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RESEARCH ARTICLE

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Investigation of glass fiber reinforced aluminum honeycomb panel repair performance according to aviation standards

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Abstract

Aluminum honeycomb structures are widely used in aviation and aerospace engineering designs due to their high strength/density properties. Although they are resistant to atmospheric conditions and acceptable impacts, they can suffer from corrosion and mechanical damage in some cases. This damage that occurs over time can affect the structural integrity and maintenance-repair process, which in turn can affect the safety and service life of this material. In this study, a different repair technique was tried by giving artificial damage to aluminum honeycomb structures. Repair procedures were carried out in accordance with the maintenance protocols of the manufacturing companies in order to restore the original strength properties of the material. After the repair, various non-destructive testing (NDT) methods, such as visual inspection and ultrasonic testing, were employed to inspect for discontinuities. A bending test was subsequently conducted to evaluate the material's strength, and the results were analyzed. The bending test results indicate that the repaired structures exhibited structural integrity close to their pre-damage state. The results of this study demonstrate that the repaired aluminum honeycomb structures achieved strength levels comparable to the original, undamaged material, meeting aviation industry standards. This highlights the effectiveness and reliability of the developed repair methods for ensuring safety and functionality in aerospace applications.

Keywords: Honeycomb composite, Aviation material, Glass-fibre reinforced, Aluminum honeycomb.

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1. Introduction

The main reason for using composite materials in the aviation industry is to reduce the weight of the aircraft and save fuel. However, composites used in aviation industries have important advantages such as superior corrosion resistance, durability, high temperature tolerance and reduced maintenance requirements, in addition to their lightness.

Since aircraft are often exposed to harsh atmospheric conditions, it is necessary to use materials that are resistant to temperature fluctuations, corrosion and corrosive substances. Honeycomb composites, which are the subject of this study, perform well under such extreme conditions, thus increasing the safety of aircraft structures and extending their operational life [1-6]. The integration of composite materials into aircraft structures has led to transformative advances in design methodologies. Traditional metallic materials require a significant number of fasteners (e.g. bolts and rivets) for assembly, creating significant problems such as increased weight and long production processes. In contrast, composites allow large, geometrically complex components to be manufactured in one piece. Therefore, the need for numerous joints is reduced. Thus, assembly processes are accelerated and structural fit and integrity are ensured. In addition, flight performance is increased because honeycomb structures provide superior aerodynamic properties [7,8]. Another advantage of composite materials is their potential to mitigate the environmental impact associated with aviation. Given the significant contribution of the sector to global carbon emissions, achieving sustainability goals is imperative. At this point, composite materials significantly reduce fuel consumption and therefore carbon emissions by reducing the total weight of the aircraft [9-11].

One of the main reasons for the adoption of composite materials in aviation is that the desired matrix and reinforcement material can be selected during the production process. At the same time, the form of the fiber material can be selected, and structural composites such as honeycomb can be preferred when it is necessary. Therefore, appropriate optimization can be made by taking into account the relevant parameters in the entire production process. For example, multilayer honeycomb composite structures can be designed to exhibit distinct mechanical properties in different areas of an aircraft. Thus, while weight is reduced for non-critical areas, specially designed reinforced structures provide increased strength in parts exposed to high stress. This versatility and depth of possibilities allow aerospace engineers not only to optimize the use of composites such as honeycomb effectively but develop superior structural designs as well [12-17]. However, there are also some disadvantages of composite materials in aviation. For instance, include complex manufacturing processes, high costs, technical difficulties associated with maintenance and repair. In particular, damage detection and repair for composites are more complex and time consuming compared to traditional metallic materials. cFor this reason, it is aimed to increase the flight performance of glass fiber reinforced aluminum honeycomb panels used in aircraft by developing new, fast and efficient maintenance processes [18,19].

1.1. Honeycomb Composite

Honeycomb sandwich composites based on the inherent features of composite materials is subclass out of regular and periodic hexagonal repeating unit cell configuration being the hallmark of cellular materials. The design of materials are designed specifically to fit the particular context in which material is used for. Key factors to consider are corrosion, creep performance, stiffness, strength, fatigue resilience, low mass characteristics and cost. For applications that are very mission critical such as weight be as little in any case the use of flat layers of thin would lead to local buckling.

Honeycomb sandwich composites are widely utilized in structural applications requiring a combination of high strength and low weight. These composites consist of two thin, stiff, and strong outer layers that primarily bear the applied loads. These outer layers are bonded to a relatively thicker, low density core structure positioned between them, with an adhesive layer ensuring the structural integrity of the assembly. Figure 1 provides a schematic representation of a typical composite sandwich structure [20,21].

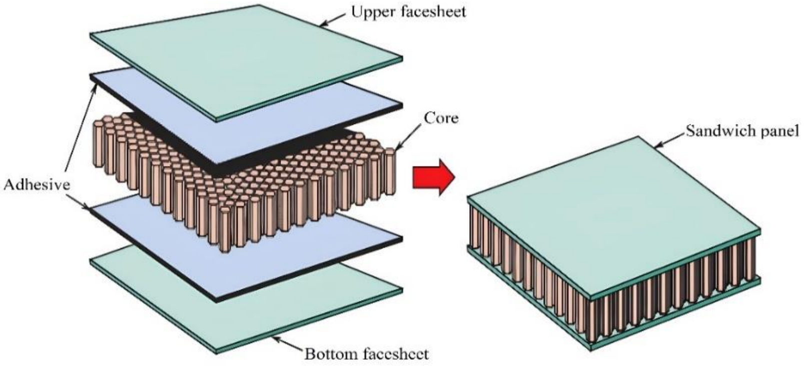


Fig. 1. A general representation of composite sandwich structures.

