Towards green engineering designs: Natural fibre-based hybrid composites for structural applications

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Abstract—**In this paper, the effect of intra-yarn hybridisation on the macroscopic homogenised properties of natural fibre-based hybrid composites (NFHCs) was computationally investigated. Many researchers have experimentally investigated hybrid effects on their mechanical properties. Only a limited number of computational studies on NFHCs have been reported. Four hybrid plain weave laminates: jute-glass, hemp-glass, jute-carbon and hemp-carbon were studied using a two scale modelling approach. The approach is based on homogenisation in which micromechanical representative volume element (RVE) model and mesomechanical repeating unit cell (RUC) model are established separately. The results indicate that hemp-glass hybrid 2D woven composites may be more cost-effective than glass woven composites in structural applications.**

I. Introduction

Composites are made of reinforcing fibres and a polymer matrix that, when used in combination, achieve optimal material properties. Synthetic fibres, such as glass or carbon fibres, have excellent specific strength and stiffness, but a major problem is that they are not biodegradable and not environmentally friendly. On the other hand, natural fibres such as jute, hemp, kenaf, flax, ramie or sisal fibres, are biodegradable and environmentally friendly, and at the same time, they are very cheap and readily available [1]. However, natural fibres may not be sufficient for structural applications. Because the quality of natural fibres is lower than synthetic fibres. Since natural fibres are short in length, it is difficult to arrange them into an orderly composite structure. In addition, the interface between natural fibre and polymer matrix is weak because natural fibre absorbs moisture [2]. Although synthetic fibre reinforced composite offers several advantages over metal and metal alloys in structural applications, some synthetic fibres can be replaced with natural fibres to achieve similar structural performance. The use of two or more fibres in a matrix is called fibre hybridisation. The mechanical properties of hybrid composites are between two fibres and a matrix, in which one fibre balances the deficiencies of the other fibre. Hybrid composites achieve certain characteristics that non-hybrid composites cannot achieve.

The combination of synthetic and natural fibres has been experimentally studied [3-9]. However, different fibre and matrix combinations with different fibre volume fractions require extensive experimental testing. Therefore, experimental methods to study all these combinations seem to be expensive and time-consuming. On the other hand, Finite Element Analysis (FEA) of natural fibre-based hybrid composites (NFHCs) appears to be an economic method that has not been widely studied. There are three main hybrid configurations: inter-layer, intra-layer and intra-yarn [10]. The first two configurations [11] have been extensively studied, while the third configuration has received little attention. Hence, this paper investigates the effect of intra-yarn hybridisation on the macroscopic homogenised properties of four hybrid plain weave laminates: jute-glass, hemp-glass, jute-carbon and hemp-carbon.

II. Methodology

A. Overview

A two scale modelling approach was developed to study the mechanical behaviour of NFHCs, in which the micromechanical representative volume element (RVE) model and mesomechanical repeating unit cell (RUC) model were developed separately. These models are based on the volume averaging in the homogenisation process. In micromechanical RVE model, the distribution of fibres within one impregnated yarn is considered. The homogenised material properties of the yarn at the microscale are obtained first. This is done by homogenising the mechanical properties of both matrix and fibres constituents within one impregnated yarn. Then, the homogenised material properties of yarns can be input into mesomechanical RUC model. Consequently, the homogenised material properties of the textile composite at the mesoscale are then obtained. This is done by considering the internal structure of textile composites, in this case, repeating textile unit cell.

B. Micromechanical model

The random sequential expansion (RSE) algorithm [12] was modified in this paper to generate random fibre distributions of two fibres with two different radii. In this algorithm, one fibre is around the first fibre within the bounded inter-fibre spacing without overlapping. When no more fibres can be added around the first fibre, the algorithm proceeds to add fibres around the second fibre. The matrix is assumed to be an isotropic material and the fibres are assumed to be transversely isotropic material. All fibres are assumed to have a constant circular cross-section.

Perfect bonding between matrix and fibres is assumed and interphase between matrix and fibre is neglected. The length and width of RVE model are set 20 × the radius of larger fibre, as this is sufficient to compute homogenised material properties. The micromechanical RVE model was meshed using linear elastic 8-node hexahedral 3D solid reduced integration and hourglass control (C3D8R) elements. The element size of approximately 0.7 μm is considered to be the optimum mesh size to accurately characterise the effective elastic constants of unidirectional FRCs [13]. Thus, it is adopted in this study. A total of seven simulations were generated for each set of volume fractions with an average element size of 0.7 μm, and only one element through the thickness direction.

