ASSESSING THE FEASIBILITY OF NATURAL COMPOSITE FOR STRUCTURAL APPLICATIONS

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Keywords: Natural fibres, Reliability analysis, Grillage structures, Top-hat stiffeners

Abstract

Composite materials are widely used for structural applications however, these materials can have an adverse environmental impact. Whilst a number of natural reinforcements show promise as replacements, with comparable specific properties to conventional fibres, there is a perceived high variability due to the inconsistencies at the fibre level and poor volume fractions reduce these properties at the laminate scale. Therefore, a reliability assessment of natural composite materials was performed to investigate the applicability of natural composites to structural applications. The analysis is performed using Monte Carlo simulations, to analyse the reliability and the structural integrity of a composite grillage under out-of-plane loading. At the structural scale, the results show that even if natural fibre reinforced composite cannot compete with conventional fibres structures, they demonstrate some potential for mass constrained applications due to their low density. The paper demonstrates that whilst it is unlikely that these materials will be chosen for primary structures it is a possibility that with improved production techniques, and a reduction of cost with increased up take, that these materials might provide a sustainable alternative in secondary structural applications.

Excerpt from ISBN 978-3-00-053387-7

1. Introduction

Climate change is having an increasing impact on material choices and new potential reinforcements for composite need to be investigated to increase recyclability and decrease production emissions. Composites reinforced with natural fibres offer a number of advantages including low toxicity and lower tool wear in product manufacture, less dependence on petrochemicals in their production and have reasonable specific mechanical properties [1]. Whilst a number of natural reinforcements show promise, with comparable specific properties to conventional fibres, there is a perceived reliability problem at the laminate stage due to inconsistencies at the fibre level, preventing their utilization for structural applications. This is compounded by the low fibre volume fractions reached during production that reduces the laminate properties. Natural fibre reinforced composites are widely studied at the fibre's and laminate's scales but the possible utilization at the structural scale needs to be further investigated. It has been shown by Blanchard et al. [2] that the large variability shown at the fibre's scale does not replicate at the laminate's scale, however this influence was not studied at the structural scale. To determine the boundaries for where these materials might be applicable at the structural scale, a reliability analysis will be conducted on a grillage structure.

The reliability of a structure can be defined as the probability that the structure will perform its intended function without failing. Several techniques are used to analyse the reliability of a composite structure such as Monte-Carlo simulations, First Order Reliability Method (FORM) and Second Order Reliability Method (SORM). These reliability techniques have been widely applied to conventional composite plates by Jeong and Shenoi [3] [4], Chen et al. [5], Chen and Guedes Soares [6] [7]. A number of reliability analyses performed on structural marine applications are reviewed in Sobey et al. [8] and within this study it is noted that whilst the available literature is large few of these focus on the complex structures utilised in engineering applications.

Blake et al. [9] studied the reliability of a grillage structure utilizing Navier's Energy method derived from Vedeler [10] and successfully validated the methodology for conventional fibre reinforced composite materials. Yang et al. [11] presented an analytical method to assess the reliability of tophat-stiffened laminate panels under in-plane loading; the study was based on the Navier grillage theory and the First Order Reliability Method. Sobey et al. [8] extended the out-of-plane study by incorporating up-to-date failure criteria developed from the World Wide Failure Exercise (Puck, Zinoviev and Tsai failure criteria) and a maximum deflection limit state. The structural model and the Monte-Carlo simulation technique were both validated and the reliability method compared for carbon/epoxy and e-glass/vinylester composite plates with results from previous studies. It was shown that the Monte-Carlo method is appropriate and can be used to determine the reliability of composite plates. These studies were focussed on realistic structural applications showing that the Navier grillage theory was suitable to evaluate the reliability of composite structures made of conventional fibre reinforced laminates.

Due to the growing interest in natural composites and their environmental advantages, it is important to determine their possible applications at the structural scale. To do so, the reliability techniques already widely used for conventional material will be applied to analyse the reliability of a structure made of natural fibre reinforced composites. This paper compares the reliability of a structure made from natural fibre reinforced composites to the same structure constructed from conventional materials. This is a first step towards demonstrating the boundaries for these materials and to demonstrate the gaps in the literature to help focus future research towards providing a more conclusive study in the future.

2. Methodology

The analysis is performed using the same method successfully used by Sobey et al. [8] and Blake et al. [9] with a Monte-Carlo simulations technique on a grillage structure under out-of-plane loading. The Navier grillage model is preferred due to its fast computational time and reasonable fidelity [8]. Material properties are generated from a combination of experimental results [2] and literature review. Limit states are provided from the Zinoviev strength based criterion as recommended by the World Wide Failure Exercise [12].

