Modelling the different mechanical response and increased stresses exhibited by structures made from natural fibre composites

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Abstract

Natural fibres exhibit improved sustainability and similar mechanical properties to E-glass. However, for laminates there is a larger difference in properties and limited assessments of structural components. An analytical method for grillages is developed which is generally shown to predict the stress to within 5% of an FEA model. The simulations demonstrate a change in structural response between flax and carbon, with flax demonstrating higher stresses than expected for the lower Young's modulus for the same topology. Flax is shown to be more sensitive to transverse Young's modulus than standard composites and a better characterisation of this property is required.

Keywords: Flax fibre; A. Carbon fibre; C. Analytical modelling; A. Layered structures

1. Introduction

Composite materials are used in a range of structural applications. However, they are non-degradable and because of this there is an increasing interest in sustainable materials to replace those that are currently being used. As an example Pinto et al. [1] outline the potential for these sustainable materials such as flax, jute and hemp for structural applications. Currently the behaviour of composite structures is well understood but the structural response for natural fibres has seen limited investigations and those that have been performed show there is a change in response for these materials in the applications which have been investigated. Many authors, including Yan et al. [2] and Baets et al. [3], quantify the fibre mechanical properties and propose that flax is equivalent to E-glass in terms of stiffness. However, at the structural scale the stiffness is lower due to poor fibre volume fractions. Alkbir et al. [4], Shah et al. [5] and Bambach [6] conclude that component level analysis must be assessed before flax can be used in structural applications and to understand whether current structural analysis methods are appropriate for natural composites.

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Despite a good understanding about the behaviour of composite structures, there are few available methods to model them. Finite Element Analysis (FEA) is the standard, but is more suited for use in the detailed design stages. At an early stage of the design it can be time consuming and authors, such as Toal and Keane [7] and Forrester and Keane [8], propose using it in conjunction with surrogate models. However, Jin and Jung [9] summarise that these methods can impose some inaccuracies, are limited to problems with around 30 variables and still require a number of time consuming FEA simulations. The accuracy of these surrogates is also dependant on the sampling plan requiring the user to have some expertise using these tools, Liu et al. [10]. To counteract these issues there is the development of methods that provide a rapid assessment of structures such as Vescovini and Bisagni [11]. A number of authors: Maneepan et al. [12], Sobey et al. [13], [14], [15], [16], [17] Blake et al. [18], Yang et al. [19], Xue et al. [20] and Liu et al. [10], utilise the Navier grillage method to assess stiffened structures in applications which require computationally intensive methodologies. The grillage method provides a rapid assessment of commonly used top-hat stiffened structures which reduce the mass of large composite structures and compensate for the poor torsional rigidity. Elastic equivalent properties are often used to represent composite materials, and therefore layer by layer stresses are ignored, but the accuracy of this adjustment is unknown.

To understand whether structural components can be made from natural composites they must be analysed at this scale and the appropriateness of current modelling methods must be investigated. This paper assesses the behaviour of natural composites using Finite Element Analysis where the flax structures show a different mechanical response compared to standard composite materials. A simple analytical approach, Navier grillage method, is then investigated for modelling top-hat stiffened composite structures, including the response for standard and low stiffness materials. The accuracy of the model is improved using an empirical adjustment and incorporation of Classical Laminate Plate Theory, giving similar results to Finite Element Analysis. This provides a computationally efficient method that can predict layer by layer maximum stresses and that can capture the newly found change in mechanical response exhibited by natural composites.

2. Navier grillage method

A simple analytical model often used to model composite structures is the Navier grillage model, taken from Vedeler [21], which calculates the deflection, w, with equation (1) for a grillage under simply supported boundary conditions,

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

where length, L, in the x-direction is stiffened with transverse stiffeners, N_T, running perpendicular to the x-axis and the breadth, B, in the y-direction is stiffened with longitudinal stiffeners, N_L, running perpendicular to the y-axis. The value for the coefficient f_{mn} is calculated with equation (2) for odd wave numbers m and n, in this case up to a value of 11, where P is a uniform pressure applied to the panel, E are the elastic equivalent properties, I_L the second moment of area in the longitudinal stiffener and I_T the second moment of area in the transverse stiffener,

$$f_{mn} = \frac{16PLB}{\pi^6 mnE} \frac{1}{m^4 (N_L + 1)\frac{I_L}{L^3} + n^4 \left(N_T + 1\right)\frac{I_T}{B^3}}. \tag{2}$$

For fibre reinforced composite structures, the material properties for the Navier grillage model are defined using elastic equivalent properties taken from Datoo [22]. The longitudinal bending moment, M_L, at longitudinal position x and transverse position y is calculated from the deflection with equation (3),

$$M_L = -EI_L \left(\frac{\partial^2 w}{\partial x^2}\right)_{yi} = EI_L \frac{\pi^2}{L^2} \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} m^2 f_{mn} \sin\frac{m\pi x}{L} \sin\frac{n\pi y}{B}, \tag{3}$$

similarly the transverse bending moment, M_T, is determined with equation (4),

$$M_T = -EI_T \left(\frac{\partial^2 w}{\partial y^2}\right)_{xi} = EI_T \frac{\pi^2}{B^2} \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} n^2 f_{mn} \sin\frac{m\pi x}{L} \sin\frac{n\pi y}{B}. \tag{4}$$

The maximum stresses, $\sigma_{L,T\,max}$, on the crown element in each stiffener are derived from the moments, $M_{L,T}$, and calculated with equation (5) where $Z_{L,T}$ is the vertical distance of the centroid of an element to the neutral axis and $I_{L,T}$ the second moment of area;

$$\sigma_{L,T\,\max} = \frac{M_{L,T} Z_{L,T}}{I_{L,T}}. \tag{5}$$

The comparison to the FEA shows that the Navier grillage method underestimates, with a 30% error, the maximum stresses for composite structures as shown in Table 1 as the change in material properties isn't accounted for. An adaption to the Navier method will allow for a rapid assessment of composite grillages.

Table 1: Comparison of grillage methods for steel and composite structures

Model	Stress (MPa)	
	Steel	Carbon/epoxy composites
FEA	170.61	246.17
Navier grillage	171.46	171.46

3. Empirical improvement for low stiffness composite grillages

To derive an improved empirical formulation of the Navier grillage model for composite structures, topologies and materials, representing values from large structural applications, are analysed using a verified FEA model. To calculate layer by layer stresses Classical Laminate Plate Theory is applied to the crown element of the stiffeners, the location of the maximum stress on a grillage structure. The moments in the direction of the stiffener, $M_{x,L}$ for the longitudinal direction or $M_{x,T}$ for the transverse direction, are calculated with the grillage equations, (3) and (4). These are divided by the empirically derived factor, *F*, and the stiffener width, *a*, before being implemented into the Classical Laminate Plate Theory, shown for the longitudinal and transverse directions in equations (6) and (7),

$$M_{x,L} = -\frac{EI_L}{aF}\left(\frac{\partial^2 w}{\partial x^2}\right)_{y_i}, \tag{6}$$

$$M_{x,T} = -\frac{EI_T}{aF}\left(\frac{\partial^2 w}{\partial y^2}\right)_{x_i}. \tag{7}$$

