

Durabilité des structures composites renforcées en fibres de lin: caractérisation des performances mécaniques et environnementales.

Durability of flax fiber reinforced composite structure: characterization of mechanical and environmental performances.

Sandeep Kumar GANTALA¹, Benoît PIEZEL¹, Clémence ROUGE¹ et Olivier SICOT¹

1 : Université Bourgogne Europe, DRIVE
49, rue Mademoiselle Bourgeois, 58000, Nevers
e-mail : Sandeep-Kumar.Gantala@u-bourgogne.fr, benoit.piezel@u-bourgogne.fr,
clemence.rouge@u-bourgogne.fr, Olivier.Sicot_isat@u-bourgogne.fr,

Résumé

Les composites renforcés de fibres de lin (FFRC) suscitent un intérêt croissant pour le remplacement des composites traditionnels dans les applications industrielles semi-structurelles offrant des propriétés mécaniques spécifiques avantageuses et leur empreinte environnementale réduite. Cependant, la plupart des études d'impacts environnementaux ne prennent pas en considération la durabilité durant la phase d'utilisation par la difficulté à prendre en compte la sensibilité aux facteurs climatiques des FFRC. Cette étude est réalisée via une analyse du cycle de vie (ACV) sur une pale d'éolienne à axe verticale et fabriquée en lin-polypropylène (PP). La durabilité de ces FFRC est déterminée en extérieur par des facteurs tels que la température, l'humidité relative et l'irradiation UV qui affectent donc leur durée d'utilisation. Une chambre climatique sera utilisée pour induire des mécanismes de dégradation accélérés et qui représentent trois climats distincts, tropical, tempéré et désertique. Des tests de traction, de flexion et de caractérisation physico-chimique sont effectués au cours des vieillissements naturels et accélérés pour déterminer l'effet des facteurs climatiques sur la résistance mécanique du lin-PP. Par correspondance entre les deux types de vieillissement, les facteurs qui influencent ces performances pourront être déterminés et les durées de vie des pales estimées et intégrées à l'ACV.

Abstract

Flax fiber-reinforced composites (FFRC) have attracted interest as substitutes for traditional composites in semi-structural industrial applications, offering specific mechanical properties and reduced environmental footprints. However, current environmental impact studies of FFRCs do not account for their durability during the use phase owing to the difficulty of considering the sensitivity of FFRCs to climatic factors. This study employs a life cycle assessment (LCA) performed on a vertical-axis wind turbine blade made of flax-polypropylene (PP) by considering their durability. The durability of these FFRCs is determined by outdoor factors such as temperature, relative humidity, and UV irradiation, which consequently affect their service life. A climate chamber will be used to induce accelerated degradation mechanisms representing three distinct climates: tropical, temperate, and desert. Tensile, flexural, and physicochemical characterization tests will be carried out during both natural and accelerated aging to determine the effect of climatic factors on the mechanical strength of flax-PP. By correlating the two types of aging, the factors influencing these performances can be identified, and the service life of the blades can be estimated and incorporated into the LCA.

Mots Clés : Composites en fibres de lin, polypropylène, durabilité, ACV, caractérisation mécanique

Key Words: Flax fiber composites, Polypropylene, Durability, LCA, Mechanical characterization

1. Introduction

Flax fiber-reinforced composites (FFRC) have been extensively researched for the past two decades [1, 2, 3]. Due to their relatively low cost, low density, specific properties, and reduced environmental impacts, flax fibers have been considered as prospective substitutes to synthetic

fibers, especially glass fibers. FFRC applications are widely spread across various industries, namely automobiles,



Fig. 1. Examples of applications of FFRC: Paddle’s blade, car bonnet and a bicycle frame [3]

construction, and sports [4] as mentioned in Fig. 1. Flax fibers have a great potential among natural fibers for achieving sustainable objectives in composite constituents, which necessitates understanding their environmental performance. Martin et al. [1] compared the environmental impacts of an under-floor panel of the Mercedes A class manufactured with glass fiber-reinforced polypropylene with flax-fiber reinforced polypropylene. As shown in Fig.2., the flax fiber reinforced panel scored better across all environmental impact categories studied. Additionally, the total non-renewable energy requirement for the manufacture of glass mats (54.7 MJ/kg) is nearly 6 times higher than that of flax fiber mats (9.55 MJ/kg).

