Experimental and numerical characterization of mechanical properties of hemp fiber reinforced composites using multiscale analysis approach

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Abstract

Synthetic fibers are mainly considered as a source of reinforcement in many composites that have been studied so far. As a continuous effort is being made in the entire world to develop more sustainable products and systems, fibers obtained from natural sources (hemp, flax, jute, etc.) are being considered as substitutes to the synthetic fibers which are commonly used these days. In this study, the tensile, flexural and interlaminar shear strength properties of hemp fiber composites, bonded with an epoxy matrix, are characterized. Three-point bending tests were conducted on the hemp fiber composites and their failure modes were inspected using micrographs and documented. The short-beam shear method was utilized to investigate the interlaminar shear strength of these composites. Hemp fiber composites were found to have considerably lower flexural strength as compared to typical glass fiber/epoxy composites. Lastly, multiscale analyses were performed for the tensile case to predict the response of these composites by conducting simulations at fiber tows and matrix level rather than using typical finite element approach of homogenized properties at ply level with Altair's multiscale designer software (MDS). In the multiscale macro-simulations, a unit cell with twill weave configuration was developed, and the response of the unit cell under tensile loadings was compared to the experiment results. Excellent Correlation was achieved between numerical and experimental results for *unnotched tension/compression* MDS macro-simulation. A parametric study was conducted to investigate the effect of fiber tow minor radius on the tensile response of the hemp/epoxy composites keeping rest of the geometric parameters of unit cell similar. The smaller minor tow radius predicted higher yield and ultimate strengths as compared to larger ones. A stochastic analysis was also performed to investigate the effects of variations in the geometric unit cell parameters on the young's modulus of hemp/epoxy composite.

Keywords Hemp fiber · Mechanical properties · Multiscale analysis

1 Introduction

Currently, most composites utilized in the industry are composed of synthetic-type fibers, such as glass fiber and carbon fiber, and thermoset epoxies. Synthetic fibers have fantastic mechanical properties and can be manufactured to very precise specifications for their respective applications. Thermoset epoxies have high strengths and great durability. These advantages, however, come at a cost. The

product typically cannot be completely reused or recycled. Instead, at the end of the product's life, disposal is required to some extent, which is limited to landfill or incineration [1].

In contrary, natural fibers that come from renewable resources are eco-friendlier. Some natural fibers that have been of main interest include sisal, flax, hemp, jute and bamboo. Hemp plants contain strong and stiff plant fibers within the stem, which help hold the plant upright,

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meaning they have the necessary characteristics to be useful as a composite material reinforcement [2]. The key factors in the determination of a natural fiber's mechanical properties are its cellulosic, hemicellulosic and lignin content [3]. The benefits of reinforcing composites with hemp fibers include low cost, low density, high stiffness-to-weight ratio and easy processability [3–5]. The industrial sector and academic community have shown interest in natural fibers and their composites due to these advantages. Applications of natural fiber composites include components such as seat backs, pillar covers, parcel shelves, dashboards and headliner panels [6–9]. Natural fiber composites can be utilized in sports commodities [10], the construction industry [11] and other consumer products.

Continuum damage mechanics models have been utilized for characterizing the failure in composites for a few decades now. However, their use to predict the response of natural fiber composites is fairly recent. Panamoottil et al. [12] predicted the tensile failure of thermoplastic and thermoset matrix-based flax fabric composites by combining experimentally determined damage rules with discrete representations of fabric geometry. The analytical/semi-analytical models that have been used for natural fiber composites are based on point stress criterion that is semiempirical [13] and modified point stress criterion [14, 15]. These damage criteria can only be applied within the limits from which their test data are derived. Bougherara et al. [16] used an energy-based damage model to investigate the damage growth of angle-ply $[\pm 45]_{16}$ flax-reinforced epoxy composites. They found out that the above-mentioned damage model was able to predict the damage rate in both fiber and matrix directions under applied loads. Pan and Zhong [17] conducted research activity to predict material property degradation of sisal fiber composites due to moisture absorption through the proposed micromechanical model. Modified Mori–Tanaka method was used in this study after introducing a damage variable to consider mechanical property degradation.