The empirical factor, *F*, is calculated to reduce the error in the stresses found between the FEA model and the grillage analytical model for the standard materials: E-glass, Kevlar and carbon. A second order polynomial regression analysis is then performed using a least squares fit to determine the equation for the empirical factor *F* as a function of E_1/E_2 which is calculated as shown in equation (8) with E_1 and E_2 being the longitudinal and transverse Young's modulus of the laminate,

$$F = 0.003\left(\frac{E_1}{E_2}\right)^2 - 0.1202\left(\frac{E_1}{E_2}\right) + 3.9721. \tag{8}$$

The matrix with the resultant forces and moments is inverted to calculate the middle-surface strains, ε^0, and middle-surface curvatures, κ, as presented in equation (9),

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} A' & B' \\ B'^T & D' \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix}. \tag{9}$$

The curvatures and strains are calculated from the extensional stiffness matrix, [A], the extensional-bending coupling stiffness matrix, [B], and the bending stiffness matrix, [D]. The crown is assumed to be in pure bending and therefore the normal forces per unit length, N_x and N_y, and shear force, N_{xy}, are assumed to be negligible and set to 0. The width to height ratio of the cross section is assumed to be small; this means that the lateral curvature is induced only due to the effects of Poisson's ratio and therefore transverse bending moment per unit length, M_y, is also set to 0. The extensional-bending coupling matrix, [B], relates in-plane strains to bending moments and curvatures to in-plane forces; the laminate is symmetric and therefore the [B] matrix is also set to 0. With these assumptions, equation (9) can be modified into equation (10),

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11}' & A_{12}' & A_{16}' & 0 & 0 & 0 \\ A_{21}' & A_{22}' & A_{26}' & 0 & 0 & 0 \\ A_{16}' & A_{26}' & A_{66}' & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{11}' & D_{12}' & D_{16}' \\ 0 & 0 & 0 & D_{21}' & D_{22}' & D_{26}' \\ 0 & 0 & 0 & D_{16}' & D_{26}' & D_{66}' \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ M_x \\ 0 \\ 0 \end{bmatrix}. \tag{10}$$

The stresses in the k^{th} layer of the crown laminate can therefore be expressed as equation (11),

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}, \tag{11}$$

where $\overline{Q}$ are the reduced stiffness terms, z is the ply centroidal value and τ_{xy} is the shear stress.

4. Development of the FEA model

Based on the size and complexity of the grillage model there are limited available experiments under out of plane loading. FEA is used, as it provides an accurate approximation to real performance, to determine the behaviour of flax structures and the accuracy of the empirical model. To verify the accuracy of the FEA model, the results are compared with experiments performed by Eksik et al. [23] on the complex to model inter-connection between two stiffeners. This model is then extended to a grillage by increasing the length of the stiffeners. The model is developed using Abaqus CAE and an automated Python code.

The plate used in Eksik et al. [23] has two identical top-hat stiffeners made from 14 layers of E-glass Epoxy with a cross-section shown in Figure 1(a). A one by one top-hat stiffened composite plate, 1000mm by 1000mm, is modelled with a uniform pressure applied to an area 800mm by 850mm of the panel, up to a maximum of 0.3 MPa. The test plates are sandwiched between two heavy steel frames and bolted. The boundary conditions are defined in Eksik et al. [24] as partially clamped. Therefore, in this study the plate corners are clamped and the plate edges are simply supported to replicate the experimental conditions as closely as possible. To determine the strain values during loading, 14 strain gauges are attached to both sides of the plate: the loaded surface and the stiffened surface; the positions of all strain gauges are displayed in Figure 1(b). A geometrically non-linear and materially linear model is developed with quadrilateral shell elements (S4R) which converges at 80000 elements. The behaviour will be dominated by the longitudinal continuous stiffener, as observed during experiments, and so it is assumed that the elements of the discontinuous transverse stiffener connection are behaving in relation to the longitudinal ones. In the real plate the connection between the stiffeners is made using resin and extra fibre during production to make it as strong as possible. Therefore, the cross-stiffeners and the contact between the plate and stiffeners are modelled using perfect tie constraints as they are assumed to be perfectly bonded. Two different approaches, plate or stiffener dominated, are compared to determine which one is more realistic demonstrating that the plate is stiffener dominated.

The finite element model is compared to the experimental strain values from Eksik et al. [23]. Results for strain gauge 11 are not included as they are not presented in the original text because of inaccurate data at this location. The comparisons from each strain gauge location are listed in Table 2 using root mean square error (RMSE) and mean percentage error (MPE). Across all the strain gauge locations the overall prediction of the FEA model gives good agreement with the experimental results until the load reaches 0.25 MPa where it diverges; it is likely that the panel sustains fibre matrix breakage damage at the intersection of the web of the stiffener at this point, since damage is observed in the experiment. However, at some locations such as strain gauges 6 and 8, the experimental results present larger differences, showing 36% mean error in comparison to these cases. These locations are described as failure-prone locations in Eksik et al. [24] because of the larger bending and the connections between the stiffeners. Therefore, the damage reduces the accuracy of the strain predictions at these positions. The uncertainties in the boundary conditions and manufacturing quality might also increase the discrepancies. Overall, these results provide confidence in the FEA model which is extended into a grillage, similar to that shown in Figure 2(a).

Different geometries are generated and used to verify the behaviour of the analytical approximations. The FEA is used to generate a parametric study to determine the stress at the interconnection between longitudinal and transverse stiffeners for different topologies and materials. There can be high variations in stress values between neighbouring elements and nodes at the contact area between stiffeners due to the interactions between the continuous and separated stiffeners. To reduce the impact of this variation, the stress values are measured on mid-nodes. Initially the stress values are calculated for each integration point of each mesh element. Then the integrated stress values are extrapolated to the element. Since the nodal values are the average of the element stresses surrounding that node they demonstrate a more consistent representation of stress values and are compared with the analytical results.

Table 2: Modelling error at each experimental gauge position

Position	Loaded surface						Crown		
SG	1	2	3X	3Y	4	5	6	7	8X
RMSE	153	234	135	201	192	287	1462	871	1196
MPE (%)	-22	6.6	-18	-20	-24	-3.3	-36	-22	-28

Position	Crown			Flange				Plate	
SG	8Y	9	10	12	12Y	13X	13Y	14	14Y
RMSE	837	1605	1375	409	131	103	203	169	199
MPE (%)	-15	1.4	-38	9.0	-22	-9.5	25	-16	-16

5. Demonstration of the empirical formula for low stiffness materials

The structural response is generated using FEA to understand the sensitivity of the stresses to changes in material properties, and compared to the modified grillage method to demonstrate its accuracy. This is performed for a range of different composite materials. Different grillage topologies are also investigated by varying: the number of stiffeners; the plate, length and aspect ratio, and the stiffener, height and width.

5.1. Base case

A base case is defined as a square grillage composed of 4 equally spaced longitudinal stiffeners and 4 equally spaced transverse stiffeners as shown in Figure 2(a) with the stiffener cross section presented in Figure 2(b). A uniform pressure of 137.9 kPa is applied to the structure. The crown element of the stiffeners is formed of 10 layers with a $[0\ 90\ 0\ 90\ 0]_S$ lay-up. The web and plate elements are composed of 8 layers with a $[0\ 90\ 0\ 90]_S$ lay-up. The base case is used to determine the influence of the material properties on the empirical factor in section 5.2 and sensitivity to topological changes in section 5.3. The response of grillage structures are modelled using different fibres representing a range of composite materials with low to high moduli: low modulus (LM) flax, flax, E-glass, Kevlar, carbon and high modulus (HM) carbon, which are reinforced with epoxy; the properties are presented in Table 3.