C. Mesomechanical model

TexGen is used to generate the geometry of the 2D woven textile. The modelling of yarn is based on three geometric properties: yarn cross-section, yarn path, and yarn volume fraction. In this study, yarns were assumed to be orthotropic materials with lenticular cross-sections and sinusoidal paths. The fibre volume fraction within one yarn is (V^f) and the volume of yarn in the RUC is (Ω_{yarn}). The volume of RUC is (Ω_{RUC}). Hence the effective fibre volume fraction ($\hat{V}^f$) of the RUC is calculated as follows:

$$\hat{V}^f = V^f \frac{\Omega_{\text{yarn}}}{\Omega_{RUC}} \quad (1)$$

The mesomechanical RUC model was meshed using voxel elements. Voxel mesh is formed by dividing the overall volume into rectangular parallelepiped cuboid elements (C3D8). The voxel elements are automatically generated in TexGen. Voxel-based meshing method is employed because voxels can be repetitively refined without mesh distortion problems, yarn volume fractions can be easily controlled and periodic boundary conditions can be easily applied [15].

D. Homogenisation of mechanical properties

The unit cell model developed by Li and Wongsto [16] is faithfully utilised in this paper to investigate NFHCs. This includes creating geometries, meshing parts, applying periodic boundary conditions (PBCs) and extracting material properties of the model. The mesomechanical models follow a similar approach to the micromechanical models. The difference between micromechanical models and mesomechanical models lies in different geometries and meshes, while the rest procedure remains the same. All simulations are performed in ABAQUS [17]. A complete set of constraint equations for the PBCs of a unit cell and loading cases can be found in [18] and will not be repeated here.

III. RESULTS AND DISCUSSION

A. Micromechanical model

Four NFHCs were investigated using the two-scale modelling framework: jute-glass, hemp-glass, jute-carbon and hemp-carbon. The total fibre volume fraction was fixed at 0.6, and the volume fraction of the two types of fibres was different. The material properties of each constituent used in the simulations are shown in Table I. For all four NFHCs, seven different volume fractions were examined and for each volume fraction, seven different microstructures were generated.

The predicted specific material properties of yarns in all four NFCHs were compared with rule of hybrid mixtures (RoHM) [19] (Figure 1). The predicted specific longitudinal modulus (E_1) does not vary microstructures as the standard deviation is close to zero and matches well with those predicted by RoHM. For hemp-carbon and jute-carbon hybrid composites, the overall specific E_1 decreases as the volume fraction of natural fibre increases. This is because the specific E_1 of carbon fibre is much higher than the specific E_1 of hemp fibre and jute fibre. The overall specific E_1 increases with the increase of the hemp fibre volume fraction for hemp-glass hybrid composites. This means that adding hemp fibre to the hemp-glass hybrid composite will optimise the specific E_1. For the jute-glass hybrid composites, as the volume fraction of natural fibre increases, the specific E_1 decreases slightly. Hence jute-glass composites can be a cost-effective alternative for glass FRCs if high specific E_1 is not required. The highest significant variation can be seen in the predicted specific longitudinal Poisson's ratio (ν_{12}) and they are all higher than the specific ν_{12} predicted by RoHM, especially hemp-carbon hybrid composite. The diameter ratio of hemp fibre and carbon fibre is highest in the four cases (Table I). Therefore, it can be asserted that specific ν_{12} has a higher variability because of the higher diameter ratio between the natural and synthetic fibres.

TABLE I. MATERIAL PROPERTIES OF THE CONSTITUENTS [1, 20-22]

Material	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12}	ν_{23}	Density (g/cm^3)	Diameter (μm)
E-glass	73	73	30.4	30.4	0.2	0.2	2.5	15
Jute	27.6	5.5	2.5	2*	0.34*	0.40*	1.3	20
Hemp	70.0	14	6	5*	0.40*	0.40*	1.5	30
Carbon	230	40	24	14.3	0.27	0.35	1.8	10
Epoxy	3.4	3.4	1.49	1.49	0.14	0.14	1.046	