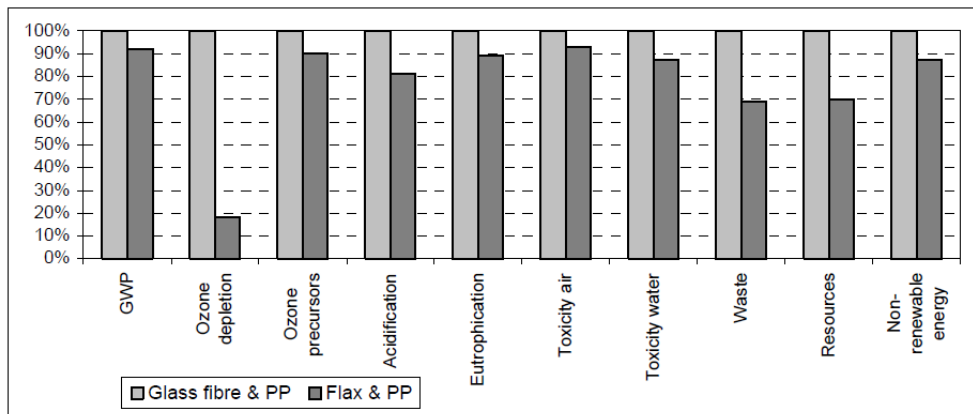


Fig.2. Environmental impacts for the production of fiber reinforced automobile panel [1]

As environmental awareness is increasing, various composite industries are exploring strategies to improve the environmental performance of their products [2]. Currently, Life Cycle Assessment (LCA) is amongst popular methods to analyze and quantify the environmental effects of a product during its lifetime.

The implementation of LCA involves systematic analysis of energy consumption and potential environmental impacts starting from the raw material extractions to a product’s end-of-life. LCA considers all relevant inputs (resources and energy) and outputs (waste gases, wastewater and solid waste) to evaluate environmental releases [4]. Technically, LCA provides a comprehensive understanding of environmental implications by compiling and quantifying inputs and outputs throughout the entire life cycle of a product.

LCA is performed by considering all the major processes within the flax fiber composite life cycle, namely flax fiber and resin extraction, manufacturing, usage phase, and end of life. Although, there have been some published results [5] on the environmental performance of flax fiber composites,

they are limited to certain phases, especially flax fiber extraction and composites manufacturing. To fully understand the environmental impacts of these composites, the use and end-of-life phases must be examined along with the above-mentioned phases.

In 2016, Le Duigou et al. [6] compared the environmental impacts of an automobile panel made of flax mat reinforced Polypropylene (PP) with the conventional glass fiber mat PP mainly concentrated on usage phase. The life cycle analysis of the flax mat panel demonstrates a lower environmental impact than glass mat panel because the flax fiber mat panel is lighter, reducing the weight of the automobile and fuel consumption over its lifetime. However, the author's analysis focused on 200,000 km functional life span of an automobile rather than the lifetime of the panel. Regardless of the type of natural fiber, their inherent characteristics lead to the varying response to diverse climatic factors, which in turn impacts the properties of natural fiber reinforced composites and their service life. [7]. When performing LCA for usage phase, determining the life span of the composite structure provides a more accurate representation than the life span of an end application.

The life span of composites can be obtained by studying their long-term durability. FFRCs are susceptible to environmental parameters due to the highly hydrophilic nature of flax fiber and sensitivity of the thermoplastic matrix to elevated temperatures. Whenever these composites are exposed to outdoor climatic conditions, they can experience hygrothermal aging, photo-oxidation, and thermal oxidation, all of which can negatively impact the mechanical performance and long-term durability of flax fiber composites [8]. Alam et al. [9] investigated the mechanical properties of flax fiber-reinforced polypropylene composites subjected to the aforementioned degradation phenomena through accelerated aging finding that tensile modulus and strength of composites were decreased by around 12% and 23%, respectively, after 504 h of aging. This degradation was primarily attributed to the matrix embrittlement and polymer chain scission caused by photooxidation. These findings emphasized the importance of considering the different degradation mechanisms induced by diverse climatic conditions and their combined effect on durability and life span of FFRCs. The objective is to conduct a LCA on FFRC structure, by considering their life span as usage phase.

