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Research Article

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Study of Drilling-Induced Damage in Water-Degraded Natural Fibre Composites

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ABSTRACT

Composite materials have experienced a growing adoption in high consumption industrial sectors such as transportation, aeronautics and aerospace, owing to their high specific strength, low density and design versatility [1,2]. However, their heterogeneous and anisotropic nature makes them particularly susceptible to several damage mechanisms, including matrix cracking, fibre breakage, delamination and interfacial degradation [3-5].

During drilling operations, many of these mechanisms occur simultaneously. Among the most common are fibre rupture, interlaminar delamination and matrix cracking, resulting from the thrust force and torque applied by the cutting tool [6,7]. Delamination, in particular, is widely recognised as the most critical failure mode, as it can significantly compromise the structural integrity of the component [8].

The objective of this study was to quantify the damage induced by drilling in natural fibre reinforced composites, assessing the influence of moisture induced degradation on their mechanical behaviour. For this purpose, specimens were prepared for tensile, flexural and bearing tests, enabling the evaluation of structural performance under different integrity conditions.

A portion of the laminated composites was submerged in water for a controlled period until saturation was reached, promoting degradation through moisture absorption.

This process is known to reduce fibre–matrix adhesion, induce matrix plasticization and accelerate delamination phenomena [9,10]. After saturation, the specimens were exposed to ambient air to allow natural evaporation, completing a hygroscopic ageing cycle that intensifies the deterioration of mechanical properties.

Subsequently, the specimens were drilled and subjected to radiographic inspection. The radiographic images were digitally processed using MATLAB®, enabling segmentation of the damaged region and quantification of the delaminated area. Based on these measurements, several delamination factors proposed in the literature were calculated, allowing a quantitative assessment of drilling induced damage [11-13].

Finally, bearing tests were conducted to evaluate the loss of mechanical strength associated with the combined effects of moisture degradation and drilling. The results were compared with previous studies to contextualize the impact of humidity on the structural integrity of the composites.

The results revealed a significant reduction in mechanical properties when the composite was first exposed to moisture and subsequently drilled. Therefore, the interaction between these two factors is critical for understanding the mechanical behaviour of natural fibre reinforced composites, corroborating findings reported in recent studies [7,9,14].

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Introduction

Composite materials are formed by combining two or more distinct constituents that, when integrated, exhibit superior properties compared to those of each component individually. These materials have gained widespread industrial relevance as alternatives to conventional materials due to their excellent mechanical performance, low density, high stiffness and favourable strength to weight ratio [1,2].

The purpose of this study is to analyse the mechanical performance of a natural fibre reinforced composite, with particular emphasis on its sensitivity to moisture exposure and on the damage generated during drilling—an essential machining process commonly used for non permanent mechanical fastening.

Delamination is the predominant damage mechanism associated with drilling and occurs on both sides of the laminate: at the drill entry and exit.

When the drill bit penetrates the upper surface, fibre pull out initiates in the first layers due to the cutting forces applied by the tool.

Conversely, during the final stage of drilling, the tool behaves like a punch, and the thrust force exceeds the interlaminar strength, promoting fibre separation and delamination on the exit side [6,7].

Both mechanisms represent a significant structural risk, reinforcing the importance of controlling drilling parameters and selecting appropriate tooling to minimize machining induced damage in composite materials.

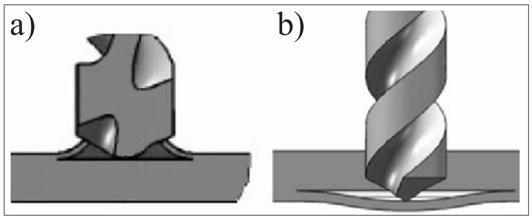

Figure 1: Drilling process: a) entry b) exit [4]

For the drilling operation, a 6 mm Brad point drill bit was used, operating at 1120 RPM with a feed rate of 0.05 mm/rev.

After drilling, it is necessary to evaluate the extent of delamination using image processing techniques to determine the diameter and area of the damaged region.

The extracted data are used to quantify delamination through several damage indices proposed in the literature. Table 1 summarizes the most commonly used delamination factors.

