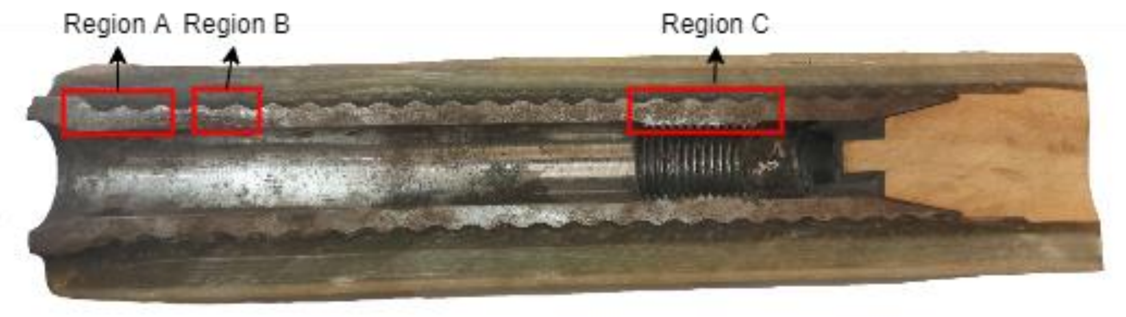
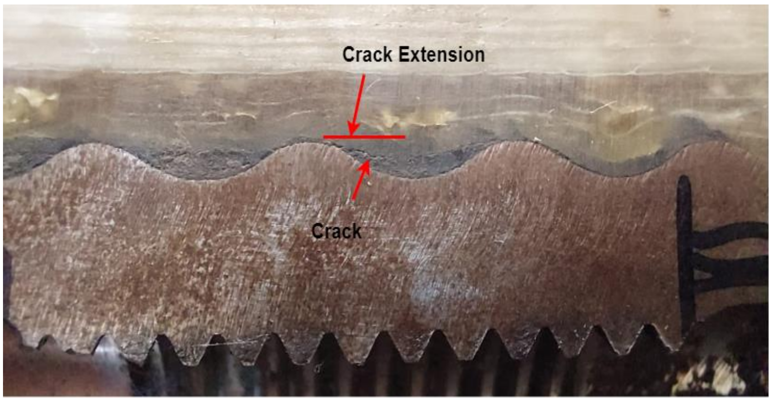


Figure 1: Post-failure cut sample of blade root

(a) Region A

(b) Region B



(c) Region C

Figure 2: Cracks presence in the root sample

Figure 2 revealed significant evidence of fatigue-promoted failure because of the cracks. These cracks are a common yet dangerous phenomenon known as intralaminar cracks. They typically nucleate in high-stress areas, possibly due to preload, and are often undetectable by conventional methods. They are particularly hazardous because they become visible only when a failure occurs, which is often catastrophic depending on the propagation velocity.

The nucleation and propagation velocity of these cracks depend on the load levels and occurrences, as well as the composite's fatigue strength (mainly thermoset fracture toughness). The former does not have straightforward validation due to the aeroelastic simulations (details are outside the scope of this article). However, according to our wind generator model and a site assessment analysis, the loads are coherent.

The degradation of mechanical properties can be explained by poor manufacturing quality, characterized by dry out of fibers resulting in voids and debondings. These phenomena likely took places during the blade/root manufacture due to insufficient resin impregnation. These defects naturally, as aforementioned in section 1, lead to decreased strengths and stiffness. Compression Young's modulus in the fiber direction and matrix-dominated properties are severely reduced (50% or more reduction) due to the found voids.

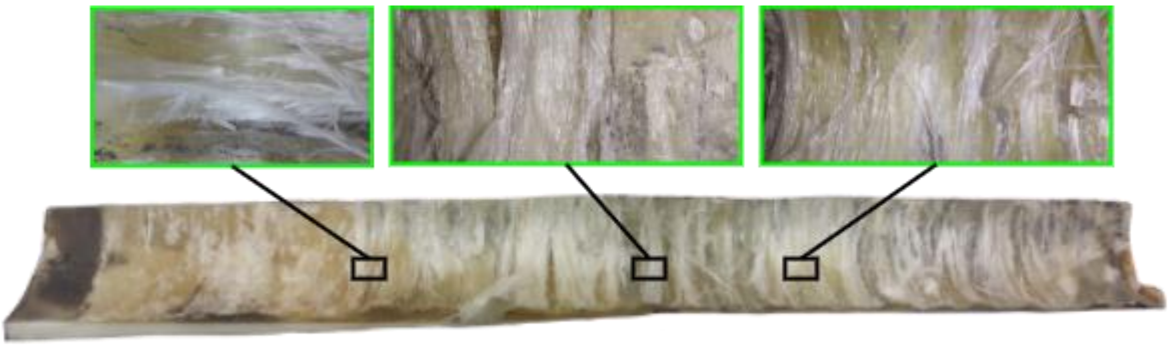


Figure 3: Dry out of uniaxially oriented roving around root steel insert.