2. Materials and Methodology

To perform LCA, it is required to have a specific composite structural application. After reviewing existing fiber reinforced composite applications, by following the selection criteria: the structure should be exposed to outdoor environment, have some relevance to the fiber reinforced composites and it must be manufacturable within the laboratory equipment and resources, H-Darrieus vertical axis wind turbine was selected as our application Fig. 3. with the wind turbine rotor blade as the structural element of interest. In this work, rotor blades with 3 mm thickness will be manufactured by using commercial twill weave textile preform named Lincore, made by hybrid yarns which contain commingled flax and polypropylene fibers with a volume fraction of 40/60 provided by Depestele.

For a life cycle assessment, a functional unit must be defined to quantify the system's function in terms of its service. For this work, the functional unit is the energy generated by a single rotor blade, over its lifetime Eq.1.

$$E = \int_0^T \int_{V_{min}}^{V_{max}} P(V, t) * f(V) dV dt \quad \text{Eq.1.}$$

where E is the collected energy (J), T is the life span of the rotor blades (years), P is the power generation at a particular time which depends on wind velocity (V) and environmental factors like

Temperature, Relative humidity, UV irradiance as rotor blades are made of flax fiber composites, in service climatic conditions has a direct influence on power generation whereas f represents the wind speed distribution at a particular geographical location.

To develop LCA models using Simapro LCA software, detailed data for each phase in Fig.4. will be gathered from literature reviews and ecoinvent life cycle inventory databases which includes information on the percentages of raw materials, processing details, energy consumption, different emissions, and real-time data from the manufacturing machines and corresponding resources.

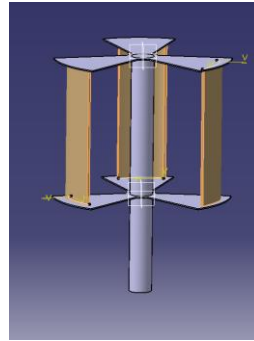


Fig.3. CAD model - H-Darrieus vertical axis wind turbine

Concerning the usage phase, the life span (T) of the rotor blades will be determined by studying their long-term durability. Typically, the life span of wind turbine rotor blades depends on wind speed and corresponding mechanical loading conditions over time. However, in this study, rotor blades are made of flax fiber and polypropylene, which are highly sensitive to climatic conditions that can significantly impact the mechanical characteristics and the corresponding power generation during their lifetime. To better understand how different environments influence the rotor blades life span, three regions with distinct climates - tropical, temperate, and dessert were chosen according to the Köppen–Geiger climate classification.

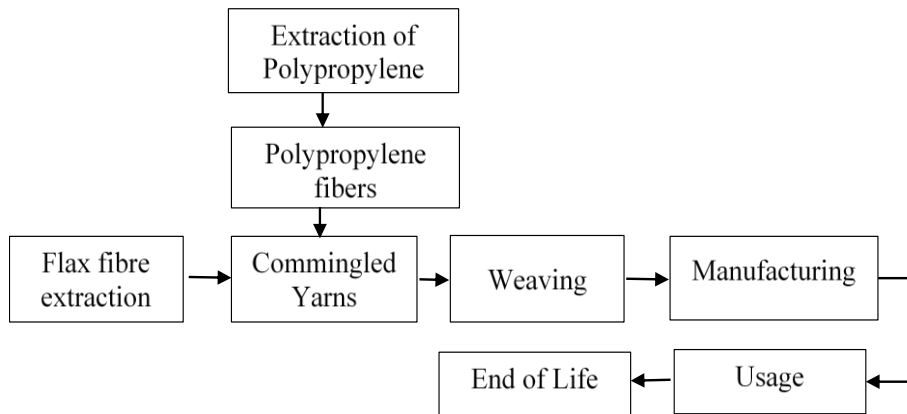


Fig.4. Major processes in LCA of Wind turbine rotor blade made of commingled flax and PP fiber preform