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2.1. Monte-Carlo simulation

The Monte-Carlo technique can be divided into the following steps:

1. A randomly distributed set of input variables for the resistance, material properties, and load are generated using statistical distribution results from experimental testing and literature.
2. The grillage analysis calculations are performed based on the set of input variables.
3. The deflection, moments, stress and shear stress are determined at the centre intersecting point between transverse and longitudinal stiffeners.
4. These outputs are compared to the limit state functions to determine if the structure has failed or not.
5. Steps 1-4 are repeated until a predetermined number of cycles have been completed and the number of failed attempts are summed to calculate the probability of failure .

2.2. Grillage

The stiffened plate was modelled using the Navier method grillage analysis taken from Vedeler [10]. The Navier method grillage analysis calculates the deflection at intersecting points between longitudinal beams and transverse girders. A representative grillage structure is presented in Figure 1.

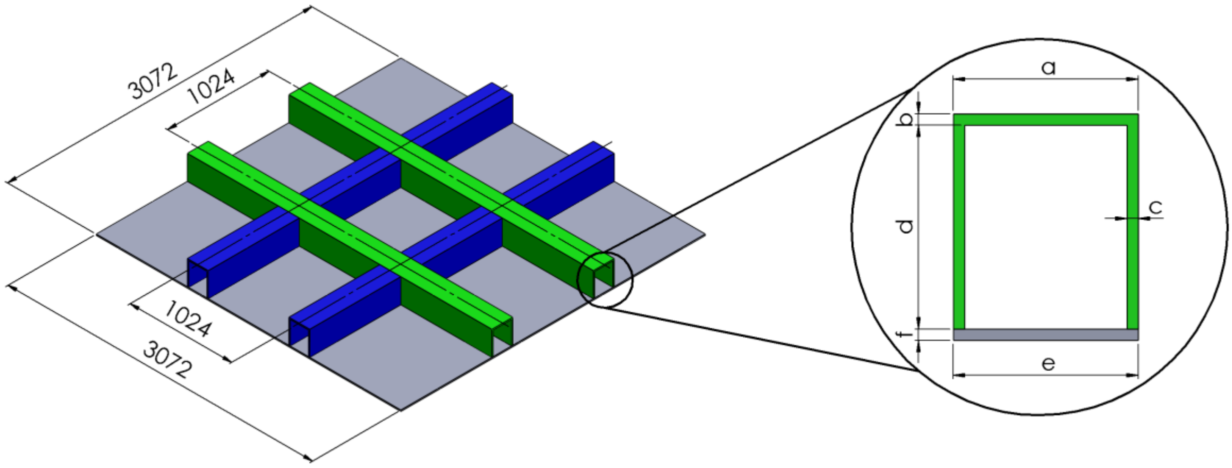

Figure 1: Submarine casing Grillage stiffened plate

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The moments within the stiffeners are determined from the deflection. The deflection, w, of the stiffened plate is calculated with equation (1), where length, L, in the x-direction is stiffened with transverse girders, g, and the breadth, B, in the y-direction is stiffened with longitudinal beams, b.

$$w = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} f_{mn} \sin\frac{m\pi x}{L} \sin\frac{n\pi y}{B} . \tag{1}$$

The value for the coefficient f_{mn} is calculated with equation (2) for odd wave numbers m and n,

$$f_{mn} = \frac{16PLB}{\pi^6 mnE} \frac{1}{m^4(b+1)\frac{I_b}{L^3} + n^4(g+1)\frac{I_g}{B^3}} . \tag{2}$$

where P is the pressure applied on the panel, E is the equivalent elastic properties and I the second moment of area.

For fibre reinforced composite structure, the Navier grillage model is combined with the elastic equivalent properties, determined by Datoo [13]. For the bending mode, the elastic equivalent properties are calculated using the bending stiffness of the laminate (D matrix) as shown in equation (3).

$$E_{bending(i)} = \frac{12\left(D_{11}D_{22}D_{33} + 2D_{12}D_{23}D_{13} - D_{22}D_{13}^2 - D_{33}D_{12}^2 - D_{11}D_{23}^2\right)}{(D_{22}D_{33} - D_{23}^2)t^3}. \quad (3)$$

The elastic equivalent properties in the bending mode are used to calculate the flexural rigidity of the structure,$D_{g,b}$.