Zhong et al. [18] reviewed the studies corresponding to microstructures, mechanical behavior and numerical modeling of plant fiber composites. Misnon et al. [19] studied the characteristics of woven hemp fiber for composite reinforcement and found that woven hemp fabrics are suitable for composite reinforcement. Panamoottil et al. [20] predicted the failure of unidirectional flax fabrics in a polypropylene matrix under quasi-static tensile loading by applying an anisotropic continuum damage modeling approach. They showed that modeling the geometric model closely to actual fabric geometry and using an experimentally-determined material degradation model can yield good mechanical response of the composite. Panamoottil et al. [21] proposed a hierarchical framework to investigate the macroscale properties of composites based on

the properties of microscale. They used this framework to obtain properties of impregnated fiber tows from the characteristics of the fibers, the matrix material and the interface between them. Russo et al. [22] compared the performance and damage extent in jute, flax and basalt fibers composites impregnated in a polypropylene matrix and subjected to flexural loads. Vishwas et al. [23] performed a comparative study investigating the damage response of glass–epoxy (GE), jute–epoxy (JE) laminates and jute–rubber–jute (JRJ) sandwich composites using ABAQUS/CAE finite element software. No delamination was observed in JRJ sandwich composites as opposed to GE and JE laminates. This study also indicated that due to the compliant nature of rubber, JRJ sandwich composites absorbed more energy than GE laminate composites. Xiong et al. [24] recently developed multiscale constitutive models to investigate the mechanical properties of plain woven composites. The predicted results showed that the yarn twist angle has significant effects on the elastic properties of the composites.

It was found out that in terms of numerical simulations, the plant fiber composites have not received sufficient attention as synthetic fibers composites [25, 26]. It was also found after detailed literature consultation that research studies involving the mechanical characterization of hemp fiber-reinforced epoxy composites at unit cell level are rather scant. In light of these facts, this study was developed to examine the mechanical behavior of hemp fiber–epoxy composites. In this study, the tensile, flexural and interlaminar shear strength properties of hemp fiber composites, bonded with an epoxy matrix, are characterized in order to have a better understanding of the response of hemp/epoxy composites under mechanical loadings. The main aim of this research study was to find out the possibility of replacing the synthetic fibers (Eglass) with the natural fibers (hemp) under similar mechanical loading and having the same fiber volume fraction. It was found out that hemp might only be a suitable replacement in non-structural, low load-bearing applications to prevent early product failure and frequent replacement. The multiscale analysis simulation performed in this research study helps to predict the response of the system at fiber tow and matrix scale rather than at homogenized ply level. Thus, the practical multiscale approach considers the effects of unit cell geometric parameters on the mechanical response of the hemp/epoxy composites and predicts the response of the system more accurately and consistent with experimental results.

2 Materials and methods

A woven 100% hemp fabric, which could be easily wetted with an epoxy matrix, was utilized as reinforcement in this research study. Hemp composite panels having thickness

of 1.91 ± 0.04 mm were manufactured with hand lay-up method using 15 g of epoxy resin and 3 g of hardener per layer with an additional 10 g of epoxy resin and 2 g of hardener per 304.8 mm $\times$ 304.8 mm composite to complete the wetting process. The fiber volume fraction in the laminates was 55%. Flat steel mold plates were used to cure hemp fibers/epoxy composite specimens. The removal of specimens after solidification was facilitated by applying a mold release agent to steel plates. The entire system, including mold plates and uncured specimens, was placed in the vacuum press to cure the hemp/epoxy-laminated composite specimens. In the curing cycle, the stacked hemp fiber/epoxy system was kept under pressure of 0.35 MPa at 135 °C temperature for a time duration of 60 min. The vacuum condition was applied during the whole cure cycle to prevent the formation of air bubbles. In the cool down phase of the curing cycle, the composite system was brought to room temperature by passing mist and water over the molding plates each for 15 min. After the execution of the curing process, the fully solidified laminate was removed from the flat molding plates. Six samples of five-ply hemp fiber were tested in each tension, shear and three-point bending tests. The viewgraphs of fracture surfaces were obtained by using 50x/0.15 BD P microscopic magnification lens from failed specimens. Typical SEM cross-sectional image of the composite is shown in Fig. 1.

