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Surface Deformation Inspection on Delaminated Flax Laminate for Aerospace Structure Application

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Abstract: Natural fibre-based composites are gaining momentum in the aerospace sector, driven by their sustainable characteristics, including environmental friendliness and renewability, that align with the increasing demand for eco-friendly solutions in aerospace structural applications. However, ensuring the structural integrity of these composites remains critical to meet the aerospace industry's rigorous safety and performance standards. The flax unidirectional prepreg laminates using pressure and temperature-assisted curing methods. To simulate defects, delamination was introduced into the laminates using Teflon tape as an artificial flaw during fabrication. The samples were then cured using two distinct methods: autoclave curing and hot bonder curing. This research applies speckle shearing interferometry method as an advanced non-destructive technique to detect defects, specifically delamination, in flax unidirectional prepreg composites. Defects in autoclave-cured are visibly detected with detection efficiencies ranging from 31% to 41%. The primary objective is to investigate how the curing methods impact the effectiveness of speckle shearing interferometry in identifying these defects. By exploring the interaction between the curing process and the detection capabilities of speckle shearing interferometry, this study aims to provide insights into optimizing inspection methods for natural fibre-based composites, ensuring their reliability and safety in aerospace applications.

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1. Introduction (Section 1)

The growing interest in natural-based composites mainly caused the aerospace industry to adopt sustainable materials. The significant gain of interest in utilizing natural-based fibre, mainly in flax fibres, is due to sustainability factors such as environmentally friendly and renewable materials, which are the primary considerations for integrating flax fibre in aerospace structure applications[1], [2]. However, as natural-based composite continues to evolve in aerospace composite sectors, structural integrity remains crucial to meet stringent safety standards[3], [4]. It needs to be explored to meet the stringent safety standards for aerospace. There is still a lack of research on subsurface damage of flax fiber composites and inspection methods as a final structure application concerning damage inspection method[5].

In the aerospace industry, non-destructive inspection (NDT) ensures that the composite materials used in structural applications are safe and meet the aerospace quality standard[6]. Ultrasonic inspection, radiographic inspection, speckle shearing interferometry, and thermography are the widely used in assessing the integrity of composite materials and damage in NDT methods, including characterisation, without compromising their structural performance [7]. The advancement in NDT techniques aids in characterising the subsurface flaws such as cracks, delamination, and visible impact damage [6]. Nurul et al. highlighted that NDT methods are the preferred choice in the composite industry, especially in the aerospace industry due to their ability to evaluate complex structures, efficiently inspect large areas, and deliver real-time results critical for ensuring quality and safety[8]. Defects such as delamination, voids, and disbands often occur during the fabrication and curing process due to pressure, temperature, or resin flow variations[6], [9]. However, prominent challenges remain in inspecting natural-based composites, especially the subsurface structural flaws. The standard NDT techniques typically do not consider the anisotropic behaviour of natural fibres, which can lead to potential inaccuracies in identifying subsurface defects [10], [11]. Ahmed et al. stated that the NDT technique significantly improves the comprehensive evaluation of imperfections in structure, particularly in composite-based materials and suggests integrating several techniques to improve the detection of subsurface flaws [12]. Although NDT methods have been well-studied in synthetic composites for damage detection, more comprehensive research, established techniques, and methodologies should be needed to focus specifically on natural fiber-based composites. Applying speckle shearing inspection on flax laminate contributes to studying damage characterisation in the natural-based composite as a structure.

Advanced inspection techniques, such as speckle shearing interferometry, provide precise, real-time, and non-invasive defect detection to address these challenges [11]. Senthikumar et al. stated that speckle shearing interferometry is known for its simplicity and high sensitivity, making it an ideal method for inspecting honeycomb structures and laminated composites [11], [13]. Therefore, the sensitivity of the wave is relatively affected by the choice of curing methods and parameters, which can significantly affect the accuracy and efficiency of damage detection using speckle shearing interferometry[14]. The study of the reliability and advancements of NDT methods is crucial to ensuring that their application, particularly in sustainable composites, meets the aerospace industry's stringent safety and performance standards. This research will specifically compare the effectiveness of ultrasonic inspection methods against speckle shearing interferometry in detecting subsurface delamination damages in cured flax fibre composites produced through the curing process of hot bonder and autoclave methods.