The moments in the longitudinal beams or transverse girders are calculated with equation (4), where $D_{g,b}$ is the structural rigidity of the stiffener.

$$M_{g,b} = -D_{g,b}\frac{\partial^2 w}{\partial x^2}. \quad (4)$$

The maximum stresses on the crown element are derived from the moments and calculated with equation (5) where Z_s is the vertical distance of the centroid of an element to the neutral axis.

$$\sigma_{\max} = \frac{E_{s(i)}M_S Z_S}{D_S} \quad (5)$$

2.4. Failure criterion

The probability of failure of the structure was calculated based on first ply failure. Zinoviev failure criterion, which is taken from the recommendations of the World Wide Failure Exercise was used in this study. It was already successfully employed by Sobey et al. [8]. Zinoviev failure criterion was selected as all the variables can be determined for flax fibre reinforced composites which is not the case of the Puck failure criterion. The Zinoviev failure criterion assumes that the behaviour of the laminate is linear elastic up to failure. The ply remains elastic if the following conditions are fulfilled:

$$X_C \le \sigma_1 \le X_T\,; \quad (6)$$

$$Y_C \le \sigma_2 \le Y_T\,; \quad (7)$$

$$\left|\tau_{12}\right| \le S_{12}\,. \quad (8)$$

Where X_T, Y_T are ultimate tensile stresses along and transverse to the fibres, X_C, Y_C are the equivalent characteristics in compression and S_{12} is the ultimate in-plane shear stress.
These conditions determine a failure surface in the shape of a rectangular parallelepiped in the coordinates σ_1, σ_2, τ_{12}. When the stress reaches any of the mentioned ultimate values, the ply fails [14] [15].

3. Material properties

The material properties for flax fibre reinforced epoxy composites were derived from the experiments conducted by Blanchard et al. [2] and by Yan [16] for the compressive strength. The Poisson's ratio was estimated for flax fibre reinforced composites as it could not be found in the literature. The material properties for glass fibre reinforced epoxy vinylester composites were taken from Tekalur et al. [17].

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Table 1. Material properties for flax and glass fibre reinforced composites.

Materials	Flax / epoxy			Eglass/epoxy vinylester		
Mechanical Properties	Mean	CoV (%)	Ref.	Mean	CoV (%)	Ref.
Longitudinal Young's modulus (MPa)	8 180	5.08	[2]	29 200	6.16	[17]
Transverse Young's modulus (MPa)	8 180	5.08	[2]	23 900	7.95	[17]
Poisson's ratio	0.25	5.00	Estimate	0.16	6.25	[17]
Shear modulus (GPa)	2.07	5.31	[16]	4.5	6.67	[17]
Tensile strength in the fibre direction (MPa)	90.9	7.89	[2]	512.5	4.39	[17]
Compressive strength in the fibre direction (MPa)	90.32	4.76	[16]	363.4	20.64	[17]
Tensile strength perpendicular to the fibres (MPa)	90.9	7.89	[2]	350.9	2.54	[17]
Compressive strength perpendicular to the fibres (MPa)	90.32	4.76	[16]	336.4	7.49	[17]
Shear strength (MPa)	38.01	5.81	[16]	44.7	1.34	[17]
Ply thickness (mm)	0.539 mm wet for 221g/m^2		[2]	0.417 mm wet for 610g/m^2		[17]
Composite density (kg/m^3)	1220		[2]	1980		[17]

4. Grillage Structure

A representative submarine casing structure made of glass fibre reinforced composites was selected for this study. The grillage structure studied is made of 2 equally spaced transverse and 2 equally spaced longitudinal top-hat beams. The length and the breadth of the grillage are 3072 mm. The geometry of the panel is shown in Figure 1 with the dimensions presented in Table 2. The pressure load applied on the structure was 110 kPa following a Weibull distribution (CoV= 15%).

Table 2: Dimensions of the submarine casing grillage**.**

Variables	Definition	E-glass/ Vinylester	Flax/epoxy (same volume)	Flax/epoxy (same mass)
Nt	Number of transverse stiffeners	2	2	2
Nl	Number of longitudinal stiffeners	2	2	2
a	Crown width (mm)	211	211	211
b	Crown thickness (mm)	12.92	12.93	20.06
c	Web thickness (mm)	12.92	12.93	20.06
d	Web height (mm)	258	258	258
e	Flange width (mm)	211	211	211
f	Flange thickness (mm)	12.92	12.93	20.06

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Three different fibre reinforced composite structures were compared, the original E-glass panel and two panels using flax: one where a similar topology is compared, keeping the volume the same, and a second where an equivalent mass is compared, meaning that the thickness of the topology is increased. The thickness of flax fibre reinforced composite structure was calculated based on ply thickness and composite density derived experimentally by Blanchard et al. [2].