3 Tensile tests

Tensile tests on hemp/epoxy laminate specimens were done as per ASTM D3039 test method. Hemp/epoxy laminate of 250 mm $\times$ 250 mm with five layers of hemp fiber

Fig. 1 Typical cross-sectional image with the fiber characteristics

cloth (thickness 1.91 ± 0.04 mm) was cured for tensile tests. Laminates were cut into 200 mm $\times$ 25 mm test coupons with 38 mm grip length on each side. The rectangular cross section of test coupons is maintained to avoid failure near the grip. Due to the soft nature of hemp/epoxy composites, to avoid enormous pressure on the coupon, grit paper was used on the laminate in the gripping. Extensometer is used to obtain strain from the coupon. The hemp fiber composites were tested to determine the tensile properties in the longitudinal direction. From the load–displacement data of machine, the stress–strain curve was plotted. The values of tensile modulus, maximum strength and failure strain were calculated from the experimental plots.

4 Shear tests

Interlaminar shear properties of hemp/epoxy laminate were obtained from short-beam tests. Laminate with five plies was cut into 25 mm $\times$ 25 mm coupons for short-beam shear testing. Multiaxial stresses of both bending and shear in nature are applied on the specimen in three-point bending test. Shear stress was dominated in specimens with small span-to-thickness ratio. The load–displacement data obtained from the machine were plotted, and interlaminar stress is calculated from Eq. 1.

$$\sigma = \frac{3P}{4bh} \quad (1)$$

5 Three-point bend tests

An MTS machine with a load capacity of 200 kN was used to carry out the flexure tests. Three-point bending fixture from Wyoming Test Fixtures Inc. was employed for testing the hemp/epoxy composite beams. The diameter of the support cylinder was 12.7 mm, and the span length of the beam was kept equal to 60 mm. Quasi-static flexural tests were conducted in displacement control mode by pushing the bottom supports against the laminated beam at a rate of 3 mm/min. Load, displacement and time data were recorded for every 0.5 s by the computerized controlled machine. These output data were then analyzed by using the displacement and force data to calculate stress and strain values using the following equations, respectively.

$$\sigma_f = \frac{3PL}{2bd^2} \quad (2)$$

$$\varepsilon_f = \frac{6Dd}{L^2} \quad (3)$$

where σ_f represents stress in the outer fibers at midpoint, MPa; ε_f represents strain in the outer surface, mm/mm; P represents load at a given point on the load–deflection

curve, N ; L represents support span, mm; b represents width of beam tested, mm; D represents maximum deflection of the center of the beam, mm and d represents depth of beam tested, mm. To obtain useful data, six samples of five-ply hemp fiber (thickness 1.91 ± 0.04 mm) were tested, and the readings were compressed and combined into a single graph.

6 Multiscale analysis

Multiscale designer is an accurate and efficient tool for building multiscale material models and performing material characterization analysis for components developed from any heterogeneous material including, but not limited to, continuous and chopped fiber composites, honeycomb cores, lattice structures, reinforced concrete, soil, bones, etc. The entire multiscale simulation takes benefit from the natural division at various length scales between microstructure, fiber/matrix, tow/matrix ply, laminate and component which are found in composite structures. This natural separation allows the multiscale technique to be employed at particular length scale for any one entity (e.g., fiber tows) to compute its properties, developing a constitutive model through homogenization and giving the response to the higher level for characterizing the mechanical behavior of the larger component (e.g., individual plies). Therefore, in the multiscale technique, an analysis is executed by passing the information between various length scales and not by coupling different global–local simulation techniques. In this study, the tensile response of the hemp/epoxy fiber composite was modeled by using twill weave unit cell capabilities of multiscale designer software. The steps involved in multiscale analysis using MDS software are given as follows.