* Assumed

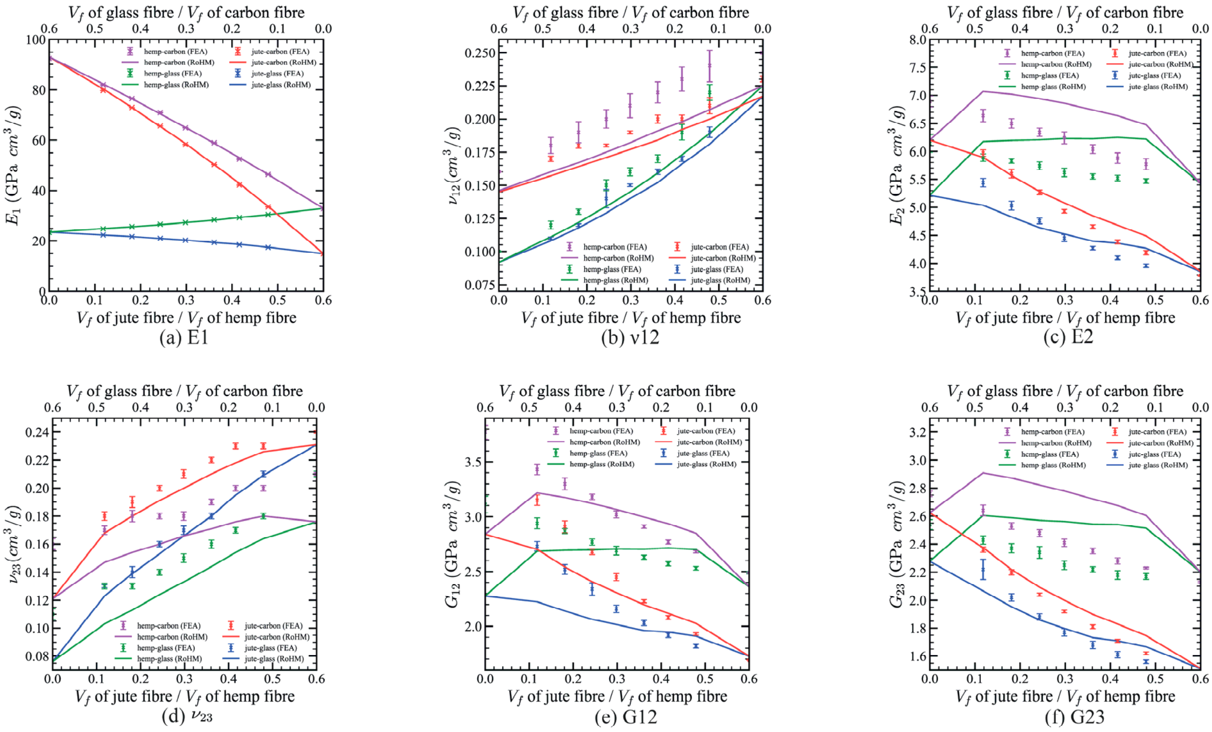

Figure 1. Comparison of the predicited micromechanical material properties: (a) E_1, (b) ν_{12}, (c) E_2, (d) ν_{23}, (e) G_{12}, (f) G_{23}, calculated using FEA with sample size N=7, with those calculated using rule of hybrid mixtures (RoHM) over a range of natural fire volume fractions for all four hybrid systems: jute-glass, hemp-glass, jute-carbon, hemp-carbon

B. *Mesomechanical model*

The geometry of mesomechanical RUC model is shown in Figure 2. Ω_{yarn} , V^f and $\hat{V}^f$ are 0.60, 0.54 and 0.32 respectively. The predicted specific material properties of plain weave for all four cases using both coarse voxel mesh with 64,000 elements and fine voxel mesh with 125,000 elements were compared with the analytical plain weave model developed by Szablewski [23] and is shown in Figure 3. In the figure, the bottom x-axis represents the relative volume fraction of natural fibres in one impregnated yarn, and the top x-axis represents the relative volume fraction of synthetic fibres in one impregnated yarn. The difference between the predicted specific material properties using fine mesh and coarse mesh is negligible (Figure 3), thus the selected fine mesh size should be sufficient to obtain a convergence result of homogenised material properties. Similarly, for hemp-carbon and jute-carbon hybrid composites, the overall specific E_1 decreases as the volume fraction of natural fibre increases. The overall specific E_1 increases with the increase of the natural fibre volume fraction for hemp-glass hybrid composites. This means that adding hemp fibre to the hemp-glass hybrid composite will optimise the mesoscale specific E_1. For all four NFHCs, except for the specific E_1, the matching of the specific material properties is inconsistent. This is because the textile geometry modelling in FEA and analytical solution are different. However, the trends for specific G_{12} and G_{23} are similar.