Composite sandwich structures exhibit outstanding mechanical properties, including low density, a high strength to weight ratio, excellent corrosion resistance and energy absorption capabilities. These advantages make honeycomb structures highly versatile and widely applicable across various engineering disciplines, particularly in the aerospace and marine industries. Due to their anisotropic nature, the mechanical properties of honeycomb structures vary along the three principal directions, as shown in Figure 2 (T, L, and W). In hexagonal configurations, the T direction (through thickness direction) exhibits the highest compressive and tensile strengths, making it the preferred direction for load bearing applications. Conversely, the L (longitudinal) and W (width) directions provide superior shear strength, with the L direction offering greater shear strength and shear modulus compared to the W direction. The cell size in honeycomb structures is the distance between parallel sides of the hexagonal cells. This parameter plays a huge role in the mechanical properties of the structure, as it is the material density and stiffness [22].

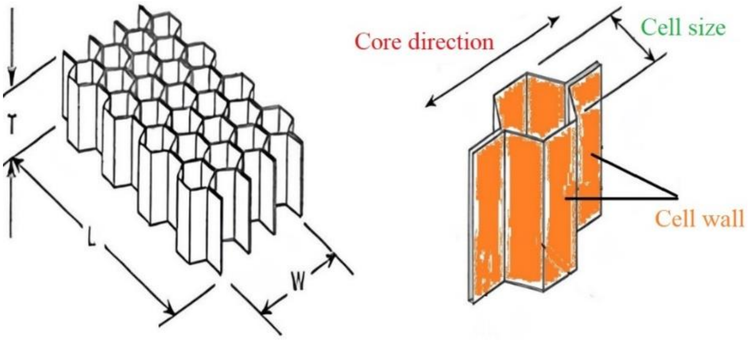


Fig. 2. A general representation of honeycomb core structures.

The face sheets are the outermost layers of sandwich composite structures and they determine all kinds of aspects. The layers are mostly fabricated using a composite of hyper materials. It is shaped to be resistant to bending, shear loading and specific face sheet materials that comprise carbon epoxy, aramid epoxy and glass epoxy for their tailored mechanical properties and matching for the expected operational environment. The sandwich core of a sandwich structure serves not only as the primary load bearing section but is also very important for supporting face sheets fastening. In aerospace, core materials such as aluminum alloys, aramid fibers, nomex honeycomb and high strength alloys of the metal are most commonly used.

The principal advantage of sandwich structures lies in their exceptional contribution to weight reduction, which is critical in aerospace applications. Figure 3 illustrates a comparison of the strength and stiffness ratios across various sandwich structures. Notably, the structure on the far right demonstrates 37 times greater stiffness and 7 times higher flexural strength compared to a solid aluminum plate, while weighing only 9% of the plate's mass [23,24].

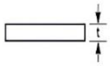
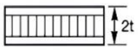
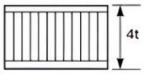
	Core	Core (t) + facesheet (t)	Core (3t) + facesheet (t)
			
Relative stiffness	1	7	37
Relative bending strength	1	3,5	9,2
Relative weight	1	1,03	1,06

Fig. 3. The strength and stiffness ratios of various sandwich structures.

2. Experimental Study

With advancements in aviation technology, new materials, devices, methods and techniques are continuously being developed. In this study, aluminum honeycomb panels widely used as primary structural materials in commercial aircraft and procured from maintenance and repair organizations were utilized. As depicted in Figure 4, the sandwich structure employed in this experiment consists of an aluminum alloy core with a surface coating made of glass fiber reinforced epoxy. The main material used in the study is identified as BMS 4-23 TYPE II, comprising a core made of aluminum alloy 5424 and surface coatings of glass fiber reinforced epoxy.

The 5000 series aluminum alloys, commonly referred to as aluminum-magnesium (Al-Mg) alloys, incorporate magnesium as their primary alloying element. These alloys are known for their medium strength, excellent formability, weldability and corrosion resistance, making them suitable for various aerospace applications. Glass fiber, characterized by high corrosion resistance, liquid impermeability, lightweight properties and good mechanical strength, is widely used in applications such as passenger floor panels and cargo floor panels, where materials must withstand high traffic and load conditions.

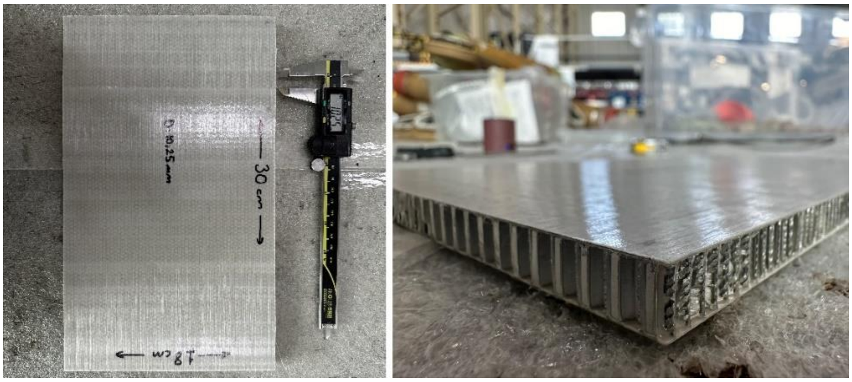


Fig. 4. A sample sandwich structure, featuring an aluminum alloy core, is constructed with glass fiber reinforced epoxy.

2.1. Artificial Damage Induction on the Sample

The sample material used in this study is commonly employed for cabin floor panels and cargo compartment floor panels in aircraft. To simulate real world conditions, artificial damage was introduced to the panel, reflecting the types of damage these components typically encounter during service. In operational environments, impact damage is prevalent, while both impact and hole damage are commonly observed during maintenance activities.

For the purposes of this study, artificial damage was applied with predefined dimensions and depths to facilitate subsequent repair procedures. As illustrated in Figure 5, impact damage was induced using a hammer, while hole damage was created using a drill. These methods were selected to replicate realistic damage scenarios and ensure the effectiveness of the repair techniques under investigation.

Fig. 5. Induction of artificial damage on the samples.