6.1 Unit cell definition

Initially, the twill weave unit cell model was developed using multiscale designer (MDS). The woven twill weave unit cell model requires five parameters to be defined. The cross section of each tow is assumed to be an ellipse. The XY -plane is the plane of the weave with the z -direction as thickness direction. Different tow spacing values in each of the two in-plane directions can be specified during the unit cell creation. The description and the specific values of geometric attributes of twill weave unit cell are given in Fig. 2 and Table 1. The twill weave woven unit cell having 2×2 pattern was created using the minimum spacing as a real-time assistant option, and the direct element size used was 0.25.

6.2 Linear material characterization

After the unit cell definition and the meshing of the unit cell model using hypermesh in batch mode, the linear material characterization step was performed. Linear material properties such as density, thermal conductivity and diffusivity and differential vector fields (such as elastic mechanical properties) were defined in the linear characterization step of the analysis. Forward homogenization approach was chosen to calculate macro-elastic material parameters of the unit cell for each type of field. In the

Table 1 Geometric attribute values used in this study

Geometric attributes	
Tow major radius; w	5 mm
Tow minor radius; z	0.6 mm
Tow center spacing in x -axis; a	12 mm
Tow center spacing in y -axis; b	12 mm
Tow volume fraction (%)	55

Fig. 2 Geometric attributes description for twill weave unit cell

forward homogenization approach, all the micro-phase properties were prescribed a priori, and the corresponding macro-unit cell homogenized properties were computed by solving a forward homogenization problem. In this step, the matrix was modeled with the isotropic material model, whereas tows of the unit cell were modeled by considering transversely isotropic material model [27]. The constitutive equations for isotropic and transversely isotropic material models are given as:

- The isotropic material stiffness matrix

$$\begin{bmatrix} \delta + 2\varphi & \delta & \delta & 0 & 0 & 0 \\ \delta & \delta + 2\varphi & \delta & 0 & 0 & 0 \\ \delta & \delta & \delta + 2\varphi & 0 & 0 & 0 \\ 0 & 0 & 0 & \varphi & 0 & 0 \\ 0 & 0 & 0 & 0 & \varphi & 0 \\ 0 & 0 & 0 & 0 & 0 & \varphi \end{bmatrix} \quad (4)$$

where

$$\delta = \frac{\nu E}{(1 + \nu)(1 - 2\nu)} \text{ and } \varphi = \left(\frac{E}{2(1 + \nu)} \right) \quad (5)$$

$$\text{Stability Conditions : } E > 0 \text{ and } -1 < \nu < 0.5 \quad (6)$$

- Material stiffness matrix for transversely isotropic linear material law (23-plane of isotropy)

$$\begin{bmatrix} n & l & l & 0 & 0 & 0 \\ l & k + m & k - m & 0 & 0 & 0 \\ l & k - m & k + m & 0 & 0 & 0 \\ 0 & 0 & 0 & m & 0 & 0 \\ 0 & 0 & 0 & 0 & p & 0 \\ 0 & 0 & 0 & 0 & 0 & p \end{bmatrix} \quad (7)$$

where

$$G_{23} = \left(\frac{E_2}{2(1 + \nu_{23})} \right); \quad \nu_{21} = \frac{\nu_{12}E_2}{E_1};$$

$$k = -\frac{1}{\left\{ \left(\frac{1}{G_{23}} \right) - \left(\frac{4}{E_2} \right) + \frac{4\nu_{12}^2}{E_1} \right\}}; \quad l = 2k\nu_{12} \quad (8)$$

$$n = E_1 + \frac{l^2}{k}; \quad m = G_{23} \text{ and } p = G_{12} \quad (9)$$

Stability conditions: $E_1, E_2, G_{12}, G_{23} > 0$; $|\nu_{23}| < 1$; $|\nu_{21}| < \sqrt{E_2/E_1}$; $|\nu_{12}| < \sqrt{E_1/E_2}$ and

$$1 - \nu_{23}^2 - 2\nu_{21}\nu_{12} - 2\nu_{23}\nu_{21}\nu_{12} > 0 \quad (10)$$