Additionally, certain regions exhibited oil contamination from the generator hydraulic system, as seen in Figure 4. This contamination is exacerbated by the high porosity of the matrix and the presence of cracks or delamination, which facilitate fluid migration. Under cyclic loading, the presence of oil may introduce additional loads in the radial root direction, worsening delamination and promoting crack propagation. This condition weakens the material, resulting in reduced strength and rendering it incapable of withstanding the design loads.

(a) (b)

Figure 4: Oil contamination among layers and through the cracks

The degradation of the material properties in certain regions is evident; however, failure only occurs if the applied loads result in stresses that exceed the material's strength. Therefore, the next step in this analysis involves creating a finite element model to identify critical regions, specifically stress-concentration spots. The results of this analysis will then be compared to the **failed regions** observed in the received root sample.

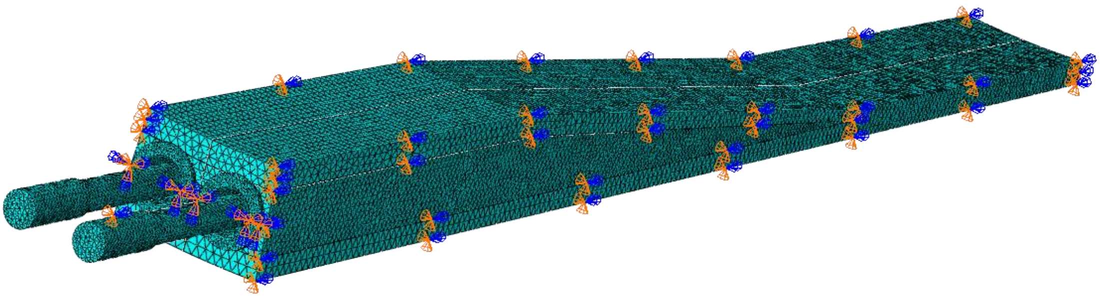


Figure 5: Finite Element Model of the original blade root

Having built the model, it was found that there is a critical stress direction, with the highest stress level occurring where the out-of-plane shear (S_{23}) is maximum. These regions, highlighted in the Figure 6, represent ideal candidates for crack nucleation or failure. As expected, when this distribution is compared with the root sample, we observe that the maximum stress values in the FEM results correspond to the locations of the cracks observed in the studied sample.

Regions A, B and C, highlighted in figure 6 by a red box, are depicted zoomed in the Figure 2a, 2b and 2c, respectively. In the region A can be evidenced intralaminar crack, starting at the stress concentration point (beginning of the striction zone) and developed along the waviness of the insert. Regions B and C are, indeed, similar cases.

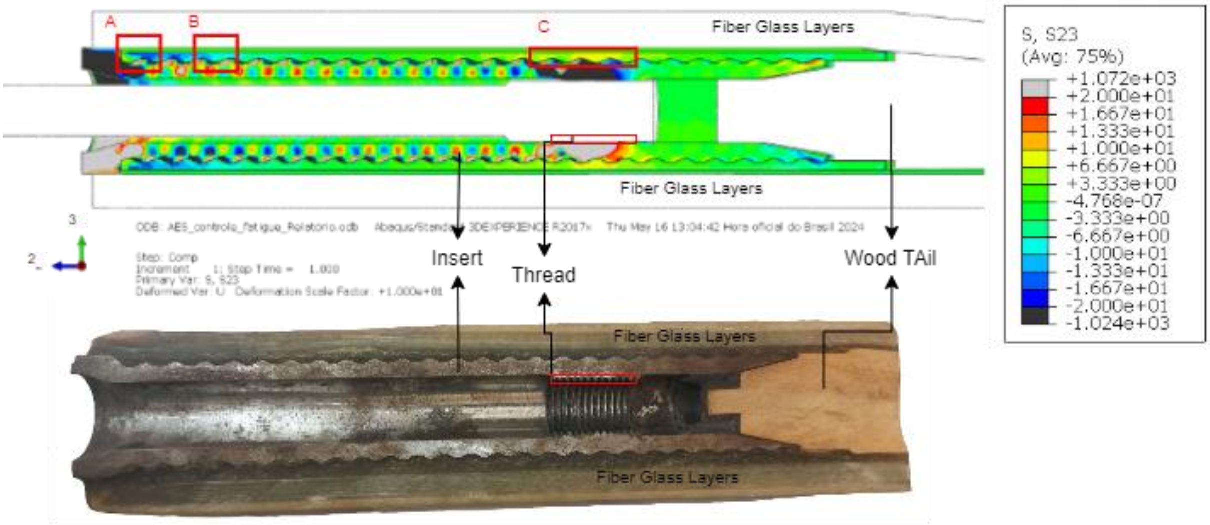


Figure 6: Stress concentrator regions in the model and crack regions in the sample

In closing this section, it is evident that imperfections during manufacturing processes weakens the material, with porosity being a significant indicator as it manifests as a crack.