Table 1: Delamination Parameters [11,12]

Author	Delamination Factor	Fórmula	Limitations
Chen	Conventional Delamination Factor (F_d)	$F_d = \frac{D_{\max}}{D_{nom}}$	Damage area is not considered
Da Silva	Minimum delamination Factor (F_{dmin})	$F_{d\min} = \frac{D_{\max}}{D_{nom}}$	Damage area is not considered
Mohan et al.	Delamination Factor (F_d)	$F_d = \frac{A_d}{A_{nom}}$	Maximum Diameter is not considered
Tsao et al.	Equivalent Delamination Factor (F_{eq})	$F_{eq} = \frac{1}{D_{nom}} \sqrt{\frac{4(A_d + A_{nom})}{\pi}}$	Maximum Diameter is not considered
Xu et al.	Three-dimensional Delamination Factor (F_v)	$F_v = \frac{1}{p} \sum_{k=1}^{p} \frac{A_d^k}{A_{nom}}$	Maximum Diameter is not considered
Faraz et al.	Two-dimensional Delamination Factor (F_a)	$F_v = \left(\frac{A_d}{A_{nom}} \right) \%$	Maximum Diameter is not considered

In the image processing stage, MATLAB® was used. RGB radiographic images were converted to grayscale and subsequently to binary format (black and white), facilitating the identification of boundaries between the drilled hole and the damaged region.

In the binary conversion, each pixel is assigned a value of 0 (black) or 1 (white), forming a two tone matrix that enables precise contour detection.

This technique, known as thresholding, applies a threshold value that separates grayscale intensities into two categories. This enhances the visibility of the damaged region and allows the generation of well defined contours around the hole. The threshold may be determined automatically using statistical classification algorithms or manually adjusted when automatic segmentation fails to produce continuous and accurate boundaries.

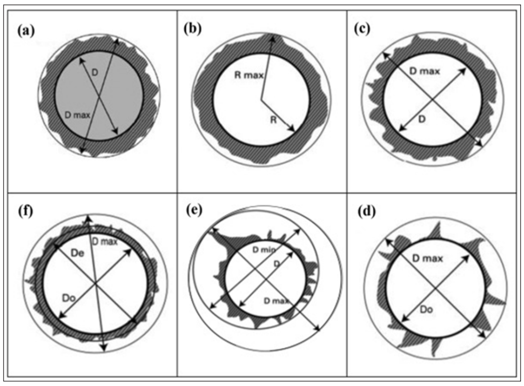

Figure 2: Schematic diagrams of delamination fator evaluation: (a) Conventional Factor; (b) Delamination size; (c) 2D Factor; (d) Adjusted Factor; (e) Minimum Factor; (f) Equivalent Factor [11]

Once segmentation is complete, the algorithm computes the damaged area, the whole area, and the radius of the circumscribed circle.

These measurements enable the calculation of the delamination factors previously described, providing a quantitative assessment of drilling induced structural degradation.

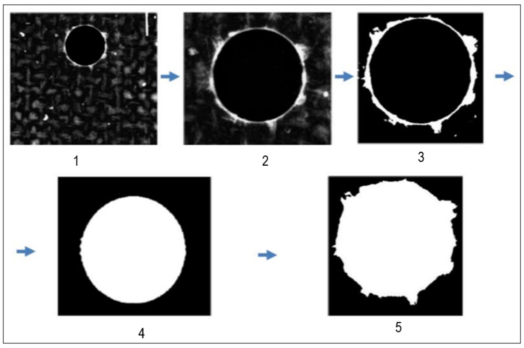

Figure 3: 1) X-Ray Image 2) Region Selection 3) Binary Image 4) Hole Area 5) Hole and Damage Area [12]

Metodology and Results

The specimens used in this study were obtained by cutting laminated composite plates manufactured in previous works [12]. The experimental programme included a controlled degradation stage, drilling operations, radiographic inspection, digital image processing and mechanical testing.

Moisture-Induced Degradation

The specimens were immersed in tap water to promote moisture absorption and induce degradation.

Once the maximum saturation level was reached, the specimens were removed from the water and allowed to dry at ambient temperature until stabilizing at the saturation limit of moisture loss. This absorption–desorption cycle is known to weaken the fibre–matrix interface, promote fibre swelling, induce microcracking and reduce the mechanical performance of natural fibre composites [9,10].

The results obtained in this study were compared with previous works conducted by B. M. Silva and S. C. J. Silva [11] and by H. Seixas and I. Ferreira [12].