3. Experimental design and methodology

Under these different climatic conditions, the long-term durability of rotor blades will be conducted to define their life span. Studying the long-term durability of rotor blades made of flax and PP is a complex challenge because several factors like fiber nature, matrix behavior, type of reinforcement, and external factors like loading and environmental conditions will affect durability.

Before studying the long-term durability of rotor blades, it is crucial to understand the long-term durability of FFRCs at macro scale by manufacturing the composite specimens with the same 3 mm thickness as rotor blades. By examining how different climate factors and their corresponding degradation mechanisms, and manufacturing process parameters affect the physical and mechanical characteristics of FFRCs at the micro scale, a detailed overview can be obtained for characterizing the performance and properties of rotor blades. This, in turn will aid in identifying key factors and methodology needed to accurately define and predict the life span of the rotor blades.

In this context, the long-term durability of FFRCs will be studied at two scales: one is at the macro scale, and another one is at the structural scale (rotor blade). Different aging tests are available, namely natural aging and accelerated aging, to evaluate the aging behavior of composites under varied conditions. For macro and structural scale, both natural and accelerated aging experiments will be conducted. To have a better representation between natural and accelerated aging, the modified Arrhenius principle will be employed to derive an acceleration factor, which provides an estimation of how much natural exposure time is equivalent to accelerated aging conditions [7].

Accelerated aging experiments will be performed in the Q-Sun accelerated climatic chamber equipped with xenon arc lamps providing an irradiance of 0.51 W/m^2 at 340 nm. To represent outdoor weather-induced degradations from tropical and temperate climate, laboratory weathering of composites based on ISO 4892.3 cycles, which has 102-min dry phase (UV irradiation) with a relative humidity of 65% followed by 18-min of wet phase (water spray), will be adopted, whereas for desert climate, 2 hours of complete dry phase will be implemented. This could reasonably simulate the sunlight in the ultraviolet and partly visible regions, aiming to mimic the outdoor weathering behavior in a shorter time interval.

By following this method, initial experiments will be conducted on a macro scale, subjecting composite specimens to 90 days of accelerated aging comprising dry/wet cycles representing temperate and tropical climate and 90 days of dry cycle representing desert climates. Parallely, composite specimens are exposed to natural aging by placing them in an outdoor environment. The tensile and flexural strength of the composites will be evaluated at regular intervals to assess the effects of the dry phase and the combination of dry and wet phase on their properties. Alongside, multiscale characterization of composites will be performed to evaluate various phenomena, including moisture absorption, thickness swelling, and color spectroscopy for photodegradation.

Similar experiments will also be conducted on the structural scale by following the same approach, subjecting rotor blades to 90 days of accelerated aging. This will allow an understanding of how the performance of FFRCs varies from the macro level to the structural level under similar accelerating aging conditions. Using the acceleration factor, the performance of rotor blades after 90 days of accelerated aging will be estimated to a certain number of days in natural aging. Furthermore, outdoor weathering experiments of rotor blades will be carried out for 1 year by installing wind turbines in Nevers, France which represents a temperate climate.

During this 1-year period, the electricity generation from the wind turbine will be evaluated, and the impact of mechanical and environmental loading conditions on power generation will be analyzed. After 1 year of natural aging, the flexural bending strength of the rotor blades will be calculated and compared with the initial strength. Additionally, the strength of naturally aged rotor blades will also be compared to the accelerated aging results to understand the strength degradation trend over time. By considering this strength of the rotor blades and assuming similar degradation phenomena, the estimated strength of rotor blades will be extrapolated over time until the allowable strength is reached, to determine the life span of the rotor blades under temperate climatic conditions. Similarly, the life span of the rotor blades will be evaluated under tropical and dessert climatic

conditions. By incorporating this life span (T) as a usage phase, a complete LCA of FFRCs will be provided.