2. Methodology

2.1 Material

The material used in this research, manufactured by a France-based company, EcoTechnilin. The FlaxPreg T-UD, is a pre-impregnated unidirectional reinforcement with a fibre areal weight of 100 g/m² with an equal weight of epoxy resin and a surface weight of 200 g/m² [15]. The fibres have a density of 1.45 g/cm³ tailored for composite manufacturing with high mechanical performance and contribute to reducing carbon footprint and environmental impact. The materials are manufactured to meet the demand for lightweight and robust composite materials that enhance automotive and aerospace applications and performance [15]. The unidirectional flax prepreg was selected because it offered the benefit of a controlled and consistent resin content fibre-to-resin ratio throughout the fabrication and curing process [16].

2.2 Sample Preparation

Flax unidirectional prepreg is cut into a dimension of 10 cm (w) x 14 cm (h) and placed into a mould according to the orientation of $[0/90]_{s4}$. Each lay-up laminate set comprises 16 layers of plies with the desired orientation. Every four layers of plies are pressed together for 15 minutes using debulking techniques along with vacuum bagging techniques to make the layers of each ply more compact and reduce the chance of air getting trapped between them [17]. The vacuum bagging utilising vacuum pump pressure of 30 inHg throughout the process of debulking. Delamination defects are replicated using Teflon tape with 2 cm (w) and 2 cm (h), as shown in Figure 1 and 2. The delamination defects are induced at layer eight to ensure the defects are in the middle section of the laminates. The preparation and specimen sample process followed the ASTM Standard D5687/D5687M – 95

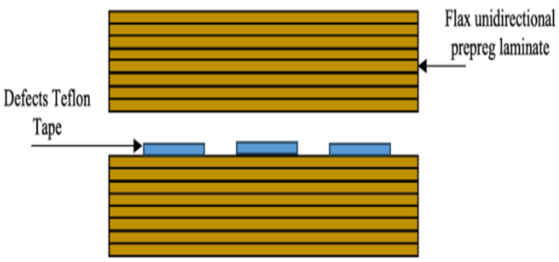

Figure 1. *Teflon tape placed at the middle layer of the flax unidirectional prepreg laminates*

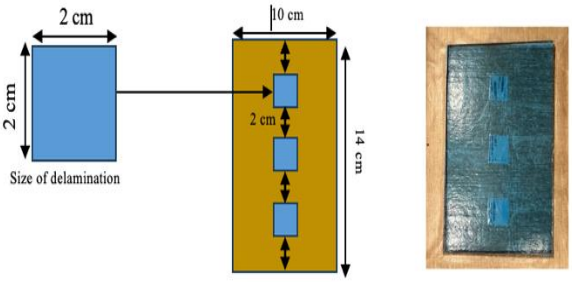

Figure 2. *The size and location of each defect induced on the surface of the ply from a top view*

2.3 Curing Process

After the final lay-up completed, the laminates are cured using two methods. The first method involves an autoclave manufactured by Akarmak, which applies controlled heat and pressure within a sealed chamber as shown in Figure 3 (a). The laminates are pressurise inside the autoclave chamber up to three bars. The aid of a pressurized chamber ensures uniform resin flow and adequate compaction, resulting in minimal voids in the laminates [18]. The second method uses the ANITA 2.0 hot bonder from GMI. The Anita 2.0 system utilizes localized heat and vacuum pump pressure of 30 inHg throughout the curing process as shown in Figure 3 (b). Hot bonder method preferred for on-site repairs or curing applications where an autoclave is inaccessible [19]. Both methods complement each other, offering flexibility to meet various application demands. However, the autoclave excels in producing large-scale, high-performance laminates. At the same time, the hot bonder is a practical choice for specialized or repair-focused tasks in which the final product meets stringent quality standards.