2.2. Application of the Repair Procedure

During the repair phase, the latest revision of the Structural Repair Manual (SRM) provided by Boeing was utilized as a reference. All repair steps were executed by qualified and experienced personnel to ensure adherence to industry standards. Initially, critical information, including the appropriate repair method and the specific materials required, was determined in accordance with the guidelines outlined in the SRM. The repair process commenced with cleaning the sample and removing the damaged layers. As depicted in Figure 6, the removal of the damaged area was conducted based on the shape and extent of the damage. Following this step, the depth of the damage was meticulously measured to guide subsequent repair actions.

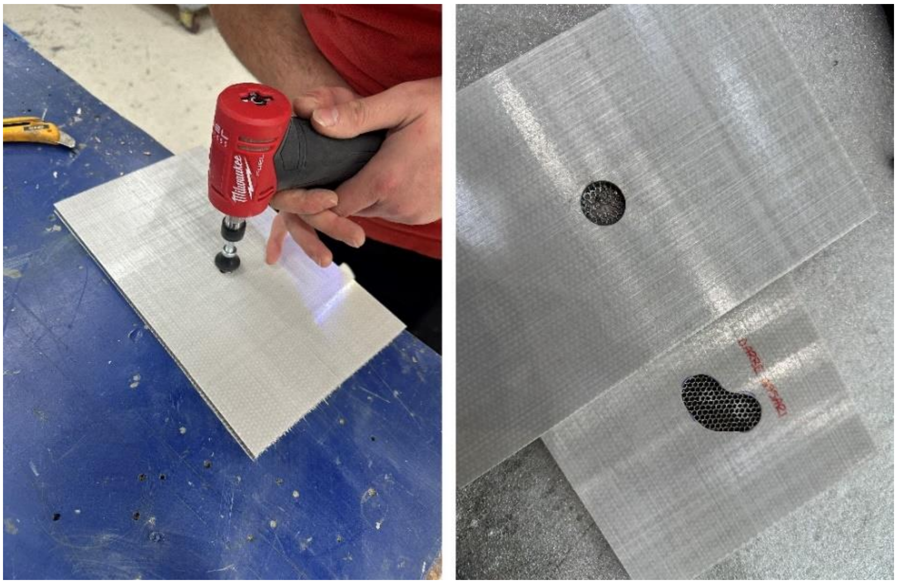


Fig. 6. Removal of the damaged area.

After the damaged area has been removed, the surface is carefully cleaned to remove burrs and dust. A template is then created on the damaged region using tape, which will serve as a fabric pattern for subsequent stages of the repair process. To address the core deficiency in the damaged area, the procedure involves filling the void with BMS 5-28, Type 19 filler material, as specified in the repair manual. This filler material can cure either in 7 days at room temperature or in 5 hours at 52 °C, depending on the chosen curing conditions. The filler material consists of two components that must be mixed in the prescribed ratio of approximately 20:1 (base material to activator). It is crucial to ensure that the entire damaged area is completely filled, and the filler level should be leveled with the surface of the sample. Once the filler material is applied, it is allowed to cure until it hardens. Following the curing process, the surface is shaved to achieve a smooth and level finish. During the shaving operation, safety precautions must be followed: safety goggles should be worn to prevent exposure to dust, or a vacuum device should be employed to minimize airborne particles. The shaving process continues until the filler material is even and flush with the surface of the sample. These steps are illustrated in Figure 7.

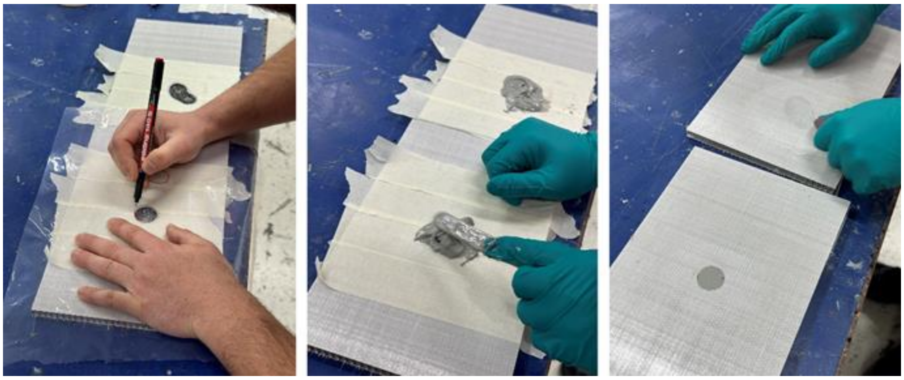


Fig. 7. Template creation, filler material application, and shaving process.

Following these procedures, fabric dimensions are measured based on the size of the damage, as previously outlined in the template. According to the repair protocol, three layers of fabric will be applied. The dimensions of each fabric layer should be 0.50 inches wider than the previous one. The BMS 9-3 repair fabrics are used in accordance with the measurements specified by the template. Since these fabrics are not preimpregnated, an impregnation process is required. The impregnation is carried out using BMS 8-201 resin, which is composed of two chemicals that must be mixed in the appropriate proportions as per the application instructions. Each fabric layer is individually impregnated with epoxy in an approximately 1:1 ratio (Figure 8).

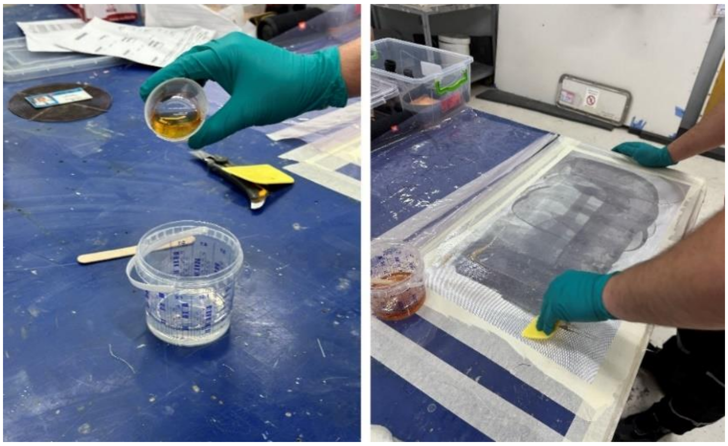


Fig. 8. Epoxy impregnation of the fabric and template creation for the fabric layers.