Table 3: Material properties for the case studies

	(LM) Flax/epoxy	Flax/epoxy	E-glass/epoxy	Kevlar/ epoxy	Carbon/epoxy	HM carbon/epoxy
E_1 (MPa)	22300	29700	43000	75000	172400	300000
E_2 (MPa)	4200	4800	8000	6000	6900	12000
ν_{12}	0.35	0.36	0.28	0.34	0.25	0.3
G_{12} (MPa)	1970	2190	4000	2000	3450	5000
F	3.42	3.34	3.41	2.94	2.84	2.84
Ref.	[25]	[25]	[26]	[27]	[28]	[27]

5.2. Influence of the material properties

The base case topology is assessed and compared to stresses calculated from the FEA model, presented in Figure 3 where the line splits area A, representing low stiffness natural fibre composites, from area B, representing standard moduli composites. As the material properties change from low Young's Modulus to high the rate of change of the stress varies. At high values the stress decreases slowly, with a small variation between the two types of carbon. There is an increase in this rate for lower moduli, Kevlar and E-glass, before a small increase in stress for the higher modulus flax before decreasing again for the lower modulus flax. This demonstrates a different response for the lower stiffness materials as they are more sensitive to the value of E_2, small changes in this value make a much larger change to the structural response.

When modelling this change in behaviour the Navier grillage model does not consider the impact of the material properties on the stress prediction and so is incapable of giving the correct response. This is heavily influenced by the ratio of E_1 to E_2; which is reflected in the empirical factor, F, in equation (8). The model is validated for the different materials and the calculated values for the empirical factor are shown in Table 3. The addition of the empirical factor allows accurate predictions of these stresses, in comparison to FEA, for all the materials tested. The maximum stresses, in the outer layer of the laminate, have an error smaller than 2.5% for all the materials down to 0.3%; the absolute mean error is 1.0% across all the material properties for the top ply. To demonstrate the accuracy through the thickness the inner layer is also compared where the stresses are overestimated but with all the errors below 3.8% and the lowest error is 1.3%.

5.3. Topological factors

To compare the behaviour of flax and carbon the response is determined over a range of topologies suitable for large composite structures by varying the number of stiffeners; the plate, length and aspect ratio, and the stiffener, height and width. The material properties are presented in Table 3 and the stresses in the top ply are compared, as they represent the maximum stress and show a similar accuracy to the bottom ply.

5.3.1. Number of stiffeners

The effect of changing the number of stiffeners in both the longitudinal and transverse directions is evaluated from values of 2 to 5 stiffeners, also changing the stiffener spacing. The comparison between the FEA and the empirical grillage model is shown in Figure 4. At low numbers of stiffeners the stresses are relatively high with only a small decrease between 2 and 3 stiffeners. There is a larger drop when there is an increase of stiffeners between 3 and 4 because the stress is taken at the intersection between the stiffeners, not the centre of the plate, followed by another small decrease between 4 and 5. The grillage model overestimates the stresses on the top ply for carbon with a mean error of 2.0% whereas for flax this is only the case for 4 stiffeners with an absolute mean error across the entire range of 2.6%. The largest errors, 4.1% for carbon and -6.2% for flax, are both for the smallest number of stiffeners, also giving the largest stiffener spacing. This is considered to be a wide spacing for large composite structures, at a distance of 1270mm, and taking an example from leisure boatbuilding would be treated as exceptional by ISO 12215-5 [29] as it is over the maximum stiffener spacing of 500mm. The minimum error is 0.5% for carbon and -0.8% for flax.

5.3.2. Area of plate and plate aspect ratio

The base case is extended so that square plates with different areas are investigated by increasing the length and width from 2000mm to 4000mm in increments of 500mm; meaning that the stiffener spacing ranges from 400mm to 800mm. The stresses predicted by the FEA and calculated with the empirical grillage model are compared in Figure 5(a). The maximum stresses on the outer layer of the stiffeners are accurately predicted by the grillage model for lengths and widths above 2000mm, with a maximum error of -5.2% for carbon and -4.3% for flax. However, for lengths and widths below this the error is higher, -10.0% for carbon and -14.5% for flax. However, this gives an absolute difference in stress of 4 MPa for carbon and 4.8 Mpa for flax, and so it is still judged to have a reasonable accuracy. The minimum error for carbon is 0.8% and 1.3% for flax and the absolute mean error is 4.0% for carbon and 5.5% for flax.

The base case is extended for rectangular panels with aspect ratios from 1 to 3, in increments of 0.5. The width is kept constant, equal to 2000mm, and the length varies from 2000mm to 6000mm. The structure is composed of 2 equally spaced stiffeners in the longitudinal direction and 4 equally spaced stiffeners in the transverse direction. The stresses predicted by the FEA and the empirical grillage results are presented in Figure 5(b). The stress increases almost linearly from a square plate to the largest aspect ratio of 3 where the carbon case has a slight S shape across the range but the flax is straighter. For carbon, the maximum stresses on the outer ply of the laminate are overestimated by the grillage for aspect ratios 1.5 and 2 whereas these are underestimated for aspect ratios 1.0, 2.5 and 3.0; the absolute mean error is 5.2%. The maximum error is an overestimation of 10.4% for an aspect ratio of 1.5 and the minimum error is an underestimation of -2.4% for an aspect ratio of 2.5. For flax, the grillage underestimates the maximum stresses for all the aspect ratios except for an aspect ratio of 1.5, which shows a minimum error of 1.6%. The absolute mean error is 7.0% and the maximum error is -11.7% for the largest aspect ratio, 3. Therefore, the empirical formula is judged to have a good accuracy at aspect ratios below 3 for both materials.

5.3.3. Stiffener height and width

The base case is extended for a range of stiffener heights from 100mm to 250mm in increments of 50mm, varying the height to width ratio of the stiffeners, and the results are presented in Figure 6(a). For the FEA carbon case the stress values initially decrease steeply at lower stiffener heights with a reduction in this trend for the largest stiffener sizes; this trend is followed by the analytical model. The FEA flax case has a smaller change in stress between the highest and lowest values, showing a change in behaviour between the two materials. The maximum stresses are overestimated by the grillage model compared to the FEA prediction for carbon with an absolute mean error of 2.6%, showing good accuracy. For flax, the empirical model overestimates the maximum stresses for 100 and 150mm as it has a different trend but accurately predicts the stress for 200 and 250mm. The absolute mean error is 21.1% due to the high error at 100mm, which has a maximum error of

71.0% for flax compared to 4.9% for carbon and is 4.5% without this value. However, for this value the stiffener height is reduced to below the width, 127mm, which is uncommon in practice. As the stiffener height is reduced the flax structure changes behaviour in the FEA model from local bending dominated to global bending dominated, but this non-linearity is not predicted in the analytical model leading to a higher discrepancy. Along with this change in bending there is a difference in the distribution of stresses. For the local bending cases, the carbon grillages and the taller stiffened flax grillages, the stresses are predominantly along the continuous stiffeners but in the global bending case the stresses are proportional in both directions; which reduces the magnitude of the increase in stress. The change is perceptible for the 150mm tall flax stiffened plate but not for any carbon panels as they have a higher Young's modulus and therefore structural rigidity. The deflection FEA contour plots for the 100mm high flax stiffened plate are presented compared to the 250mm high grillage in Figure 7, and for carbon in Figure 8, to illustrate this response. The minimum error is -0.1% for flax and 0.7% for carbon.