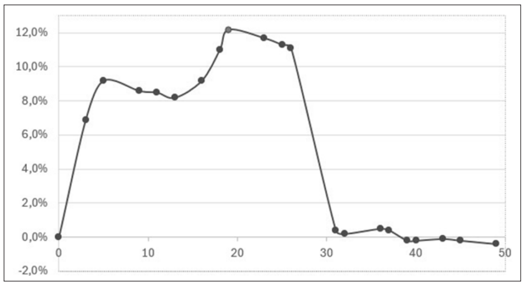

Figure 4: Specimen degradation process (X-axis: days; Y-Axis: Weight Variation)

Four material conditions were analysed:

- ND – Non degraded
- D – Degraded
- FD – Drilled before degradation
- DF – Degraded before drilling

Tensile and Flexural Testing

Tensile tests were performed according to ISO 527 4 [15], while flexural tests followed ISO 178 [16].

A comparison between degraded (D) and non degraded (ND) composites is presented in Table 2.

Table 2: Mechanical Test Comparison [11]

	Tensile Strength [MPa]	Maximum Strain [%]	Elastic Modulus [MPa]
Tensile (D)	43,8 ± 5,8	3,60 ± 0,05	2601 ± 346
Tensile (ND)	66,59 ± 1,78	1,83 ± 0,09	6584,7 ± 80,69
Flexural (D)	91,23 ± 2,94	4,3 ± 0,9	4396,8 ± 279,8
Flexural (ND)	105,62 ± 4,74	4,69 ± 0,20	6605,9 ± 350,83

Moisture degradation significantly compromises fibre–matrix cohesion, resulting in reduced mechanical strength, as evidenced by the tensile tests.

Tensile strength decreased by 34%, while flexural strength decreased by 14%. The tensile modulus decreased by 60.5%, and the flexural modulus by 33.4%.

These results are consistent with the expected behaviour of natural fibre composites subjected to hygroscopic ageing [9,14].

Radiographic Inspection and Image Analysis

Radiographs were obtained using a SATELEC X ray system equipped with a Toshiba DG 073B detector. Diiodomethane was applied for 15 minutes as a contrast agent. Exposure time was 0.16 s.

Linear and area measurements were extracted through digital image analysis, using pixel based quantification. Conversion to SI units was performed using the following calibration factors [12]:

- 1 pixel = 0.0185496 mm
- 1 pixel^2 = 0.00034375 mm^2

Table 3: Image Analysis Results

	Perimeter [mm]	Hole Area [mm^2]	Damage Area [mm^2]	Circumscribed Radius [mm]
	46,7079	29,3288	6,2593	4,77
	34,1869	29,1758	6,5625	3,96
	32,3691	29,4011	6,7953	4,00
Mean	37,76	29,30	6,54	4,25
Std. Dev.	7,81	0,12	0,27	0,45

Table 4 compares these results with previous studies.

Table 4: Comparative Image Analysis

Condition	Perimiter [mm]	Hole Area [mm^2]	Damage Area [mm^2]	Circumscribed Radius [mm]
ND	22,878 ± 1,15	28,681 ± 0,38	3,743 ± 0,53	3,878 ± 0,15
DF	37,76 ± 7,81	29,30 ± 0,12	6,54 ± 0,27	4,25 ± 0,45
FD	44,556 ± 3,57	28,866 ± 0,29	8,86 ± 0,95	4,535 ± 0,25

The FD specimens exhibited the largest delamination areas, confirming that drilling before degradation promotes microcrack formation and facilitates water ingress [11,12].

Bearing Tests

Bearing strength was determined according to ASTM D5961/D5961M [17].

Table 5: Bearing Tests Results

Specimen	Thickness [mm]	Diameter [mm]	Area [mm^2]	Force [N]	Bearing Stress [MPa]
Provete 1	4,4	9,54	41,976	3626,331	86,39
Provete 2	4,4	7,92	34,848	3647,455	104,67
Provete 3	4,6	8	36,8	3662,825	99,53
				Mean	96,86
				Std. Dev.	9,43

Table 6: Comparative Bearing Strength

Condition	Bearing Stress [MPa]
ND	136,9 ± 13
DF	96,86 ± 9,43
FD	91,94 ± 6,26

Bearing strength decreased significantly in degraded and drilled specimens, especially in FD samples.

Delamination Factors

Delamination indices were calculated according to several authors.

Table 7: Delamination Factors

Condition	Chen	Faraz [%]	Mohan	Tsao
ND	1,365 ± 0,08	15,4 ± 2,8	0,154 ± 0,03	1,074 ± 0,01
DF	1,414 ± 0,15	24,4 ± 0,6	0,244 ± 0,006	1,086 ± 0,015
FD	1,512 ± 0,08	31,4 ± 3,4	0,314 ± 0,03	1,422 ± 0,004

All models showed higher delamination in degraded specimens, with FD presenting the worst performance.