After the impregnation process, the templates are carefully cut from the fabric, and the laying process begins immediately. Prior to initiating the laying process, resin is applied to the surface to be treated. The fabric layers are then applied sequentially, one at a time, to complete the repair. These procedure steps are illustrated in Figure 9.

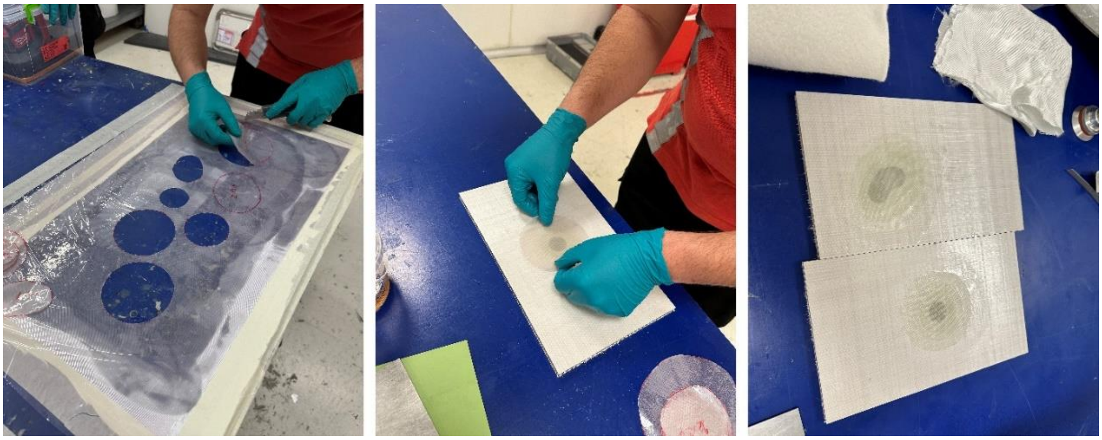


Fig. 9. Removal of fabric templates and fabric laying process.

After completing the laying process, the vacuum process is initiated immediately. The first step involves placing the vacuum bag over the sample. The sample is then positioned on the blanket with the untreated surface facing down. Once the sample is placed, fabrics are applied to prevent the blanket from adhering to the sample while allowing air to pass through. A flat plate is employed to ensure more uniform pressure distribution across the sample. The vacuum bag is sealed tightly using double sided tape to prevent air from entering. Subsequently, the vacuum bag is carefully cut to accommodate the insertion of the vacuum probe, which is then positioned. The sample is then subjected to the vacuum process in accordance with the procedure. The vacuum process is carried out at room temperature as specified in the procedure. The vacuum device is equipped with a warning system that detects any pressure loss or temperature variation. It is capable of adjusting the temperature if necessary. According to the procedure, the sample must cure for 24 hours. After curing, the vacuum probes are removed. The double sided tape is carefully taken off, and the sample undergoes an initial visual inspection by authorized personnel. During this inspection, the sample is checked for bubble formation or any other unusual conditions. For a more detailed assessment, non-destructive testing methods, as outlined in the procedure, are applied to the sample. These process steps are illustrated in Figure 10.

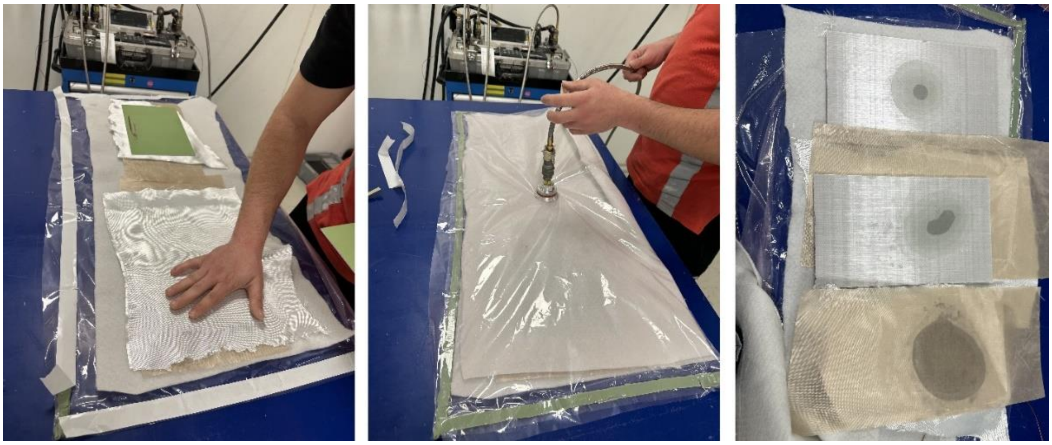


Fig. 10. The vacuum process implementation.

2.3. Non-Destructive Testing Procedure

To detect any invisible defects in a composite sandwich structure that has been repaired, a non-destructive testing (NDT) method is applied. This method enables the identification of discontinuities within the material without causing any damage, thereby allowing a decision to be made about whether the structure is fit to return to service. According to the Boeing procedure, the repaired sample undergoes a non-destructive inspection in accordance with the relevant control procedures. The procedure specifies that, at the repair site, delamination, separation between layers, and any voids in the filler material must be checked. For this purpose, ultrasonic testing, a detailed acoustic inspection method, is performed. The tests were carried out in the non-destructive testing laboratory, under the supervision of authorized personnel.

Two types of techniques were used for the acoustic testing method: the bond test and the transmission path test. The bond test procedure is employed to detect core damage and separations between the core and the surface layers. A low frequency testing device is utilized for this test. The relevant procedure specifies the suitable devices for this type of testing. The sensitivity of the device must be adjusted based on the material thickness. Since low frequency is used, there is no requirement for a liquid medium between the sensor and the structure. Prior to testing, both the sample and the surrounding environment were thoroughly cleaned. The appropriate procedure for material thickness was determined, and Bondmaster 600 and Olympus devices were used for the test. To calibrate the device, either an undamaged sample with the same thickness or calibration packs made from the same material can be used. The probe is slowly moved over the undamaged sample to obtain a clean signal. Figure 11 illustrates how the device generates response signals for both undamaged and damaged areas.