Parallel to this issue, there are numerous methods available for detecting these cracks; however, some lack accuracy, while others are prohibitively expensive. The implementation of these methods often incurs high costs due to on-site activities, which frequently occur under adverse conditions. While the ultrasonic method seems to be the most suitable, it requires specialized operators and is incapable of detecting microcracks. Therefore, its implementation results in an increased cost without providing significant benefits. The presented results were like the first wind blade root replacement project, affecting Vestas V82 generators, not detailed here due confidentiality reasons.

3. POSSIBLE SOLUTION METHODS

This section presents the main characteristics of the three solutions considered, comparing the advantages and disadvantages of each one.

3.1 Replacement of damaged inserts

Among the solutions proposed for repairing wind blades, replacing damaged inserts stands out for its relative simplicity and apparent low cost.

The solution consists of removing the old damaged insert, either by pulling out, machining or chemical corrosion, and attaching a new insert into the root, with adhesive or with resign injection. In this case, there are no significant modifications to the composite structures of the blade root, with a new metallic insert being placed into the original root of the blade.

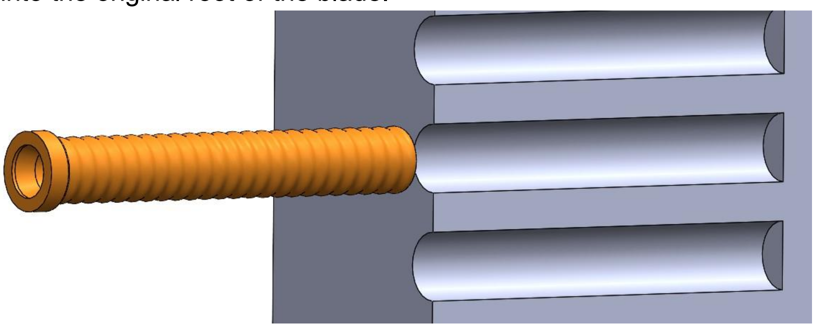


Figure 7: New insert being placed in the original blade root

Therefore, at a first thought the insert replacement solution should have lower repair costs and less downtime, when compared to solutions that involve root replacement. Since there is no pre-fabrication of a new root, the insert replacement service can be done entirely in the field with specialized machinery.

However, this solution has disadvantages that become impediments when considering the risks of removing damaged inserts. Three possible ways to remove the insert was studied and tested:

- Mechanically: pulling out the insert by pulling the stud with a hydraulic system. This is the simplest and cheapest solution, however, the procedure causes irreparable damage to the root laminate structure, in addition to being a high-risk job, as the screw or the laminate can break abruptly. Also, some suds reach their failure limit and breaks, even with cracked bonding inserts.
- Machining: uses a specialized drill system to remove material from the metal insert. There is a risk of the insert rotating with the drill, which can aggravate the damage to the composite structure. Additionally, the need for a very specialized machinery makes the procedure more expensive.
- Chemically: uses strong acid to corrode the steel insert, as a strong basis will attack glass fibers. This solution is expensive and environmentally aggressive, as hazard to operators, and is prone to attack some of the composites

.

Therefore, ways to remove damaged inserts prove to be inefficient, risky, or too costly.

Addressing the issue of coupling new inserts to the blade root, as introduced in the root cause analysis section, the presence of porosity and microcracks in the root composite material is a widespread problem in wind blades. Porosity and microcracks are difficult and costly to detect, such that, even with strict quality control, their inspection presents a high level of inaccuracy, not achieving acceptable safety for a blade repair project. Oil absorption in the micro-cracks and porosity worsens the problem, as the presence of oil would prevent a strong bond between the new insert and the blade root.

Due to the high level of uncertainty and risks of this solution, it was discarded, and no further analyses, such as FEM or fatigue tests, were conducted.

3.2 Root replacement without bevel

The solution of replacing the root without applying a bevel involves removing the entire blade root through a flat cut. A new root is manufactured with new inserts and layers of fiber glass and resin. The attachment area of the new root is flat, as is the area of the blade that will join with the root. The parts are joined with butt joint adhesive, matching the blade's flat surface with the root's flat surface. New layers of laminate reinforcement are added around the repair area to increase the structural strength of the repair. The Figure 8 shows a representation of the junction of the solution.