Dimensionless Damage Index

A dimensionless comparison was performed using

$$\frac{\sigma_B}{\sigma_{Tensile\,ND}} \quad (1)$$

Table 8: Dimensionless Index

CONDITION	$\frac{\sigma_B}{\sigma_{Tensile\,ND}}$
ND	2,06
DF	1,45
FD	1,38

Table 9: Percentage of Damage Absence

	Ausência de dano
ND	100 %
DF	70%
FD	67%

FD specimens showed the lowest structural integrity, confirming that drilling before degradation exposes fibres, increases water absorption, and accelerates mechanical deterioration.

Conclusions

The analysis of the effect of tap water immersion on jute fibre natural composites revealed that the degradation rate is directly related to the exposed surface area in contact with moisture.

This behaviour is consistent with the hygroscopic nature of lignocellulosic fibres, which absorb water rapidly due to their hydrophilic chemical structure [9,10].

The combined action of drilling and moisture exposure significantly intensifies the degradation process, as drilled holes increase the available surface area and act as stress concentration sites.

These regions facilitate water ingress and accelerate the loss of fibre–matrix adhesion, a mechanism widely reported in natural fibre composite ageing studies [5,14].

As a result, the composite becomes more susceptible to interfacial debonding, fibre swelling, and microcrack propagation.

This degradation leads to a substantial reduction in mechanical strength, evidenced by lower load carrying capacity and increased deformation under applied stress.

The difficulty in obtaining low noise radiographic images limited the precision of digital image analysis, highlighting the need for improved imaging conditions or alternative non destructive evaluation techniques.

This limitation motivated the development of an alternative damage assessment methodology, which, although promising, still requires validation across different composite systems.

Overall, the damage indices employed in this study proved effective for quantifying drilling induced damage in moisture degraded natural fibre composites.

Nevertheless, enhancements in image acquisition and processing are recommended to improve accuracy in future investigations.

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References

1. Hsissou R, Bekhta M, El Idrissi M, Elharfi M. Polymer composite materials: A comprehensive review, Composites Part B: Engineering. 2021. 212: 108675.
2. Friedrich K, Almajid AA. Manufacturing aspects of advanced polymer composites for automotive applications, Applied Composite Materials. 2013.
3. Moreira LHM. Identification and quantification of damage in composite material structures via digital image correlation applied to machine learning, M.Sc. Thesis in Mechanical Engineering, State University of Santa Catarina, Brazil. 2020.
4. Coelho BMA. Defect detection in composite materials using ultrasound technology, M.Sc. in Polymer Engineering, University of Minho, Guimarães, Portugal. 2020.
5. Harding J. Composite materials: properties, testing and applications, Materials Science Forum. 2015.
6. Durão LM, Gonçalves DJS, Tavares JMRS, Albuquerque VH, Panzera TH, et al. Study of Delamination Associated with Drilling in Glass Fiber and Sisal Reinforced Composites, CMNE'2011 – Congress on Numerical Methods in Engineering, Coimbra, Portugal. 2011.
7. Davim P. Drilling of composite materials, Springer. 2013.
8. Abrate S. Impact on composite structures, Cambridge University Press. 2005.
9. Jawaid M, Abdul Khalil HPS. Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review, Carbohydrate Polymers. 2011.
10. Dhakal A. Water absorption behaviour of natural fibre composites, Composites Science and Technology. 2007.
11. Silva BM, Silva SCJ. Study of Drilling Damage in Natural Fiber Composites, Final-year project, B.Sc. in Industrial Production Engineering, ISVOUGA, Portugal. 2023.
12. Seixas HJL, Ferreira IAN. Study of Drilling Damage in Natural Fiber Composites, Final Year Project, B.Sc. in Industrial Production Engineering, ISVOUGA, Portugal. 2022.
13. Tsao L. Delamination analysis in drilling composite laminates, Journal of Composite Materials. 2012.
14. Chandra SP. Moisture-induced degradation in natural fibre composites, Polymer Degradation and Stability. 2019.
15. Plastics: Determination of tensile properties-part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites. 2021. 527-534.
16. Plastics - Determination of flexural properties, ISO, Geneva, Switzerland. 2019. 178.
17. Standard Test Method for bearing response of polymer matrix composite Laminates, ASTM International: West Conshohocken, PA, USA. 2017. ASTM D5961/D5961M-17.