The stiffener width is also varied from the base case for values from 100mm to 250mm in increments of 50mm. The comparison between stresses predicted by the FEA and the grillage results are presented in Figure 6(b). The maximum stresses are underestimated by the grillage model, except for a width of 100mm, with an absolute mean error of 4.9% for carbon and 15.2% for flax. The maximum error for carbon is 12.6% for a width of 100mm which is reduced to -1.7% minimum error at 200mm. Whereas the maximum error for flax is for a width of 250mm, -24.7%, with a minimum error of -8.4% at 150mm. The carbon and flax results follow different trends, showing a change in behaviour. However, the model with a stiffener width of 100mm does not converge for flax because of some local instabilities in the simulation. An automated stabilisation is added to the analysis where the dissipated energy fraction is employed using as low a value as possible with a convergence at 2.0×10^{-5}. An initial damping factor 2.1×10^{-9} is calculated and a default accuracy tolerance of 0.05 is used throughout the simulation with an adaptive scheme. Since the flax demonstrates a smooth curve it is assumed that this make a minimal difference to the results. The stiffener width and height are therefore deemed to be acceptably accurate between aspect ratios of 1 and 2.

6. Modelling capabilities and implications for natural composites

Flax mechanical properties are often considered to be equivalent to E-glass by many authors including Yan et al. [2] and Baets et al. [3]. A number of authors including Blanchard et al. [30] show that the characteristics at one scale don't transfer to another; for example the variability of flax fibres is high but at laminate scale it is the same as E-glass. So there is a need to study flax at the structural level to understand the mechanical behaviour, as underlined by Bambach [6] and Shah et al. [5]; but these studies are limited in number. As part of understanding flax behaviour at the structural scale it is important to evaluate if the available models, such as Navier grillage, are accurate for flax fibre reinforced laminates.

The original Navier grillage model is found to be inaccurate for all composites and an empirical addition is made which captures the change in structural response for composite grillages. For most of the cases the errors are low, defined here as having a maximum error less than 5% compared to FEA. In the topological cases the predictions are accurate but in some cases the empirical formula has reached the limits of its capabilities, meaning for more extreme topological cases the formulation might not be accurate. E-glass cases are also simulated but the results are not documented as they exhibit similar relationships to carbon, with only a few discrepancies.

Of the limited literature looking at natural fibres at a structural level Bambach [31] showed the applicability of these materials to form light structural applications, but with no comparison to the response of standard composites. Shah et al. [5] investigated flax wind turbine blades demonstrating that at structural scale flax had lower mechanical properties than E-glass. For the E-glass blade the displacement–load curve is linear but for flax the low stiffness produces a different, non-linear, response and the blades are found to fail differently. This paper expands on these conclusions by showing that flax has a different structural response compared to conventional composites and can demonstrate an increase in stress for a reduction in Young's modulus. This is because these lower modulus materials are more sensitive to changes in E_2. Topologically, changes to the plate show limited differences in behaviour between conventional composites and flax. However, changes to the aspect ratio of the stiffener showed substantial differences in behaviour. This is interesting and isn't captured in other analyses of flax, but will further inhibit the suitability of these materials for structural applications as they can exhibit higher than expected stresses. While the results are not conclusive they indicate a requirement for more studies at the structural level including experimental analysis at this scale and the investigation of a wider range of structural elements. Furthermore, flax laminates exhibit a non-linear behaviour where the initial stiffness decreases by up to 50% between the initial strain profile and values above 0.4% strain, as demonstrated by Shah [32]. This behaviour has an impact on the calculation of the Young's modulus where current values taken from the literature are likely to be determined at lower strains and therefore higher than expected at structural scale. A lower stiffness is likely to exacerbate the difference in behaviour between the carbon and flax structures already seen for the extreme cases with a larger range of flax grillages exhibiting a different behaviour than would be expected in comparison to their current standard composite counterparts.

7. Conclusion

Natural fibre composites are increasingly investigated as a sustainable replacement to standard composites. Despite this the numbers of investigations at the structure scale are limited, meaning their mechanical response isn't understood and neither is the applicability of current analytical methods. An analytical method, Navier Grillage theory, is therefore compared to FEA for flax, E-glass and carbon showing poor accuracy even for standard composites. This method is empirically modified demonstrating an accuracy generally below 5% compared to FEA for a parametric study bounded by topologies and material properties commonly used in large composite structural applications. The flax and carbon FEA analysis demonstrate a change in response with an increase in stress for a reduction in Young's modulus. This is because these lower modulus materials are more sensitive to changes in E_2, and it is recommended that further effort is put into more rigorously defining these values and its relationship to E_1. Changes to the aspect ratio of the stiffener also show substantial differences in behaviour between flax and traditional composites.

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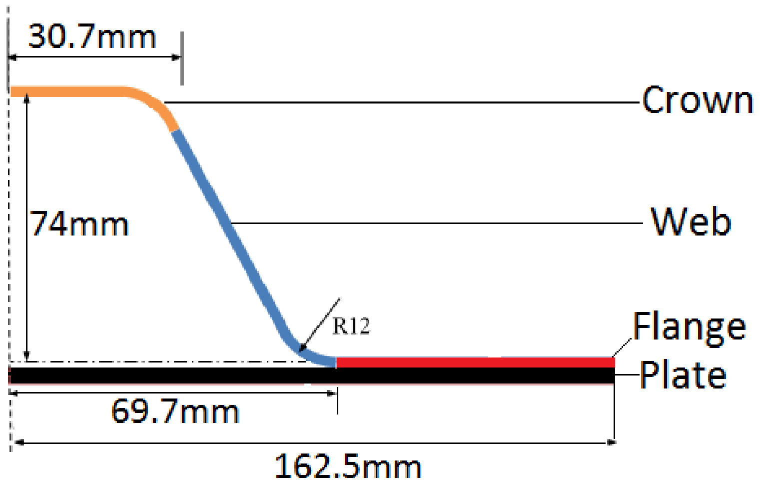
(a)



(b)