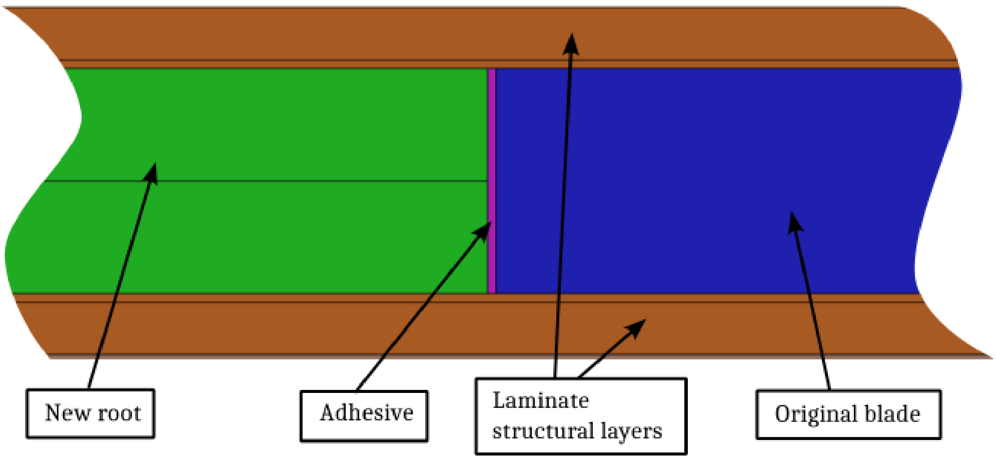
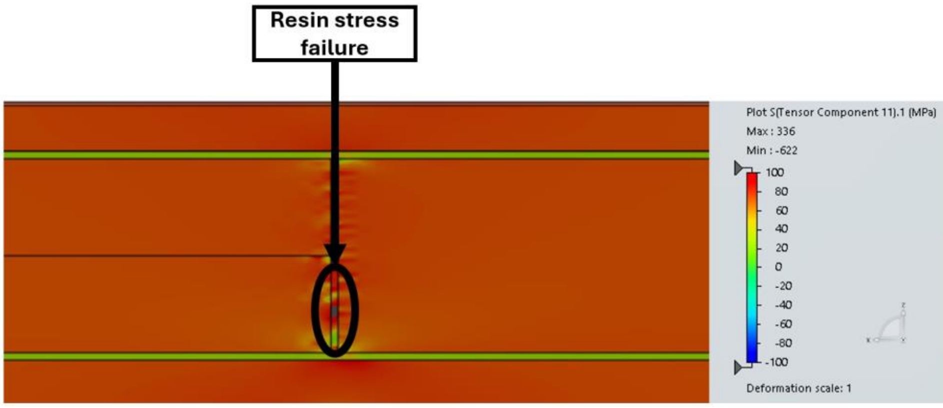


Figure 8: Root replacement attachment without bevel

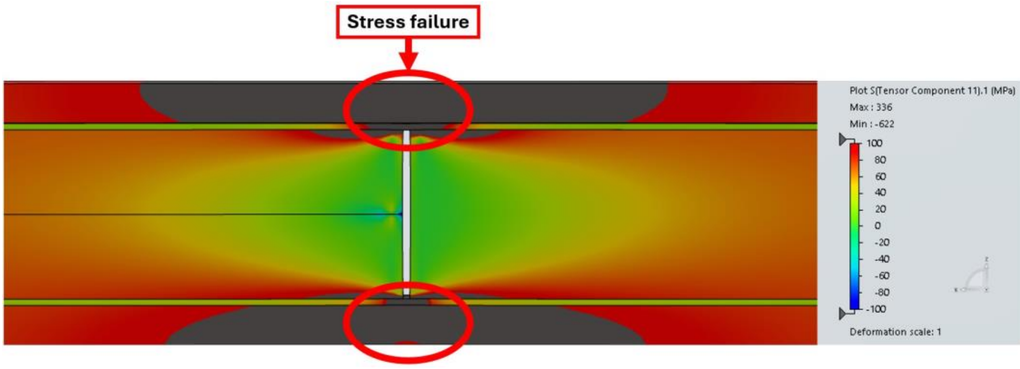
Qualitative analysis of this solution reveals lower levels of uncertainty in the repair procedures compared to insert replacement. This is because a new root is produced using established composite manufacturing techniques. These techniques provide greater predictability and control in the repair process. Additionally, the implementation of stringent quality controls in both the manufacturing and joining of the new root ensures the integrity and reliability of the solution.

Issues such as microcracks, porosity, and oil permeation are less severe than with the insert replacement solution. This is because the entire damaged root region is replaced by a new root that has not experienced fatigue and is manufactured with better design and adequate quality control (with no contamination, no cracks and lower levels of porosity).

As presented in Figure 9, a possible attachment without bevel creates a huge stress concentration area, also the interface between the root and blade as creates another stress concentration area and a possible excess resin to fill the gaps, which would demand an even thicker reinforcement at the patch region, to overcome the stress concentration, indicating that the bevel could be a more efficient and safety solution. Figure 9a shows the stresses in the FEA model of attachment area before the failure of resin and the Figure 9b show the stress field of the attachment without resin. The stress level, even with a thick reinforcement laminate is above the fatigue allowable, turning such solution not viable.



(a) Stresses before resin failure



(b) Stresses after resin failure

Figure 9: FEA model stress for root index without taper

Since the solution cannot demonstrate acceptable levels of reliability in repair procedures, a more in-depth study of its feasibility became necessary. A finite element analysis (FEA) model was developed to apply ultimate loads and observe the structure's performance under stress. However, the FEA study revealed that the joint without the bevel is sub-optimal. It exhibited areas of high stress concentration and required a high number of laminate structural reinforcement layers. Even with large amount of reinforce layers, the stress concentration still present up to a not safety level for a fatigue life.