Table 2 Fiber and matrix phase properties for linear material characterization

Fiber micro-properties (GPa)		Matrix micro-properties (GPa)	
Parameter	Value	Parameter	Value
E_1	20	E (GPa)	3.4
E_2	3.5	ν	0.36
ν_{12}	0.28		
ν_{23}	0.28		
G_{12}	4.24		
E_{1-C}	1.5		

The micro-properties used for modeling matrix and fiber are given in Table 2. The 21 independent engineering constants that define the anisotropic stiffness matrix within the linear elastic regime are determined by placing a specimen of material under six different strain boundary conditions given by Eqs. 11–16. The macro-unit cell homogenized linear elastic engineering constants were calculated based on the micro-phase linear elastic engineering constants.

$$\varepsilon_1 = 1, \varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0 \quad (11)$$

$$\varepsilon_2 = 1, \varepsilon_1 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0 \quad (12)$$

$$\varepsilon_3 = 1, \varepsilon_1 = \varepsilon_2 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0 \quad (13)$$

$$\gamma_{12} = 1, \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{23} = \gamma_{13} = 0 \quad (14)$$

$$\gamma_{23} = 1, \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{13} = 0 \quad (15)$$

$$\gamma_{13} = 1, \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = 0 \quad (16)$$

6.3 Reduced-order model computation

The computational cost was reduced to considerably low levels through the reduced-order calculations in the non-linear material characterization and subsequent nonlinear macro-analysis. The total number of degrees-of-freedom in the unit cell is decreased by using the reduced-order model (ROM) technique [28]. A series of influence function problems are solved, and calculated tensors are obtained as a material database of the reduced-order unit cell. Phase average theory [29] is a classic example of reduced-order model. In the reduced-order unit cell model, the optimal influence functions depend on considering that whether a particular failure mode is a matrix or fiber dominant within each inclusion phase of the unit cell; the option to make this choice for each inclusion phase of the unit cell

is provided in MDS. In this study, for the Tow_X and Y fiber phases of the unit cell, the xx deformation modes were considered as inclusion dominant, and the remaining five deformation modes were taken as matrix dominant.

6.4 Nonlinear material characterization

After the computation of the reduced-order model data, the nonlinear material characterization step was performed. The inverse homogenization approach was used to compute the nonlinear macro-homogenized properties of the unit cell. In the inverse characterization approach, the nonlinear macro-homogenized properties are defined (typically based on experimentally observed test data from one or more coupon tests) and the unknown nonlinear micro-properties are characterized by solving the inverse optimization problem. For an inverse characterization of the mechanical solution sequence, macroscopic stress–strain experimentally observed test data from different coupon tests can be considered simultaneously in constructing the inverse optimization objective function. The nonlinear material characterization (simulation) with the inverse homogenization approach was performed by assigning each micro-phase a damage law and entering the necessary nonlinear parameter values. In the nonlinear material characterization, matrix phase is modeled with the orthotropic damage and plasticity continuum damage model, whereas the Tow_x and Tow_y phases were modeled with the orthotropic damage bilinear continuum damage model.

Overall, the continuum damage model formulation within multiscale designer follows the continuum damage mechanics (CDM) framework. In the continuum damage mechanics framework, material degradation is formulated by the degradation of the elastic stiffness tensor L_{ijkl}^0 by the damage state variable, a scalar (w) or a higher-order

tensor W_{ijkl} . Damage initiation and evolution are assumed to be a function of a scalar strain invariant $\hat{\varepsilon}$ or individual principal strains ε_i . Kuhn–Tucker complementarity condition and consistency condition must be satisfied to ensure that the damage accumulation can only take place on the damaged surface and persist on the surface. The formulation equations for the damage evolution in the isotropic damage and plasticity model are described below.