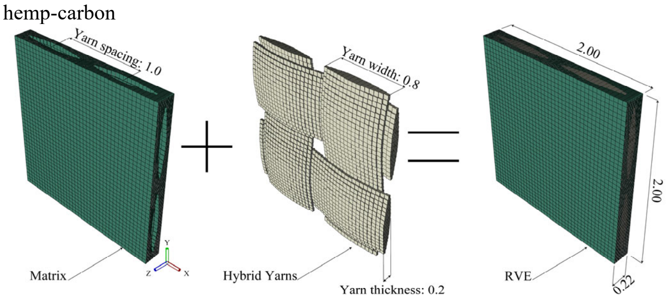

Figure 2. Plain weave composite *(Unit: mm)*

IV. Conclusion

In summary, macroscopic homogenised properties are a function of relative volume fraction of the fibres constituent. The overall specific E_1 increases with the increase of the hemp fibre volume fraction for hemp-glass hybrid composites. This happens in both micro and meso scales. The results indicate that hemp-glass hybrid 2D woven composites may be a cost-effective alternative to glass woven composites for secondary structure applications.

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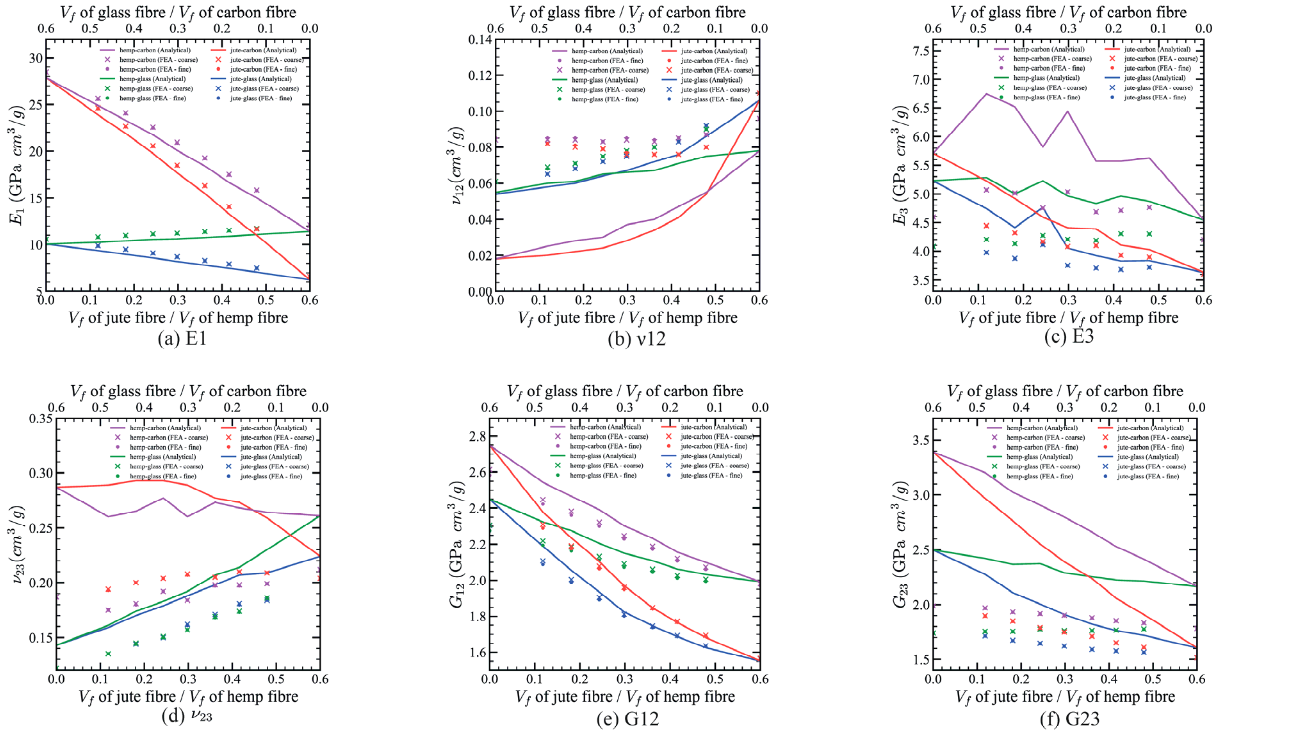

Figure 3. Comparison of the predicited mesomechanical material properties: (a) E_1, (b) ν_{12}, (c) E_3, (d) ν_{23}, (e) G_{12}, (f) G_{23}, calculated using FEA with fine and coarse voxel meshses, with those calculated using the analytical model developed by Szablewski [23] over a range of natural fire volume fractions for all four hybrid systems: jute-glass, hemp-glass, jute-carbon, hemp-carbon

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