3.3 Root replacement with bevel joint

The bevel idea is commonly used for composite repair, which consists in machining a taper from both sides of the connection (new root and original blade) and bonding a composite for assembly, reinforcing the structure until every possible stress concentration is within safety margins from ultimate and fatigue. Figure 10 illustrates the junction region in this solution.

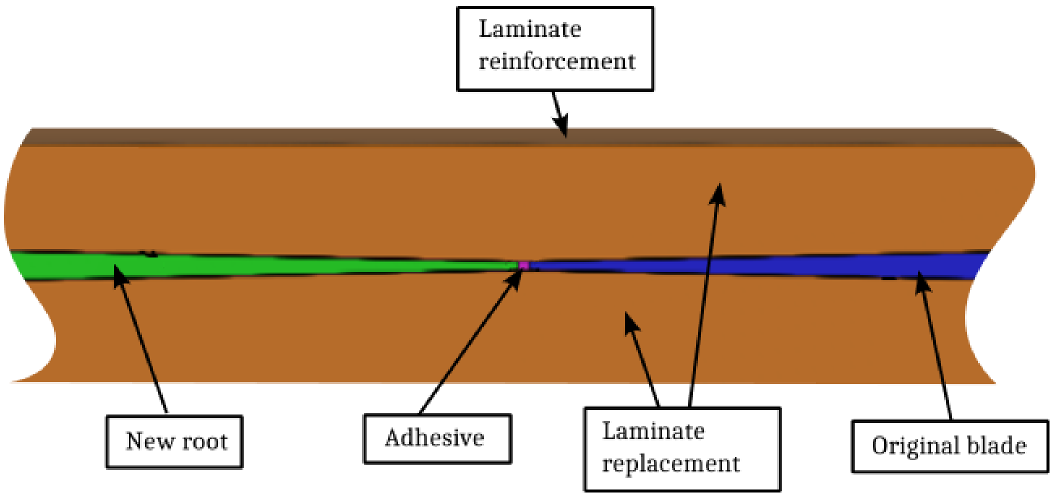


Figure 10: Root replacement junction with bevel

The reliability of this process is like the root replacement without bevel solution and superior to the insert replacement solution. The machining of bevels represents an additional step in the repair process compared to the root replacement without bevel, adding some repair time and complexity.

The high reliability of the procedures prompted FEA analyses of the solution. These analyses yielded satisfactory results, proving superior to the non-beveled solution. The bevels with the replacement laminate provide a more homogeneous load distribution and reduce the number of necessary laminate reinforcement layers.

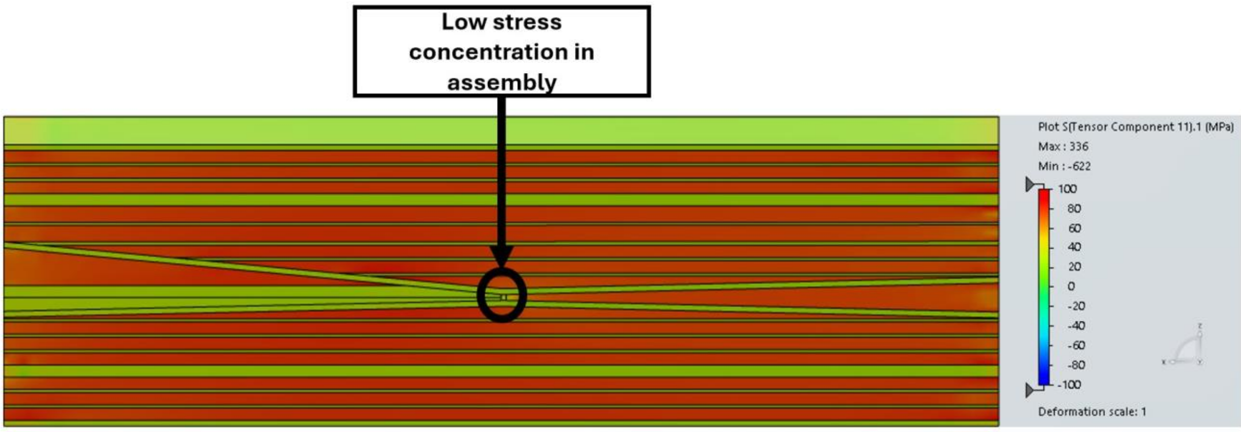


Figure 11: FEA model stress for root index with taper

With better load distribution and fewer laminate reinforcement layers, the solution proved to be structurally superior and more optimized. Therefore, in-depth analyses were conduct, including coupon tests and full-scale tests, confirming the solution's integrity and its capacity to withstand fatigue stresses.