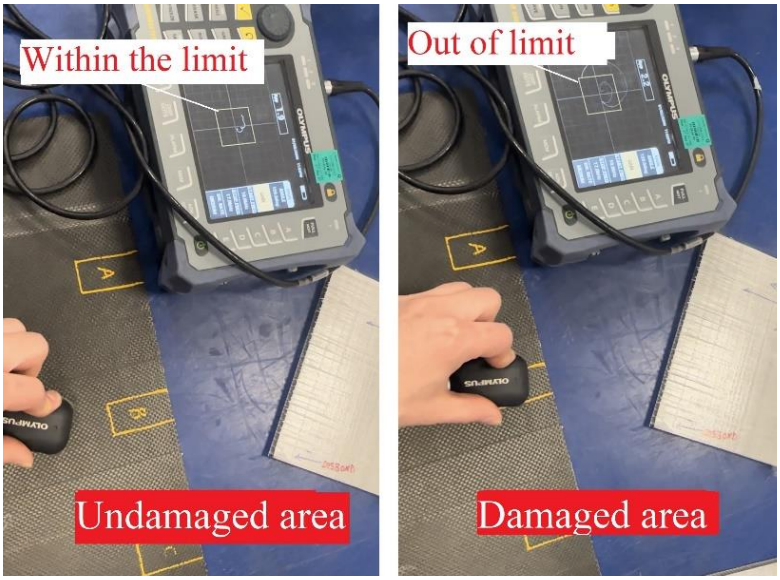


Fig. 11. It illustrates how the device generates response signals for both undamaged and damaged areas.

After the device is calibrated, the test is conducted on both specimens (Figure 12). During the test, no signal distortion is detected in either specimen. It is observed that there are no defects in the filler material or its adhesion to the surface layer.

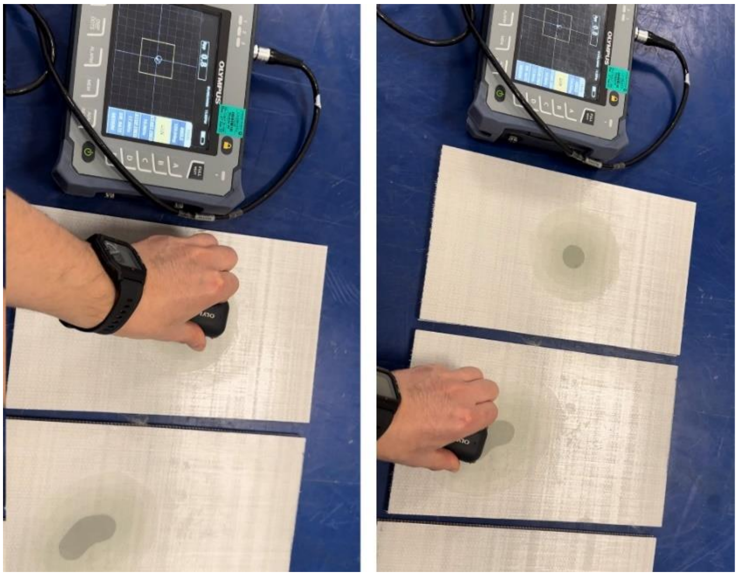


Fig. 12. A bond test is performed on the specimens.

In the transmission test, interlayer delaminations and separations between the core and the surface layer are detected. The test is conducted using sound transmission sensitivity. The sound wave striking the ramp is subsequently received by the probe, with detections made based on the intensity of the sound. Different ramps with varying angles can be employed, making the test applicable for angular structures. Both the environment and the specimen must be clean prior to testing. To eliminate air contact, gel is applied between the probe and the structure.

For this test, the Sonatest D-70 device, which complies with the procedure, was used. Initially, the device is calibrated. Unlike the bond test, this test can detect separations between fabric layers, making the number of fabric layers repaired a critical factor. Therefore, a calibration plate is used during the calibration process. Based on the repair performed, the device is calibrated according to Region B of the plate shown in Figure 13.

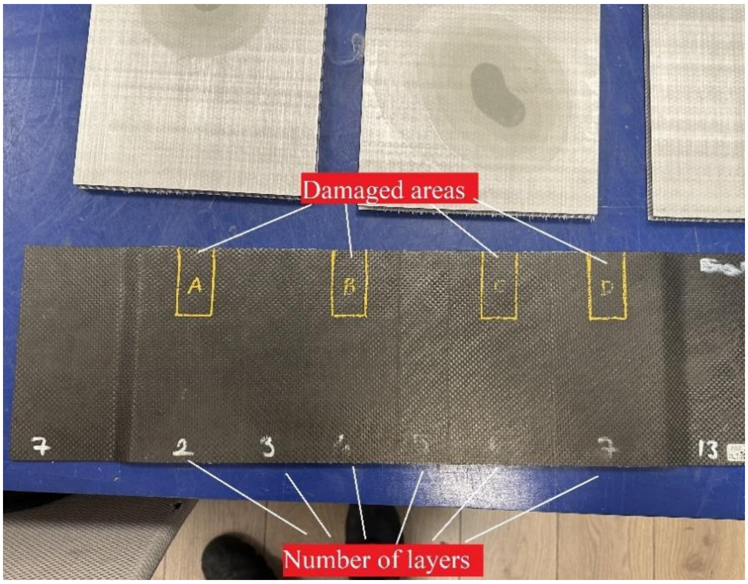


Fig. 13. A device calibration plate.

During calibration and testing, the probes must be perfectly aligned. No signal should be received when the probe is positioned over the damaged area. Signals should only be detected outside the damaged areas. The resulting signals are clearly shown in Figure 14.