(a) (b)

Figure 3. *Curing methods (a) autoclave machine from Akarmak, and (b) hot bonder ANITA 2.0 from GMI*

2.4 Laser Shearography Inspection

Speckle shearing interferometry consists of a compact design of the NDT method that integrates imaging and control systems manufactured by Dantec Dynamics, Denmark. The inspection was conducted at Skyways Technics Asia Sdn. Bhd. is an approved maintenance organisation. Category C (CAT C) structure repair approval is under EASA 145. Lingtech Instrument Sdn. Bhd. provides the equipment that consists of two Complementary Metal-Oxide-Semiconductor (CMOS) sensors with a specified megapixel (MP), a fixed-focal-length lens, dual Class 3R laser diodes, automated shearing capabilities, and a phase-shifting piezo actuator as shown in Figure 4 a, b, c and d. When the speckle shearing wavelength projected on a surface, an optical effect called speckle pattern are created the cause uneven surface scattered the projected speckle wave into different direction [14]. The scattered speckle wave colluded, creating a bright and dark sports pattern. This anomaly resulted from wave disturbance reflected from the surface, reaching the imaging sensor in irregular phases. The phenomena of the colluded waves influence the intensity captured by each camera pixel and are characterised by bright and dark points, resulting in a speckle pattern [20]. Speckle shearing interferometry analyses changes in the surface displacement when a defect occurs in the structures. When there is a hidden flaw beneath the surface, the surface changes take the measurement of the defect before and after a speckle wave is applied, and the result is based on the localised variations in the rate-of-change (gradient) of out-of-plane deformation [20].

The result appeared in a 2D stereogram of black-and-white fringes identified as a phase map. The integrated software of the equipment applied speckle changes (Δ\Delta) to analyse defects by subtracting images captured at different states [20]. The depth of the defect displacement can be calculated as in Eq (1). The displacement (D) represents the measured displacement or deformation, lambda (λ) is the wavelength of the speckle, delta phi (Δϕ) is the difference between two points related to the deformation or displacement, n (refractive index) is the medium of the speckle wave travels, and 2 is the distance speckle wave travel back and forth [20], [21].

$$\mathbf{D} = \frac{\lambda . \Delta\phi}{\mathbf{2n}} \qquad (1)$$


(a) (b) (c) (d)

Figure 4. *a) The sample are mount for testing, b) measurement for displacement between the sample and flawscout sensor, c) arrangement of flawscout sensor focus for capturing image and d) application of red thermal excitation to the surface*

3. Results and Discussion (Section 3)

3.1 Results of Inspection on Delaminated Flax Prepreg Unidirectional Laminated cured by Autoclave

I. Results of speckle shearing interferometry inspection on three bar Autoclave

The image of flax prepreg unidirectional laminate cured using the autoclave method retrieved from the speckle shearing interferometry analysis shows a visible image of delamination occurred within the subsurface of the sample and are labelled as in Figure 5. Based on the image, all the delamination are able to be measure by the software. Defects of A1 are visible with dimensions measured at 1.42 cm (*w*) and 1.89 cm (*h*). Defects A2 are visible with dimensions measured at 1.30 cm (*w*) and 1.82 cm (*h*), and defects A3 with dimensions measured at 1.53 cm (*l*) x 1.84 cm (*h*). The autoclave curing process utilized a high pressure of three bar, which minimises the laminate structure's void formation. The reduction of void resulted in less disturbance of wave and enhanced the effectiveness of identifying the subsurface defects [22], [23]. Hu et al. explained that reduction of void formation are strongly influenced by the high pressure in the autoclave and crucial in consolidating composite laminate [24]. Santos et al. stated that autoclave processing, though complex in its development, remains a well-established technology and the preferred choice for high-quality composite structure [25]. In conclusion, autoclave processing, the application of high pressure not only minimizes void formation but also consolidates the laminate and improves the effectiveness of laser signals for more precise detection [25], [26]. In conclusion, the results highlight the importance of pressure parameters in curing in relation to enhancing wave propagation and resulting in better inspection efficiency.