4. SOLUTION DEVELOPMENT

At this step, it was already known that the safest solution for the root failure was to remove all the damaged region from the root and replace it with a new structure, removing all uncertainties from possible cracks at the composite failure region. So, a new root design, with a more robust quality control which addresses the issues from the original project could be indexed to the original blade, granting a new life for an old turbine. The steel insert was also redesign in order to allow higher fatigue loads, therefore creating a higher safety margin, welcome to manufacturing process. This concept proves much lower cost than blade replacement, and possibly lower than just the insert change.

A viable solution requires modifications to the original project and proper validation afterwards, using IEC requirements [3] and [4] as following schedule suggests:

- Wind blade laser scan for aerodynamic loads calculations;
- Wind blade structure sampling for mass and stiffness calculations;
- Scada data analysis for control system behavior estimation;
- Load calculations, including fatigue loads and maximum load cases under IEC 61400;
- Design a new root insert as well as ply stack;
- FEA analysis for root redesign;
- Manufacturing with adequate Quality control;
- Root/blade fatigue test (component level);
- Full scale blade fatigue testing.

4.1 New insert

To address the issues from the old blade root, a new insert had to be designed based on successful concepts already implemented on other blades. This change also requires a complete resize and redesign for the structure, once the root still has to match the original blade structure and bearing.

The original insert, had several discontinuities and stress concentration because of composite laminate and the wooden tail interfaces. The answer to this problem was to design an insert with an embedded tail, but still including a mechanical fail safe by maintaining the ripples from the original concept, which enhances adhesion for the interface between steel and composite. (Patent Pending by NewCo Blades).

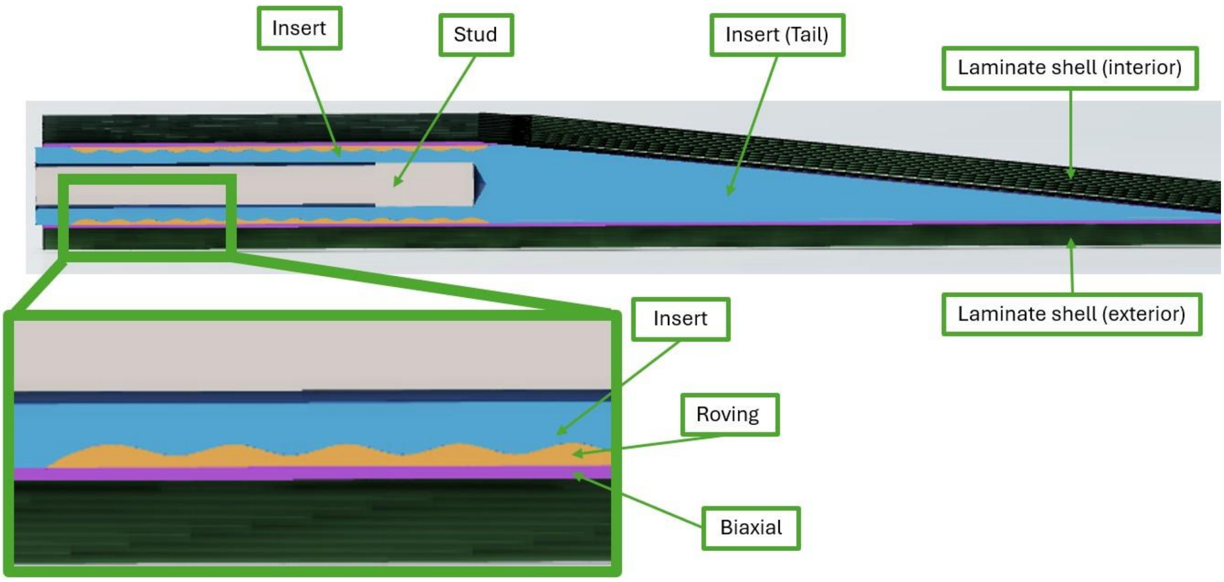
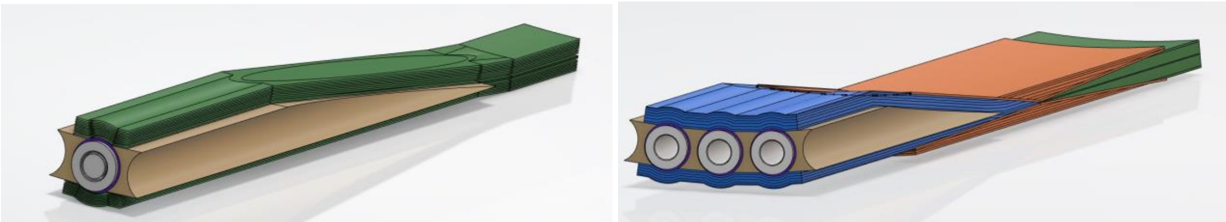


Figure 12: Insert model design in *Simulia* with section cut

4.2 Finite element analysis

The FEA model was created on *Simulia* [5] with the new geometry and the *Design Load Cases* were applied for structural static analysis validation.