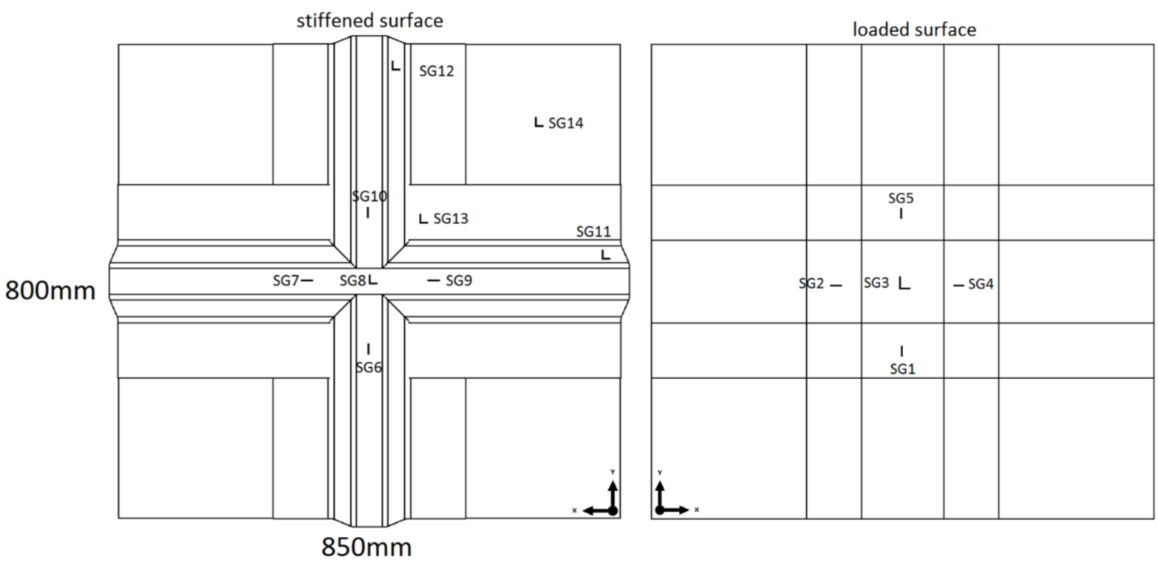
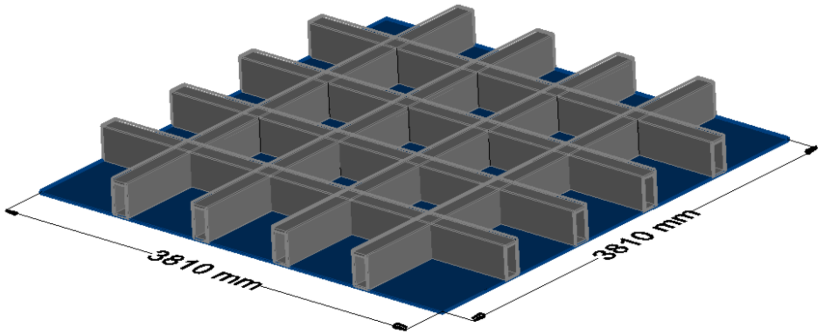


Figure 1: Verification geometry (a) stiffener topology (b) strain gauge placement

(a)



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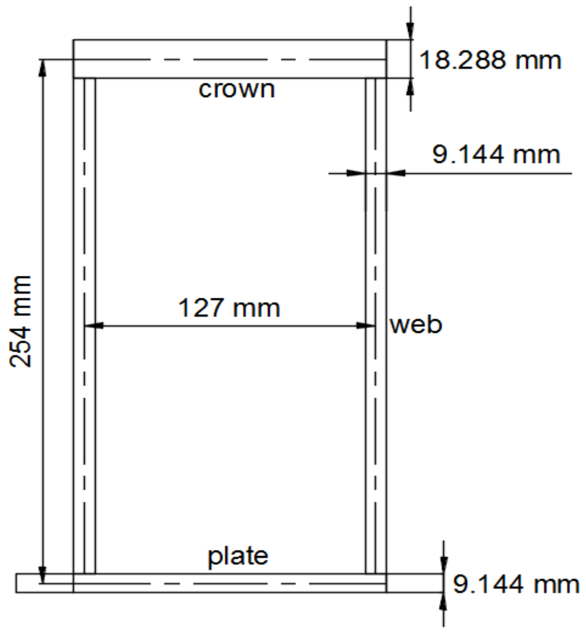


Figure 2: Base case definitions for (a) grillage and (b) stiffener

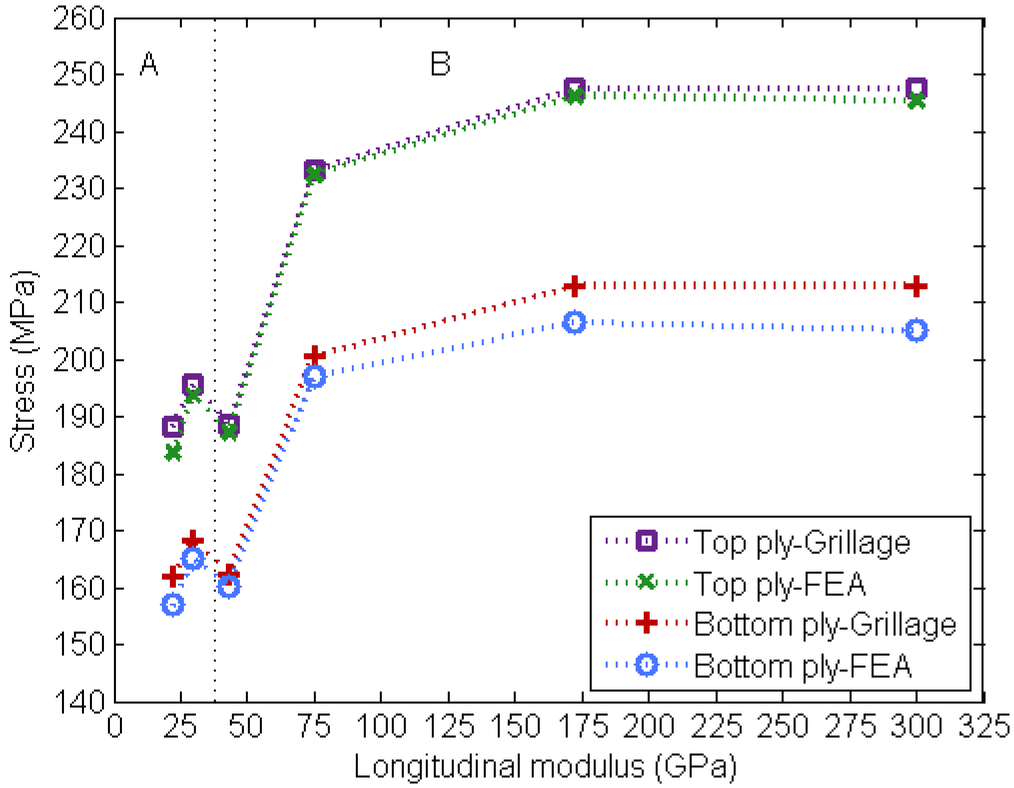


Figure 3: Comparison between stresses obtained from FEA and empirical model for different material properties