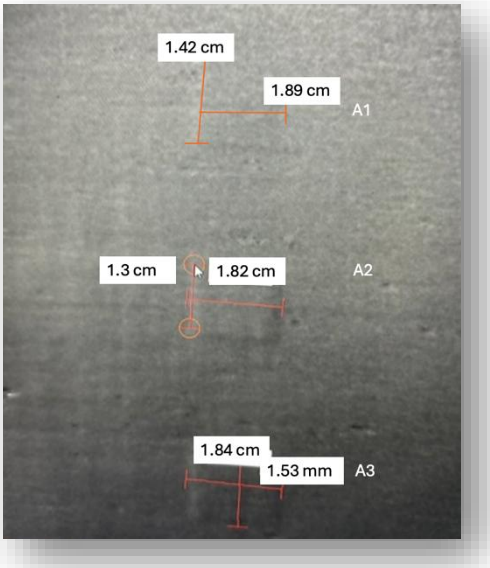

Figure 5. *The image retrieved from speckle analysis on autoclave cured flax laminate*

II. Results of speckle shearing interferometry inspection on hot bonder cured laminate

The image shows a flax unidirectional prepreg laminate cured using a hot bonder with an assisted pressure of 28 inHg. No visible defects were detected in the image as shown in Figure 6. The undetectable defects are due to the factors related to the hot bonder method, the applied pressure, and the natural characteristics of flax fibres. The hot bonder method uses localized heat and vacuum pressure of 30 inHG from a pump to cure laminates. Compared to autoclave methods, hot bonders was unable to provide and ensure uniform pre ssure distribution across the entire laminate. The flax fibres, as a natural material, introduce additional variability[19]. Unlike synthetic fibers, flax fibers can exhibit uneven distribution, micro-voids, or inconsistent resin absorption [27]. The applied pressure of 30 inHg (approximately one bar) is relatively low compared to autoclave systems operating at three bar or higher pressures inside an enclosed chamber. The lower pressure might not have been sufficient to consolidate the layers of the laminate, leaving the potential for internal voids or incomplete bonding, creating a significant surface deformation and making them undetectable with speckle shearing interferometry[8], [28]. Anisimov et al. mention that the pressure factor and void formation cause unnoticeable surface strain that speckle shearing interferometry can detect [29]. In conclusion, the efficiency of defect detection is related to optimizing the hot bonder process. In their study on out-of-autoclave composites, Chong et al. highlighted that the composite laminates cured using hot bonding with vacuum bagging exhibited a higher porosity level of 3.5% ± 1.5% [17], [30]. This increased porosity was attributed to the insufficient pressure applied during the process, which could not fully consolidate the laminate and eliminate entrapped air. Controlling the temperature and vacuum pressure can lead to more consistent resin flow and improved bonding quality. Sun al. suggested that the speckle shearing inspection should focus on applying the inspection material particularly on natural based fibre to analyze future trends potential and limitation [31]. Addressing these factors through process optimization and additional testing methods could enhance defect detection and overall laminate quality.

It can be concluded that based on both image retrieval and results of the dimension of the defects, the research results show high pressure of three bar pressure achieved from the autoclave chamber relatively enhances the defect detectability in flax-based composite laminate compared to hot bonder curing that deliver one bar of assisted pressure from vacuum pump as shown in Figure 7 (a) and (b). Flax laminate cured using autoclave methods demonstrated clear visibility of defects and were measurable, with detection efficiencies ranging from 31% to 41% as show in Table 1. In contrast to the flax laminate cured using a hot bonder, no visible defects were identified. The findings show that the speckle shearing interferometry inspection effectiveness are relatively dependent on the curing pressure value to consolidate the laminate. Flax-based composite produced by the autoclave curing process can achieve high-quality laminate and reliability in composite manufacturing, as it enhances the efficiency of inspection for NDT purposes[32].