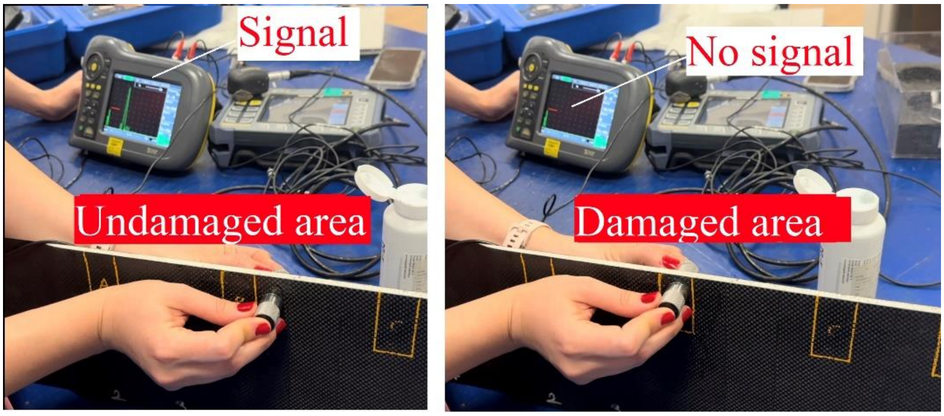


Fig. 14. The display of signals on the calibration plate.

After the device is calibrated, the test is applied to the specimens. Since the areas where filling has been done are not suitable for the transmission test, the test is only applied to areas without filler material. The test is conducted over the entire repair area. According to the procedure, to determine whether the repair is suitable, the signal must be transmitted with a minimum efficiency of 40%. The signals for the specimen are shown in Figure 15. It has been determined by authorized personnel that the specimens successfully passed the transmission test.

Fig. 15. The signals for the specimen.

2.4. Bending Test Implementation

A bending test of a material allows for the determination of its ductility, bending strength, fracture strength, and resistance to fracture. If a material begins to crack or fracture during the testing phase, it can be assumed that the material would similarly fail in active use, potentially leading to failure. The testing procedure was conducted by authorized personnel in accordance with the relevant standard. The bending operation was performed on an Instron brand three point bending device, which is equipped with an adjustable mandrel and has a capacity to apply a load of up to 100 kN. Real time data can be monitored through the device's display.

The bending process was applied sequentially to the unblemished specimen, the damaged specimen with renewed surface coating, and the specimen with both surface and core repair. During all three tests, the following parameters were maintained: the support span was set to 100 mm, the mandrel width was 77 mm, the mandrel diameter was 10 mm, and the compression force speed was 2 mm/min. The test points were positioned at the center of the specimen for the original specimen and aligned with the center of the damage area for the repaired specimens. The setup for the bending operation is shown in Figure 16.

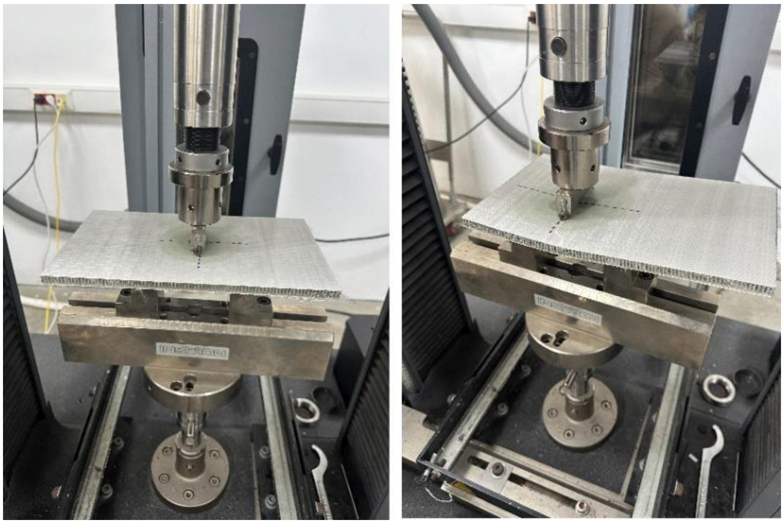


Fig. 16. The setup for the bending operation.

The test continued until the material fractured and for a period following the fracture. Upon examining the final condition of the specimens, it was observed that the fracture point passed through the center of the repaired areas, as desired, as shown in Figure 17.

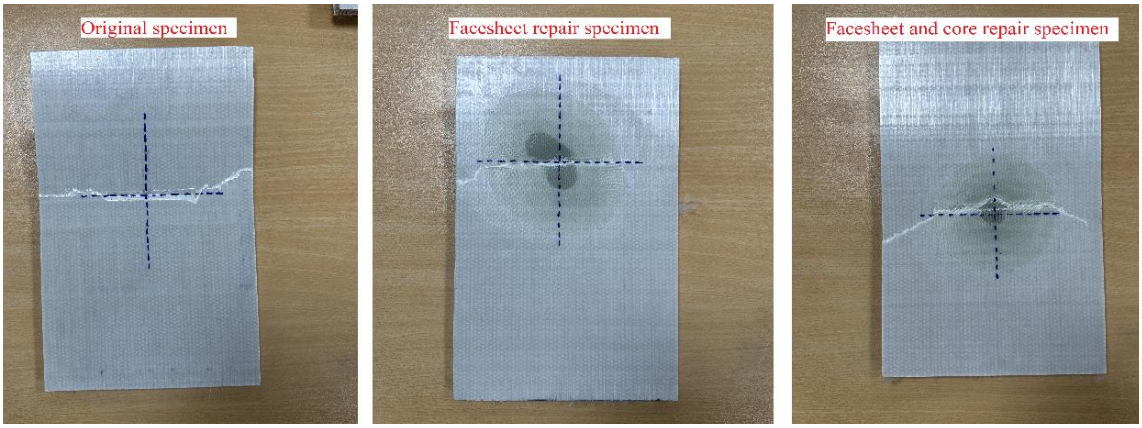
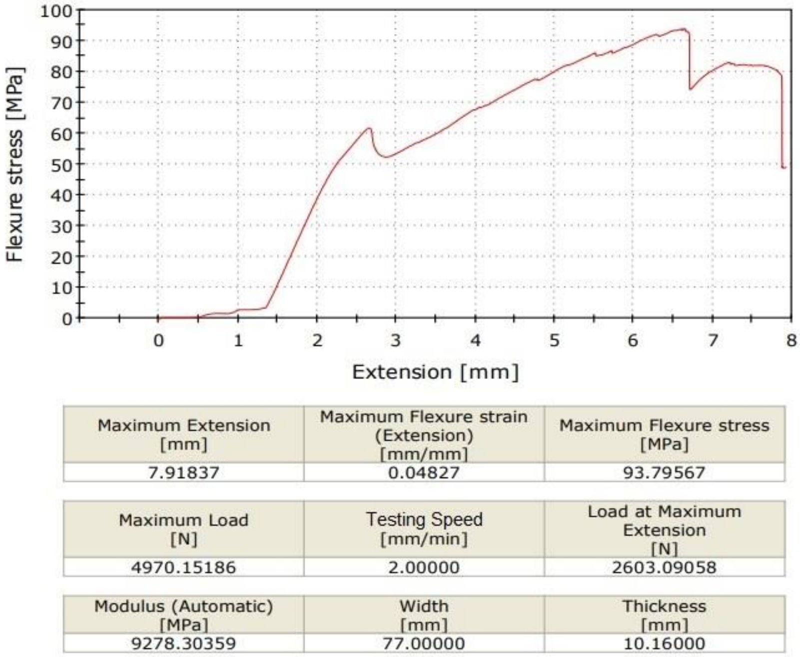