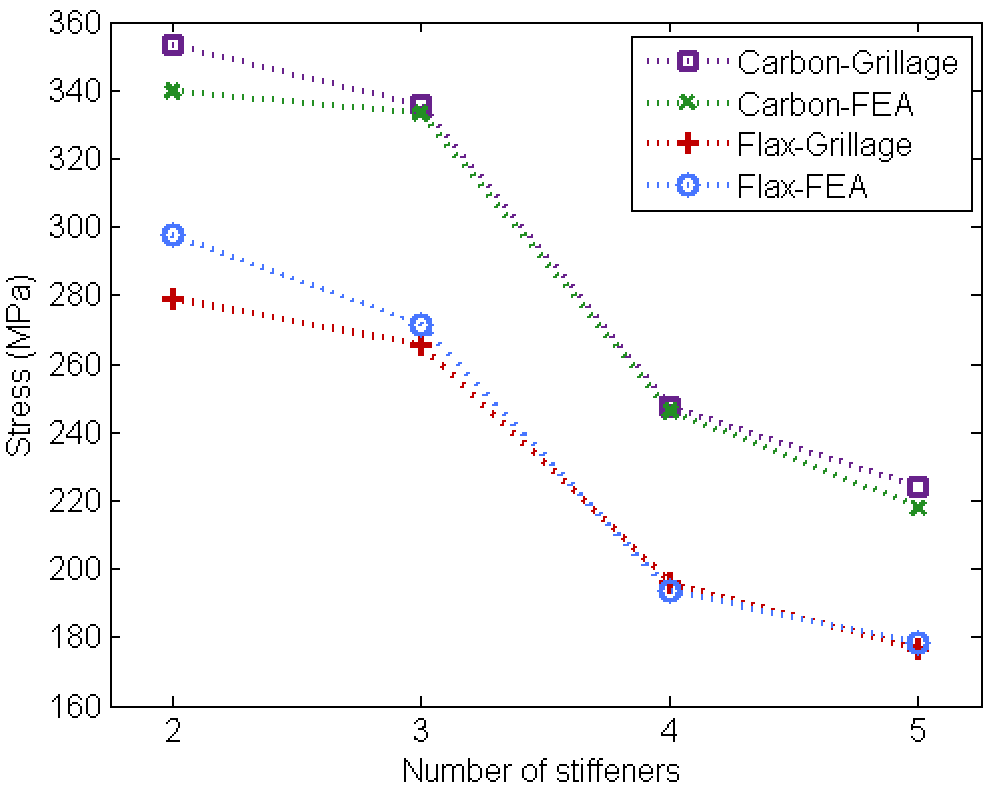
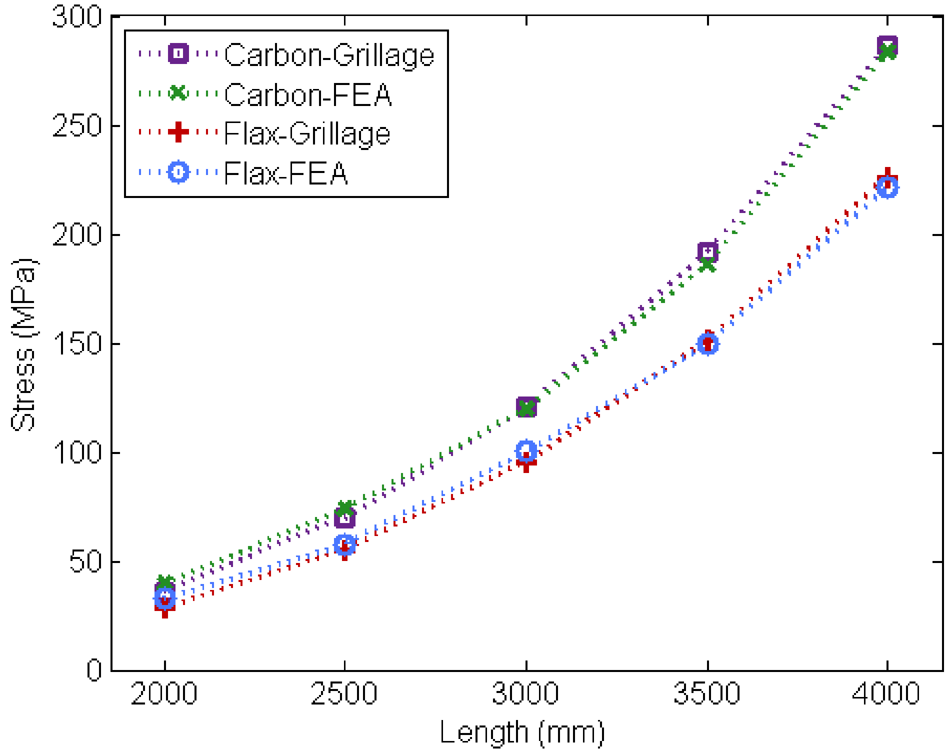


Figure 4: Comparison between top ply stresses obtained with FEA and empirical model for varying number of stiffeners

(a)



(b)

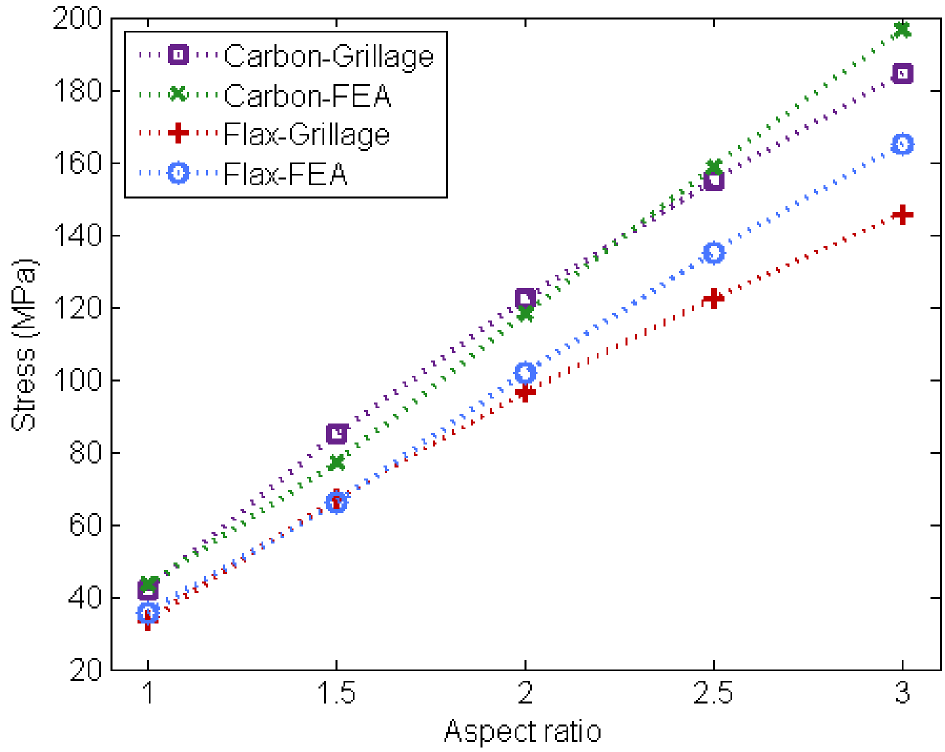
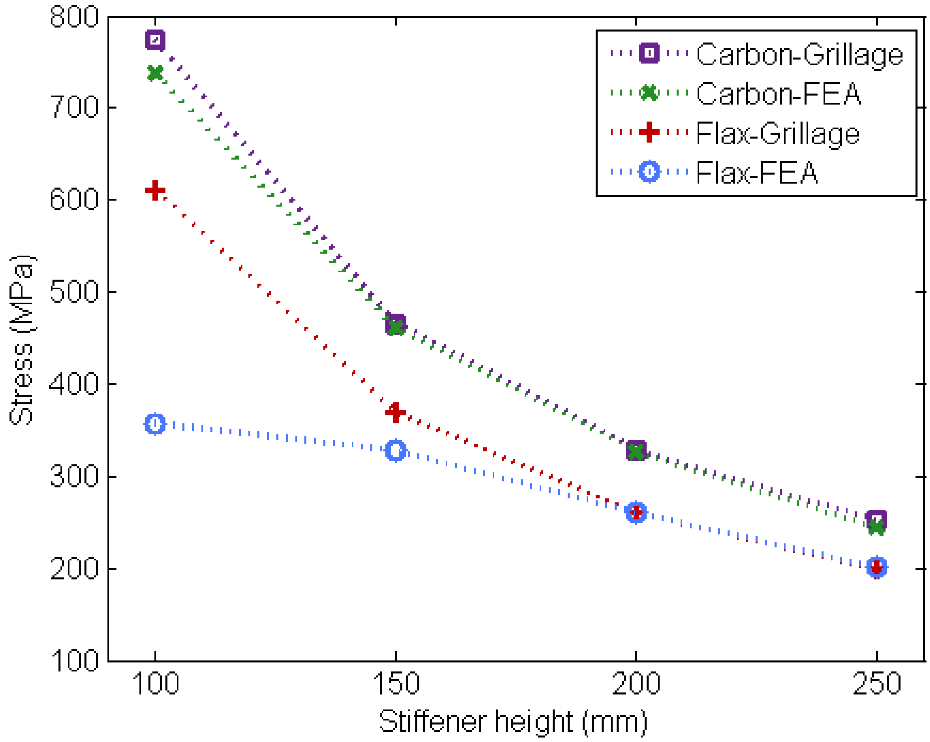