5. Results and discussion

Table 3 presents the probability of failures for the glass fibre reinforced structure and the two derived flax fibre reinforced composite structures. The mass of each grillage and the normalised probability of failure compared to the mass are also presented.

Table 3: Comparison of the probability of failure between glass and flax fibre reinforced structures

	Eglass/ Epoxy Vinylester	Flax/ Epoxy (same volume)	Flax/ Epoxy (same mass)
Probability of failure (P_f)	0	0.146	$3*10^{-6}$
Normalised probability of failure compared to mass (P_f/kg)	0	$7.9*10^{-4}$	$1.05*10^{-8}$
Volume of the grillage (m^3)	0.145	0.145	0.234
Mass of the grillage (kg)	286.96	176.96	285.00
Mass of the fibres (kg)	216.55	78.32	125.4
Mass of the resin (kg)	70.41	99.13	159.7
Thickness of the laminate (mm)	12.92	12.93	20.05

Flax fibre reinforced composite structures have a higher probability of failure than the equivalent glass fibre reinforced composite structure, as expected due to the lower mechanical properties. In the case where volume is a key constraint it is shown that the flax cannot compete with glass as each layer is thick and the laminate contains only a few plies of flax, in this case the panel is predicted to fail almost 15% of the time based on a strength criterion alone. However, the low density of the flax fibre reinforced composite can be advantageous in structures which have weight restrictions, where the size of the stiffening structure is less constrictive. The probability of failure of flax fibre reinforced composite with the same mass as the original glass composite structure is equal to $3*10^{-6}$ which is acceptable when comparing to the current design practice as shown in Table 4 in which the probability of failure for stiffened flat plates should be at least as low as 10^{-5}-10^{-4}.

Table 4: Annual Pf in existing structures **[18]**

Type of Structure	Relevant Code	Annual P_f
Stiffened Flat Plates	NPD/DNV API RP2T	10^{-5}-10^{-4}
Stiffened Panels	API RP2T, RCC/API Bul-2U	10^{-4}
Stiffened Plates	API RP2T, RCC/API Bul-2U	10^{-3}

Flax fibre reinforced composite structures are considerably lighter for the same volume compared to glass structures even if the fibre volume fraction is equal to 37.24% for flax [2] compared to 60.5% for glass [17]. For the “same mass” case, the volume varies considerably between glass and flax reinforced composites and the mass of resin for flax is more than twice the mass of resin for glass

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laminates. Therefore, any improvement on the fibre volume fraction for natural fibre reinforced composites should significantly increase the material properties and further reduce the mass of the structure.

The large variability seen at the fibre's scale for flax is highly reduced at the laminate's scale with a coefficient of variation for the longitudinal young's modulus of 5.08% for flax and 6.16% for glass reinforced composite as shown in Table 1. The higher probability of failure of the structure made of flax is caused by the lower properties of the fibres themselves and the low fibre volume fraction reached during production.

The geometry of stiffened structures needs to be adapted for natural fibre reinforced composites alongside an improvement in the manufacturing process to increase the fibre volume fraction and therefore the material properties. However, the current study shows that these materials, might be beneficial for some lightly loaded structural applications with mass driven constraints and a willingness to integrate environmentally friendly materials to the structure.

Finally, this study utilises a standard resin to be used with the natural fibre. This reduces the sustainability credentials for these materials and may not provide optimal production quality. Additional research into feasible, sustainable, alternatives may provide results closer in performance.

6. Conclusions

This paper performs a reliability analysis comparing glass fibre composite grillage structure with a natural fibre reinforced composite structures with two approaches: "same volume" and "same mass". A Monte Carlo simulations technique was used with an efficient analytical model to determine the probability of failure for the three different structures with the material properties derived from literature and experiments. The results show that the probability of failure of natural composites is lower than for conventional fibre structures while also requiring a structure with a larger volume. However, due to the low density of natural fibre reinforced composites, it can be applicable to secondary or tertiary structure with light mass requirements. The large variability shown at the fibre's scale for flax does not seem to be influencing the results at the structural scale and the higher probability of failure for natural fibre reinforced composites is caused solely by the lower mechanical properties due to the low fibre volume fraction.

Acknowledgments

The research is kindly sponsored by the Lloyd's Register Foundation (LRF)

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Excerpt from ISBN 978-3-00-053387-7