Elastic stress–strain relationship

$$\sigma_{ij} = (1 - W)L_{ijkl}(\varepsilon_k = \varepsilon_{kl}^p) \quad (17)$$

Scalar equivalent strain or the volumetric strain (J_1)

$$\hat{\varepsilon} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \quad (18)$$

Damage criterion

$$g(\hat{\varepsilon}, r) := \hat{\varepsilon} - r \leq 0 \quad (19)$$

Damage evolution

$$\dot{w} = \gamma H(\hat{\varepsilon}) \quad (20)$$

$$\dot{r} = \gamma \quad (21)$$

Kuhn–Tucker complementarity conditions

$$\gamma \geq 0, g(\hat{\varepsilon}, r) \leq 0, \gamma g(\hat{\varepsilon}, r) = 0 \quad (22)$$

Consistency condition

$$\gamma \dot{g}(\hat{\varepsilon}, r) = 0 \quad \text{if} \quad g(\hat{\varepsilon}, r) = 0 \quad (23)$$

The micro-properties used for modeling matrix and tows in nonlinear material characterization are given in Table 3. A schematic representation of orthotropic damage and plasticity model parameters is shown in Fig. 3. The nomenclature of the parameters given in Table 3 is

Table 3 Tow and matrix phase properties for nonlinear material characterization

Tow-x and tow-y micro-properties					Matrix micro-properties				
Parameter	Value	Active	Lower bound	Upper bound	Parameter	Value	Active	Lower bound	Upper bound
$\sigma_{0(1)}$ (GPa)	0.12	✓	0.1	0.16	σ_Y	0.0326	✓	0.0286	0.050
$\varepsilon_{1(1)}$	0.2	✓	0.16	0.3	σ_1	0.0532	✓	0.070	0.12
$\sigma_{0(2)}$ (GPa)	0.1	✓	0.007	0.12	δ_{42}	1000	✓	800	1200
$\varepsilon_{1(2)}$	0.017	✓	0.0119	0.018	H	0.0034	✓	3	10
$\sigma_{0(1)_C}$ (GPa)	0.16				θ	1			
$\sigma_{0(2)_C}$ (GPa)	0.13				β	0.15			
D_{12}	0.0				ε_{p0}	1.0			
D_{23}	0.0				ε_{p1}	1.1			
					σ_{mean}	0.0283			
					J_1	0.008			
					C	0			
					W_{max}	1.0

Fig. 3 Orthotropic damage and plasticity model parameters

as follows: σ_y is yield strength, σ_1 is ultimate strength, δ is exponent for the evolution law, H is the linear term for the hardening law, θ is the balance factor for kinematic and isotropic hardening, β is the parameter accounting for increase in yield strength based on the volumetric strain (J_1), ε_{p0} is equivalent plastic strain at which damage begins, ε_{p1} is equivalent plastic strain at which damage causes zero stress, σ_{mean} is the mean stress at damage initiation $= (\sigma_1 + \sigma_2 + \sigma_3)/3$, J_1 is volumetric strain to failure $= (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$, C is the compression factor and W_{max} is the maximum allowable damage. D_{12} and D_{23} are shear factors in the axial and transverse direction.

7 Results and discussion

7.1 Experimental results

7.1.1 Tensile properties

The Young's modulus is essentially the measurement of the stiffness of a material, or the material's opposition to

elastic deformation, and is represented by the slope of the elastic region line of the stress–strain curve (first part of the graph). The ultimate tensile strength (UTS) is a measurement of the maximum stress that a material, which is being stretched, can resist before breaking. The tensile stress–strain graphs for the hemp/epoxy-laminated composite are plotted in Fig. 4. A bilinear nature is observed in the tensile stress–strain plots before the failure of specimens at particular strain levels. The elastic proportionally limit for the hemp fiber composites is relatively small, and this composite material system goes into plastic deformation at very smaller strain levels (≈ 0.0035). The average values of tensile modulus, ultimate tensile strength and failure strain for hemp fiber/epoxy composites were found to be 6.7 ± 0.5 GPa, 70.0 ± 2.5 MPa and 0.0284 ± 0.0028 , respectively. This study indicates that hemp fiber/epoxy composites could achieve a maximum tensile strength of 75 MPa using 55% volume fraction of hemp fiber. The averaged experimental tensile response of hemp/epoxy composites was considered during inverse characterization of nonlinear properties in MDS simulation and is shown in Fig. 5. The mechanical properties of the tested hemp/