Figure 5: Comparison between top ply stresses obtained with FEA and empirical model for (a) varying areas of plate and (b) aspect ratios

(a)



(b)

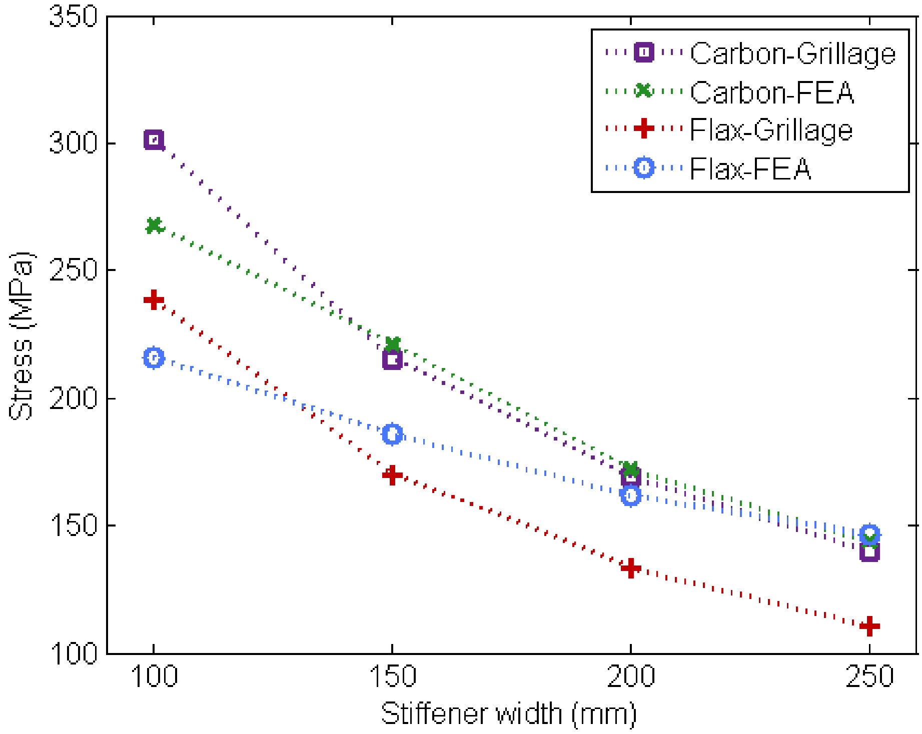
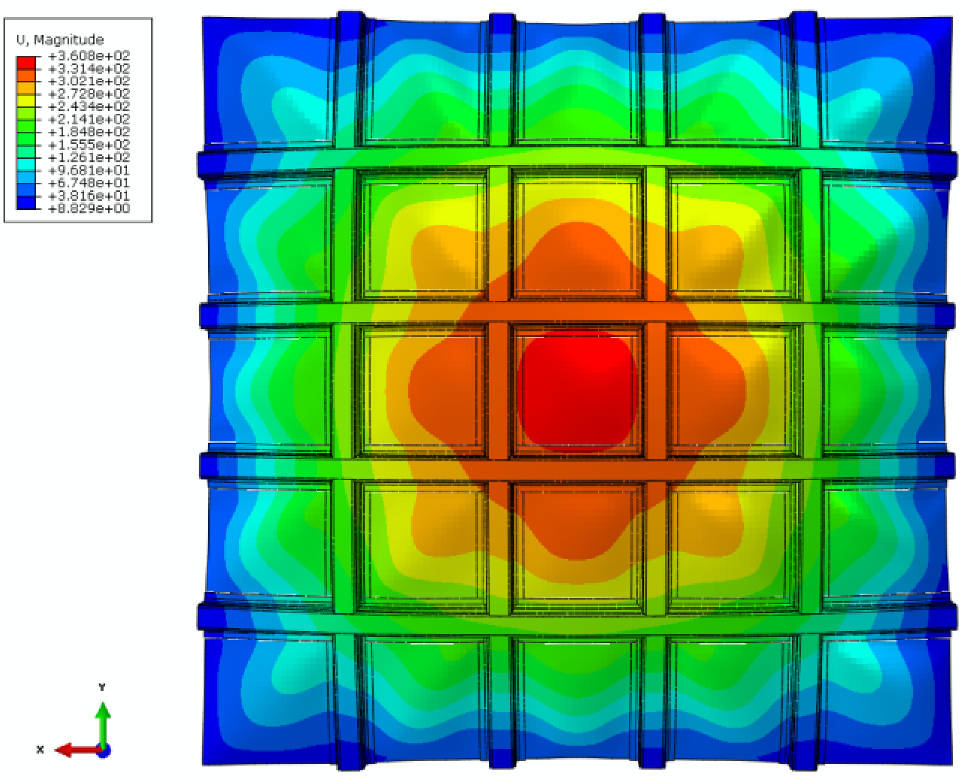


Figure 6: Comparison between top ply stresses obtained with FEA and empirical model for (a) varying stiffener heights and (b) stiffener widths

(a)