The preliminary results of FFRCs at macro scale subjected to accelerated aging were summarized in Tab.1. by following the ISO 4892.3 norm. The combination of dry and wet cycles affected the strength and modulus, whereas dry cycle primarily impacted the strength of the composites with minimal variation in modulus. This is because during the dry and wet cycles, the composites absorb water molecules, which affects the interfacial bonding between the fiber and matrix, while under dry aging, the composites undergo photooxidation due to the sensitivity of polypropylene to temperature and UV irradiation. Further prolonged accelerated aging experiments will provide better insights into the phenomena affecting the properties and the corresponding factors that are responsible for characterizing the FFRCs performance.

Tab. 1. Tensile Strength and modulus of FFRCs before and after accelerated aging

Aging time (h)	UV		Aging time (h)	UV+water spray	
	E (GPa)	σ_R (MPa)		E (GPa)	σ_R (MPa)
0	11.45	98.47	0	11.45	98.47
257	11.15	94.69	257	10.12	83.24
757	10.46	79.63	423	9.68	83.64

Conclusion

This study will outline the research methodology, selection of an application, and the importance of different climatic regions on durability of FFRCs along with some preliminary results on environmental and mechanical performance at macro scale subjected to in-service climatic conditions. The LCA results of wind turbine rotor blades will be discussed, highlighting the key environmental hotspots within their product life cycle. Furthermore, the environmental factors that affects the long-term durability of flax fiber composites will be addressed.

Acknowledgements

This work is carrying out as a part of the doctoral thesis of Sandeep Kumar GANTALA, being financed by the French Ministry of higher education, Research and Innovation. (MESRI - Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation)

Bibliography

- [1] M.Patel, C. Bastiol, L.Marini, D.Geoökol. E.Würdinger, «Environmental assessment of bio-based polymers and natural fibres,» 2022.
- [2] O.Jolliet, G.Soucy, S.Shaked, M.Saadé-Sbeih, and P.Crettaz, Environmental Life Cycle Assessment, Florida: Taylor & Francis Group, 2016.
- [3] H. Abdollahiparsa, A.Shahmirzaloo, P.Teuffel and R. Blok, «A review of recent developments in structural applications of natural fiber-Reinforced composites (NFRCs),» *Composites and Advanced Materials*, vol. 32, pp. 1-18, 2023.
- [4] A. Le Duigou, P.Davies, C.Baley, «Environmental Impact Analysis of the Production of Flax Fibres to be used as a Composite Material Reinforcement,» *Biobased Materials and Bioenergy*, vol. 5, pp. 153-165, 2011.
- [5] A.G.Campos, C.Vialle, A.Rouilly, C.Sablayrolles, L.Hamelin, «Flax fiber for technical textile : A life cycle inventory,» *Journal of Cleaner Production*, vol. 281, 2021.
- [6] A. Le Duigou, C.Baley, «Coupled micromechanical analysis and life cycle assessment as an integrated tool for natural fibre composites development,» *Journal of Cleaner Production*, vol. 83, pp. 61-69, 2014.
- [7] S.A. Miller, W. V. Srubar, S.L. Billington, M.D. Lepech, «Integrating durability-based service-life predictions with environmental impact assessments of natural fiber-reinforced composite materials,» *Resources, Conservation and Recycling*, vol. 99, pp. 72-83, 2015.

- [8] W. Yan, H. Riahi, K. Benzarti, R. Chlela, L. Curtil, D. Bigaud, «Durability and Reliability Estimation of Flax Fiber Reinforced Composites Using Tweedie Exponential Dispersion Degradation Process,» *Hindawi - Mathematical Problems in Engineering*, vol. 2021, 2023.
- [9] L. Alam, «Matériaux biosourcés multifonctionnels : durabilité des composites unidirectionnels à matrice recyclée renforcés par des fibres de lin,» Ph.D. thesis, Université Bourgogne Franche-Comté, 2023.