Fig. 4 Tensile stress–strain graphs for the hemp/epoxy-laminated composite

Fig. 5 Tensile response of the hemp/epoxy composite used in the inverse characterization

Table 4 Comparative analysis for mechanical properties of flax and hemp/epoxy composites

Parameter	Hemp/epoxy	Flax/epoxy
Tensile strength (MPa)	70	68.29
Young's modulus (GPa)	6.7	5.870

epoxy are compared with the flax/epoxy [30] composites in Table 4. Based on this comparison, the tensile properties of the hemp/epoxy composites studied in the current investigation are found to be comparable to the flax/epoxy composites documented in Table 3 of Ref. [30].

7.1.2 Interlaminar shear properties

The interlaminar shear stress–strain plots obtained through short-beam shear test for the hemp fiber

composites are shown in Fig. 6. A bilinear nature was observed in the shear stress plots also before the failure of specimens at strain levels like the tensile plots. Due to the Poisson ratio effect being smaller in this case, the elastic proportionally limit in the interlaminar shear stress–strain curves is higher as compared to tensile stress–strain curves. The maximum interlaminar shear strength observed in these specimens is 9.4 MPa. The average values of ultimate shear strength and failure displacement for hemp fiber/epoxy composites were found to be 8.86 ± 0.5 and 1.23 ± 0.19 , respectively, in this study.

7.1.3 Flexural properties

The flexural behavior of hemp fiber/epoxy composite beams is plotted in the form of the stress–strain curves in Fig. 7. The stress values plateau out after the elastic limit in these curves before the failure of the samples,

Fig. 6 Interlaminar shear stress graphs for the hemp/epoxy-laminated composite

resulting in the sharp decrease in stress values at strain levels close to 0.063. The average values of flexural modulus, ultimate flexural strength and failure strain for hemp fiber/epoxy composites were found to be 7.35 ± 0.92 , 196.5 ± 8.88 and 0.065 ± 0.007 , respectively, in this study. Natural fibers, as opposed to synthetic, tend to have widely varying thicknesses, which play an influential role in the strength and ductility of a fiber. Figure 7 shows that the hemp composites withstood more stretching or elongation as compared to the typical synthetic fiber composites. The hemp fiber composites reached a failure point as evidenced by the sharp drops in the stress–strain plots for hemp/epoxy samples (around a strain of 0.064). The viewgraph of fracture

surfaces obtained from a failed specimen is shown in Fig. 8.

7.2 Multiscale numerical results

The contour plots for different stresses obtained by applying the six different strain boundary conditions within the linear elastic regime to get homogenized compliance matrix coefficients are shown in Fig. 9. The homogenized moduli and Poisson ratio under both tensile and compression loadings in the linear regime obtained from linear material characterization step are tabulated in Table 5. The predicted tensile modulus (6.67 GPa) has an excellent correlation with the experimental results. The predicted

Fig. 7 Flexural stress–strain graphs for the hemp/epoxy-laminated composites

Fig. 8 Viewgraph showing hemp/epoxy sample fracture surface

stress values in the linear regime under different loadings conditions are shown in Fig. 9.

7.2.1 Unnotched tension/compression (UNT/C)

An unnotched tension/compression (UNT/C) test conforming to ASTM D3039, D3518 and D6641 was performed during the nonlinear material characterization by defining a laminate to calibrate the unit cell predictions with respect to experimental results. The input parameters which used

macro-simulation are given in Table 6. The macro-model coordinate system is as follows: X-axis = specimen in-plane loading direction (applied displacement); Y-axis = specimen in-plane transverse direction; Z-axis = specimen through-thickness direction and laminate stacking direction.