Fig. 17. The post-bending test appearance of the specimens.

3. Conclusion and Discussion

The study proposes a new repair technique applied to aluminum honeycomb structures, which are widely used in aviation and aerospace engineering applications, subjected to artificial damage. The repair procedures were executed inaccordance with the maintenance protocols established by the manufacturing companies, with the objective of restoring the material's original strength characteristics. During the repair phase, the latest revision of the Structural Repair Manual (SRM) provided by Boeing was utilized as a reference. Following the repair, various non-destructive testing (NDT) methods were employed to assess the presence of discontinuities. Firstly, a three point bending test was conducted on an undamaged glass fiber reinforced aluminum sandwich material in accordance with ASTM standards. Upon analysis of the results, it is evident that the material initially exhibited a linear increase within the elastic region, where stress and strain maintained a proportional relationship. Following approximately 2.5 mm of elongation, plastic deformation commenced beyond the yield point, which was represented as a peak in the graph. After this point, permanent shape changes occured.



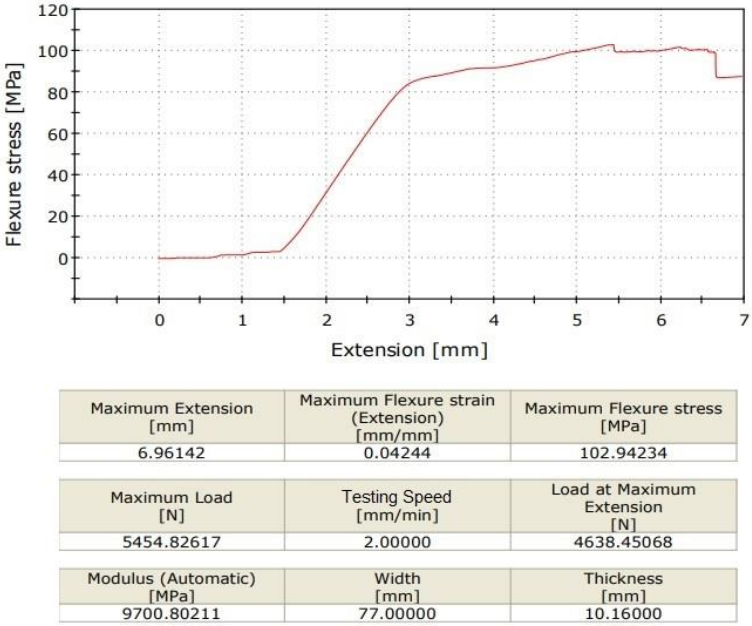
Maximum Extension [mm]	Maximum Flexure strain (Extension) [mm/mm]	Maximum Flexure stress [MPa]
7.91837	0.04827	93.79567

Maximum Load [N]	Testing Speed [mm/min]	Load at Maximum Extension [N]
4970.15186	2.00000	2603.09058

Modulus (Automatic) [MPa]	Width [mm]	Thickness [mm]
9278.30359	77.00000	10.16000

Fig. 18. The bending test result of the undamaged specimen.

Secondly, conducting the three point bending tests on the surface repaired and both surface and core repaired glass fiber reinforced aluminum sandwich materials (Figure 19 and 20), it was proved that repaired specimens displayed bending stress and elongation behavior comparable to that of the undamaged specimen. However, a closer examination of the curves at the yield points revealed a sharp drop in the original specimen, while no such abrupt decrease was observed in the repaired specimens. It was deduced that the presence of filler material may contribute to this observed difference. The results presented in the study shows that the repaired specimens achieved values similar to those of the original specimen. Additionally, the graphs indicate that composite sandwich structures retain resistance to applied forces even following fracture. As a reviewer of this manuscript, it is evident that this research may provide valuable insights for future investigations and contribute to the advancement of repair methodologies for similar structures and to the development of safe and effective repair processes in the aerospace applications by enhancing the quality of maintenance repair applications.