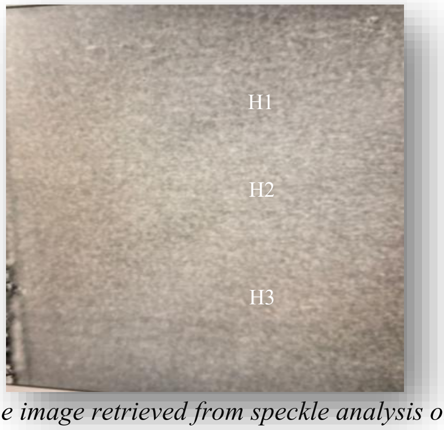

Figure 6. *The image retrieved from speckle analysis on hot bonder cured flax laminate*

Table 1. The summarize of efficiency of defects detection in comparison of autoclave and hot bonder

Methods Curing	**Autoclave**			**Hot Bonder**
Pressure (PSI)	3 bars			1 bar
Location of Defects	**A1**	**A2**	**A3**	**H1 – H3**
Measurement of the defect (cm)	2.68 cm	2.36 cm	2.76 cm	0 cm
Efficiency of detection (%)	33 %	41 %	31 %	0%
Visual Defect Visibility	Detectable			Undetectable

**Notes A-Autoclave cured laminates and H-Hot Bonder cured laminates*

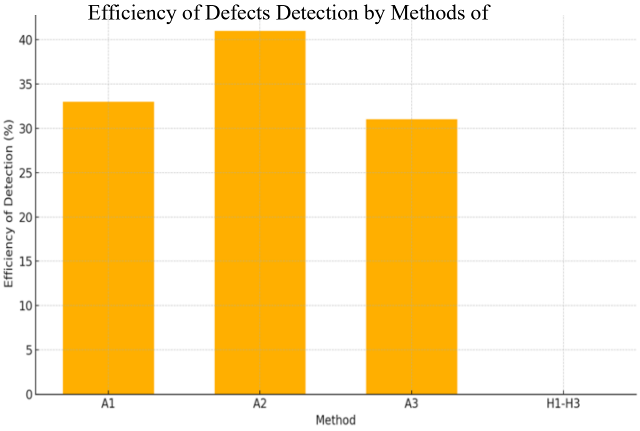

Figure 7. *The results of efficiency of defects detection in comparison of autoclave versus hot bonder laminates*

4. Conclusion

In conclusion, based on the speckle shearing interferometry inspection can be concluded as following;

1. Based on the results, pressure factors play a vital role in consolidating and enhancing the bonding within the plies of laminates. It indicates that a pressure of 30 inHg (approximately one bar) provided insufficient consolidation compared to autoclave curing, which provided higher pressures of three bars. Insufficient pressure resulted in incomplete bonding and did not minimize the formation of subsurface voids, resulting in surface deformations and interference with the efficiency of detection by speckle shearing interferometry.
2. Regarding curing methods for natural-based fibre composite, the autoclave can deliver higher and uniform pressure distribution and layer compaction, resulting in minimal void content and improved inspection quality. The hot bonder method is more suitable for localized or small-scale curing, as the hot bonder is unable to provide high pressure and depends on the vacuum pressure from the pump to ensure uniform curing across the entire laminate. Defects in autoclave-cured samples were measurable and visually detectable, with detection efficiencies ranging from 31% to 41%. It highlights the advantages of autoclave curing for high-performance laminates, especially for natural fibres like flax, which are prone to variability.

Further work could involve a comparative analysis of enhancing the pressure factor on hot bonding methods and their influence on the structural integrity of natural fibre composites, as well as the development of multi-modal defect detection techniques to complement speckle shearing interferometry.

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