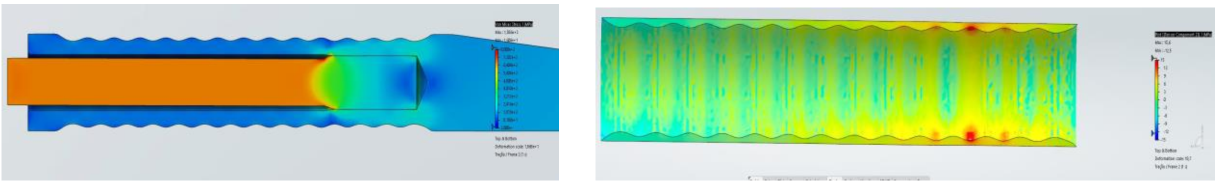


(a) Root-blade assembly model (b) Insert model

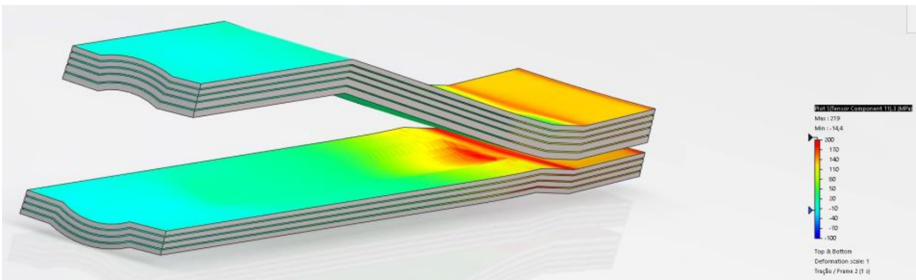
Figure 13: Models designed in Simulia

Results were accessed on critical regions of the surface focusing on stress concentrations near the insert interface, where its most likely to propagate a crack and create a new failure.

For the accessed cases, all regions were able to withstand ultimate static loads while presenting a stress below the certification allowable.



(a) Insert FEA model stresses (b) Roving FEA model stresses



(c) Root laminate FEA model stresses

Figure 14: FEA model stress results for structural validation

After FEA analysis it is possible to proceed to manufacture and testing.

4.3 Quality control

Improvement had to be done for manufacturing processes compared to the original blade, perfecting resin composition, temperature, infusion and quality control to assure there are no dry spots on the fiber and complete adhesion from the composite laminates to other components.

Problems with adhesion between polyester and epoxy parts is the main problem to focus and an issue that reduces the stress limits for this solution. This comes from the original blade, built entirely of polyester resin, and the new root, as reinforce laminate is made entirely on epoxy.

The first way to address this problem is by optimizing the root geometry using stress limits not only from raw materials, but from adhesive tests acquired using coupons, as shown in Figure 15.

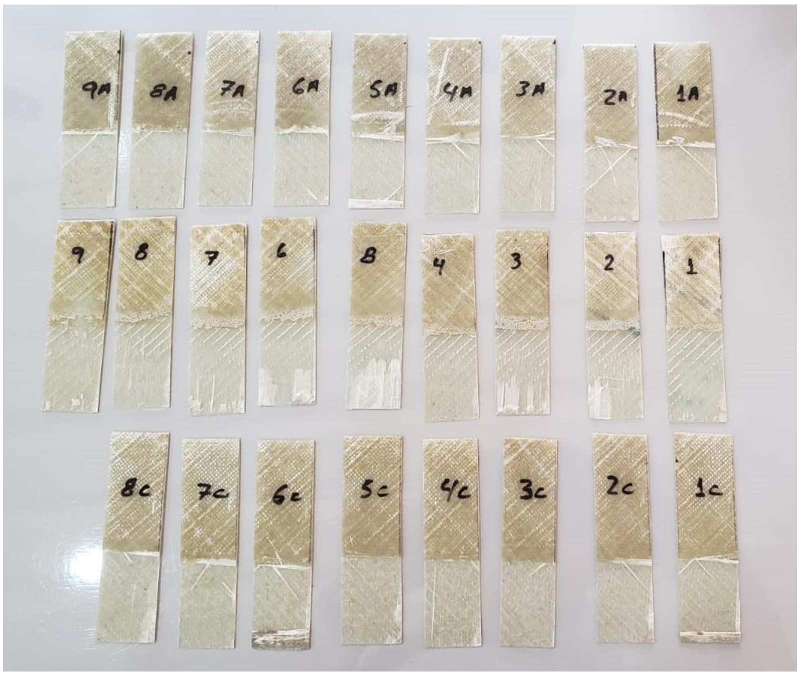


Figure 15: Lap shear test Epoxy/Polyester

For infusion, temperature control is optimized on cure and post cure to promote a low exothermic peak temperature of 65°C and maintaining infusion between 27°C and 32°C, then post cure until achieve T_G 76-80°C. By controlling those variables in time, it is possible to ensure no void spots will appear and that the cure will happen slowly to form strong bonds for the composite.