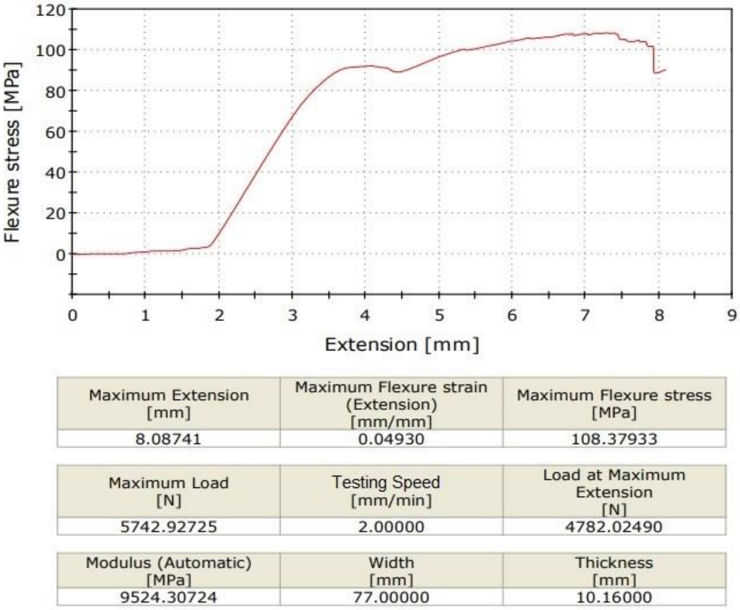


Maximum Extension [mm]	Maximum Flexure strain (Extension) [mm/mm]	Maximum Flexure stress [MPa]
6.96142	0.04244	102.94234

Maximum Load [N]	Testing Speed [mm/min]	Load at Maximum Extension [N]
5454.82617	2.00000	4638.45068

Modulus (Automatic) [MPa]	Width [mm]	Thickness [mm]
9700.80211	77.00000	10.16000

Fig. 19. The bending test result of the specimen with facesheet repair.



Maximum Extension [mm]	Maximum Flexure strain (Extension) [mm/mm]	Maximum Flexure stress [MPa]
8.08741	0.04930	108.37933

Maximum Load [N]	Testing Speed [mm/min]	Load at Maximum Extension [N]
5742.92725	2.00000	4782.02490

Modulus (Automatic) [MPa]	Width [mm]	Thickness [mm]
9524.30724	77.00000	10.16000

Fig. 20. The bending test result of the specimen with both facesheet and core repairs.

This research examined the repair and inspection methods of glass fiber reinforced aluminum sandwich composite materials tested according to aerospace standards and evaluated the conclusions derived from the flexure test. The base material is heavily structured, significantly advancing the understanding of how composites behave under stress, their response to damage, and the repair processes. However, certain aspects of the repair process can still affect damage detection and mechanical test results for composite materials and require further investigation. These factors include:

- Comparison of Repair Approaches: Various repair options are available for composite materials, each offering distinct advantages under specific conditions. While mechanical repair is typically fast and cost effective, it has been observed to result in a gradual loss of strength over time. In contrast, methods such as resin injection, while more permanent and cost effective in the long term, are time consuming and expensive. Studies by Préau and Hubert [6] have demonstrated similar repair approaches, achieving promising results in terms of both structural integrity and durability. Therefore, selecting an appropriate repair method requires careful consideration and a balance of factors based on the specific priorities of the situation. Establishing a standardized approach to repair in aircraft maintenance manuals could help mitigate these challenges and ensure more consistent outcomes.
- Inspection Method Effectiveness: NDT (Non-Destructive Testing) methods are vital for composite safety. Ultrasonic inspection and thermography have been a couple of methods to achieve that of the early damage detection highly accurately. But the accuracy of these tests varies depending on environmental conditions. High temperature and humidity can cause these tests to lose their sensitivity, highlighting the importance of taking them into account across the inspection process.
- The Human Factor Effect: Non-destructive testing operation reduces the risk of human error effect and improves the success of aerospace repair. Nonetheless, the human factor is significant in both the repair phase and non-destructive test. In repair procedures, the human factor is human responsibility that determines whether it will reach the result or not; sincerity with an operator's experience and knowledge makes or breaks the throughput of that process. It is noted that better results, especially in the manual repair operations (experienced and trained operators), have been observed. This implies that procuring human factors support for composite repair efforts can result in an improved average success of the procedure. In the literature study [5], six different repair scenarios were applied. These scenarios achieved results based on the quality of the repairs and highlighted the importance of the human factor.
- Environmental Factors Play a Role: Environmental conditions are the direct influence of repair and inspection success processes. Temperature, humidity, and dust are very essential, especially in resin repairs. High humidity, in particular, will shorten the life of repairs, and dealing with temperature fluctuation is a difficult repair process. Those results reveal issues of environmental control during repair procedures.
- Sustainability and Cost Analysis: The analysis of sustainability and cost associated with repair methods highlights an essential aspect of long term operational efficiency. While some repair methods may appear cost effective initially, as noted in reference [9], the long term financial impact can be compromised due to environmental consequences arising from the materials and methods used. For instance, environmentally harmful repair procedures can lead to higher maintenance costs over time, as the need for more frequent repairs or replacements increases. Witik et al. [10] discusses how these costs can accumulate, particularly when the durability and performance of repairs are adversely affected by improper handling of environmental factors. Moreover, as highlighted by Khalil [11], the use of advanced materials and improved repair techniques, which consider environmental impact, offers significant advantages in terms of both economic viability and ecological responsibility. These approaches ensure a longer service life for the repaired components, reducing the frequency of costly repairs and minimizing waste generation. Thus, the findings from this study reinforce that integrating sustainability into repair practices provides both environmental benefits and long term financial savings, making eco-friendly solutions a favorable option for the aerospace industry.
- Importance of Mechanical Testing: The mechanical tests of data in this study were essential to assess the strength and durability of repaired composite materials. For diagnosis, specifically tensile, compression, and bending tests are essential to evaluate the repair success. The objective of these tests is to look at how close the strength can be made to approaching the repair test result, which testifies to the validity of resin repairability. Examining the deviation rates in the repaired areas of mechanical tests provides rich data in terms of the effectiveness of reliability on these tests in order to judge the performance of the material. As an example study conducted by Tunca and Kafalı [21], it was found that the three point bending test is an effective testing method for the use of composite materials in aircraft.

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Origin of this study is master thesis.

Author Contributions

A.C. and O.T. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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