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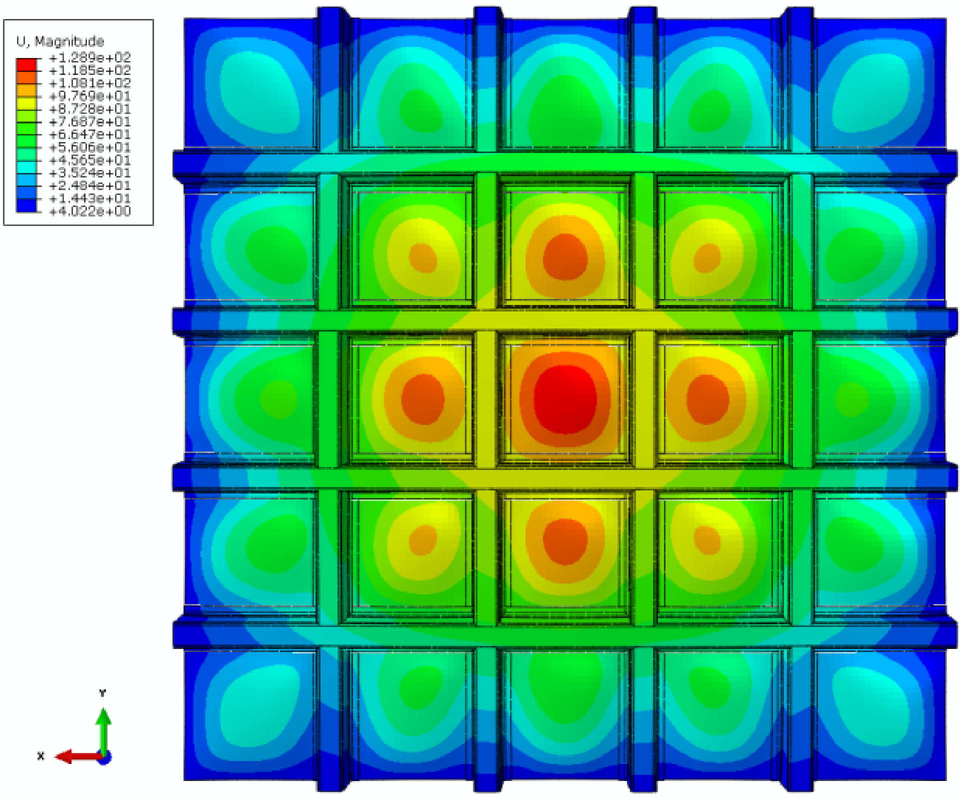
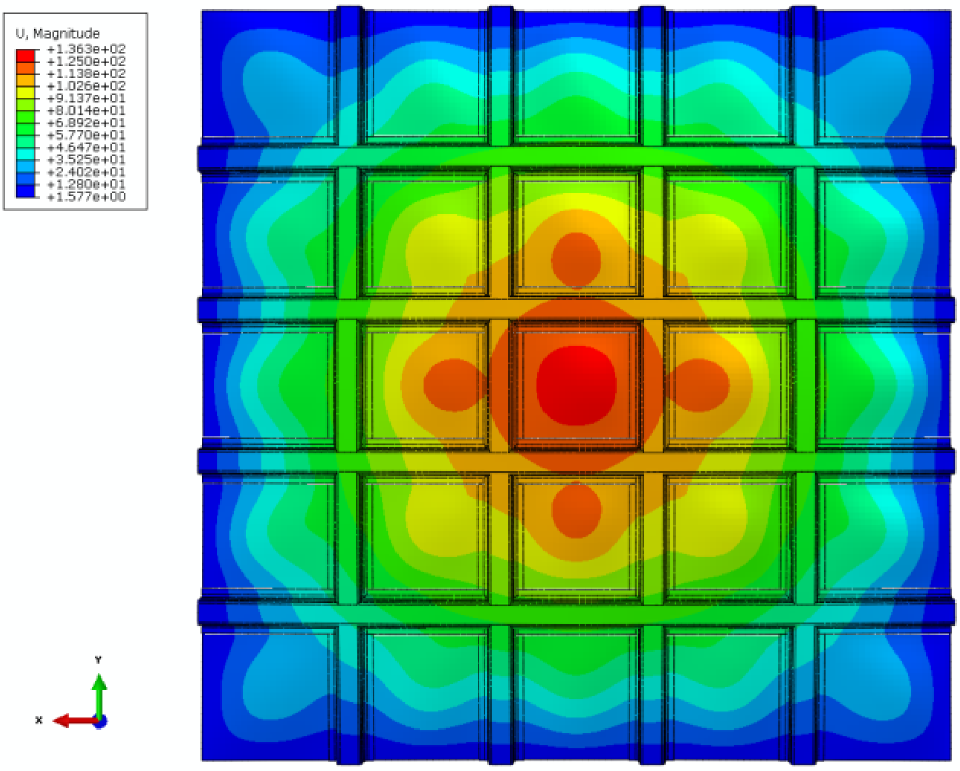


Figure 7: FEA deflection contour plots of the flax grillage for a stiffener height of (a) 100mm and (b) 250mm

(a)



(b)

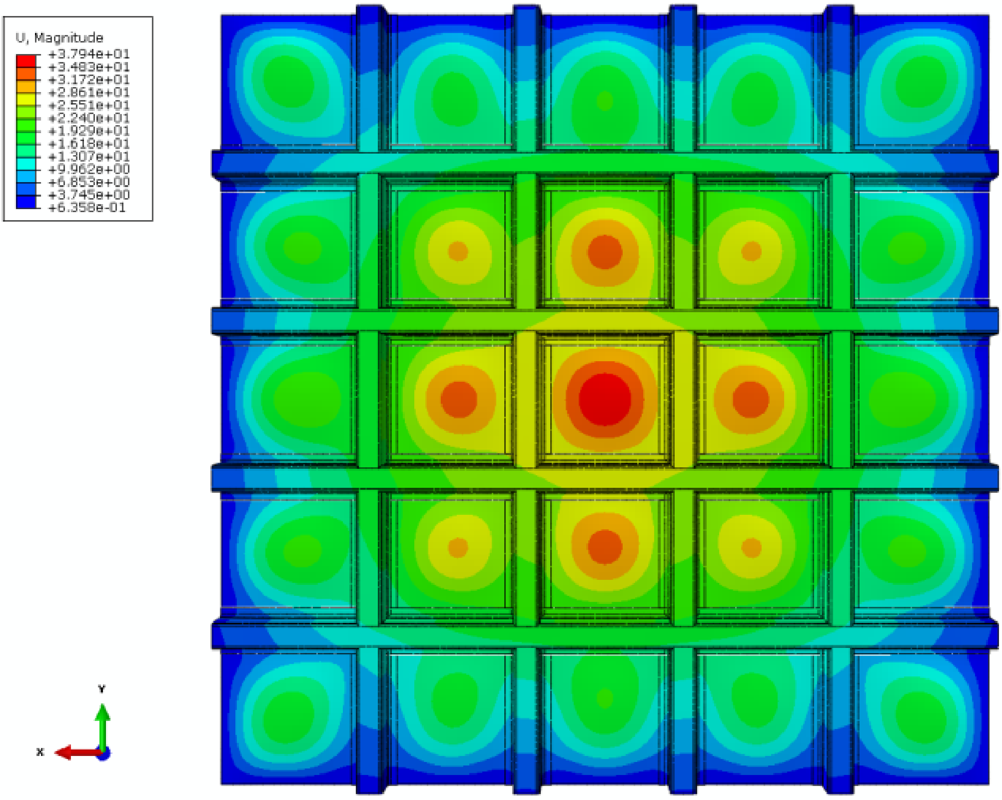


Figure 8: FEA deflection contour plots of the carbon grillage for a stiffener height of (a) 100mm and (b) 250mm