4.4 Fatigue tests

After the successful manufacture of the root and its assembly, it is required to set up tests for those structures, including a component and a full-scale test as IEC [6] recommends for a new blade design so the solution is validated and can be implemented to all other blades safely while reducing safety factors applied because of uncertainties.

The component represents a patched root section with only one insert and it is the first set of testing to validate the design. Test results were successful with alternate cyclic forces beyond design load cases, proving that the new root is more robust than the original and concepts for this design are valid to blade repair.

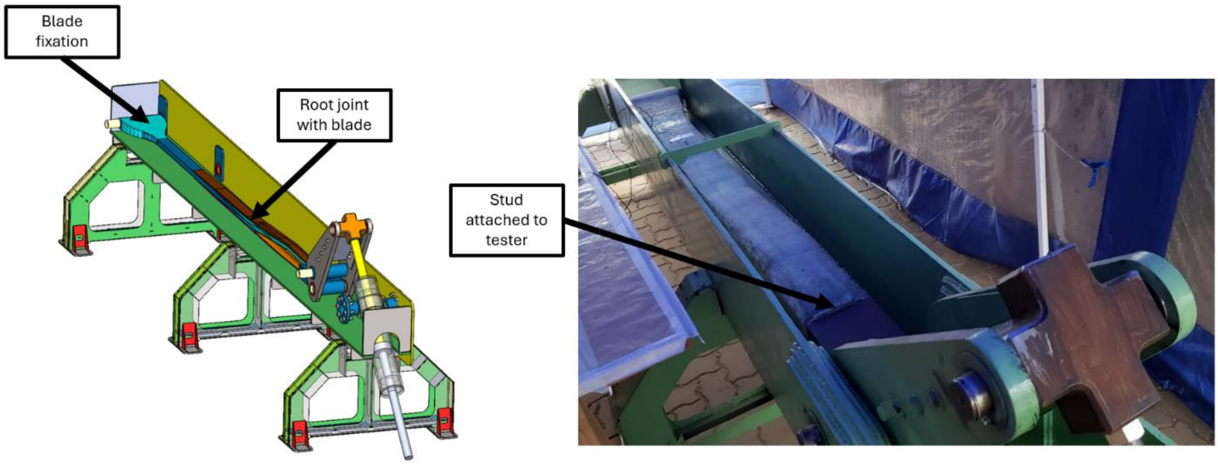
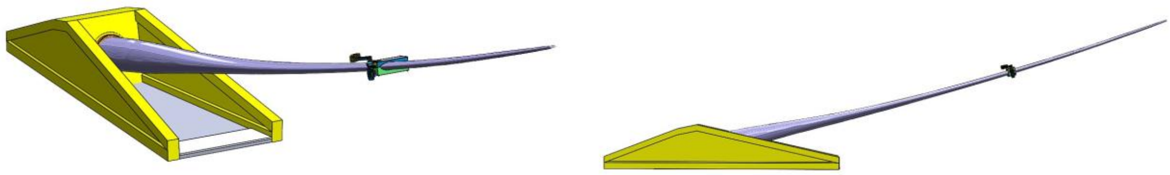


Figure 16: Component test setup

The fatigue tests prove the new insert has a pulling allowable force beyond expectation, also fatigue test shown equivalent life of more than 100 years for the insert/root, and more than 20 years for the new root/old blade area interface. The results are a major upgrade from the first root replacement project done to V82. The results also make it possible to extend the blade life and therefore generator life, helping on the investment recovery for root replacement.

Further validation with full scale testing is being developed for this solution, generating concrete evidence that it’s the safest and cheapest way to solve insert detachment failure. Other full-scale test was already developed by NewCo’s team for the first design of blade root replacement on a very similar blade, but it is restricted by client contract and confidentiality terms. This first blade project already achieved more than 160 blades retrofitted without problems. Figure 17 represents the design for the tester.



(a) Blade fixed for full scale (isometric)

(b) Blade fixed for full scale (side)

Figure 17: Fatigue tests setups

Full scale testing is divided in two steps, one with a flap-wise load cycle, other being an edgewise load cycle. Combined, they produce the damage equivalent to 20 years of operation, proving that the new root is capable to withstand the whole design life of the blade without risking a whole wind turbine.

5. CONCLUSION

The developed root replacement solution presented proves the root replacement concept is not only possible but cost effective. Also, the concept allows a generator life extension in case the rest of the blade and generator components allows. The first blade root replacement project done reaches more than 150 blade root replacements without issues, done by a blade service company, and the new and improved design presented here can be used on any other blade model. Beside the cost saving, this project avoids a huge blade discharge, avoiding environmental issues.

Wind farms are essential to shift the energy grid for a cleaner generation and decarbonization, so developing robust solutions to address possible problems to blades reduces uncertainties to investors, thus, creates an incentive to investing by reducing its risk and reducing cost of energy and contracts in the long term. Furthermore, this is the second blade root design, as the first one, under non-disclosure agreement, was a similar blade and recovery more than 160 blades successfully, so the route is well proven.

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