In addition, the results file UCName_NLSim_ (#). hwallci was opened hyperview to obtain contour plot results which are shown in Fig. 10. Finally, the stress vs strain plots obtained from MDS analysis was compared

Fig. 9 Linear material characterization results visualization

Table 5 Homogenized linear regime material properties

Tension data (GPa)						Compression data (GPa)					
Homogenized modulus and Poisson's ratio						Homogenized modulus and Poisson's ratio					
E_x	E_y	E_z	G_{yz}	G_{xz}	G_{xy}	E_x	E_y	E_z	G_{yz}	G_{xz}	G_{xy}
6.674	6.674	1.726	0.533	0.533	0.634	2.155	2.155	1.607	0.524	0.524	0.633
ν_{xy}	ν_{xz}	ν_{yx}	ν_{yz}	ν_{zx}	ν_{zy}	ν_{xy}	ν_{xz}	ν_{yx}	ν_{yz}	ν_{zx}	ν_{zy}
0.121	0.425	0.121	0.425	0.110	0.110	0.305	0.314	0.305	0.314	0.234	0.234

Table 6 Input parameters for UNT/C macro-simulation

Parameter	Value
Loading rate (/s)	0.03
Maximum strain	0.03
Delta temperature	0
Minimum thermal increments	0
Minimum mechanical increments	300

with the typical experimental results, which is shown in Fig. 11. A parametric study was conducted to study the effect of unit cell geometric parameters on the response of composites. For instance, the minor tow radius (w) was chosen as variable while keeping the rest of the parameters identical. The model predicts higher yield and ultimate strength of the hemp composites with a smaller tow radius than that of larger ones. Figure 12 shows the response of hemp/epoxy composites with different minor fiber tow radii. A full-scale stochastic variability analysis was conducted to study the effects of

variabilities in the geometric parameters of unit cell such as tow radii's, tow center spacing and volume fraction on the E_x of the hemp–epoxy composite, and thereby optimize the design variables of unit cell. The log-normal and normal probability distributions with the mean value and standard deviation as shown in Table 7 are considered for running this analysis. Both single variable and multivariable cases are studied using Monte Carlo as the sampling method. The probability and CDF plots of E_x developed by considering each geometric parameter as variable separately are shown in Fig. 13. In the second case, the tow center spacing in x direction, tow volume fraction and tow minor radius were considered as the design variables, and a multivariable stochastic analysis was performed to understand the combined effect of variability in these geometric parameters on the E_x of the hemp/epoxy composite. Figure 14 shows the probability and cumulative density function plots for E_x of the hemp/epoxy composite for this multivariable stochastic analysis.

Fig. 10 Contour plots obtained from macro-unnotched tension/compression single-element simulation

Fig. 11 Comparison between typical experiment results and MDS prediction

Fig. 12 Model predictions of hemp/epoxy composites with different fiber tow minor radii

Table 7 Probability distribution parameters

Parameter	Mean value	# of samples	Distribution	Standard deviation
Tow major radius	5	17	Normal	0.22
Tow minor radius	0.6	68	Normal	0.25
Tow center spacing X	12	100	Log-normal	0.35
Tow center spacing Y	12	100	Log-normal	0.35
Tow volume fraction	52	50	Normal	5

Fig. 13 PDF and CDF plots of E_x of hemp/epoxy composite for different geometric parameters

Figure 15 shows the probability and cumulative density function plots for E_x of the hemp/epoxy composite for the combined multivariable stochastic analysis of tow major and minor radii. The optimum values of the unit cell's geometric parameters with the given variability for which the probability of E_x is the highest are listed in Table 8. Stochastic analysis showed that E_x is highly affected by the combined effect of the tow center spacing, minor radius and tow volume fraction.

8 Conclusions

Mechanical properties of hemp/epoxy composites are characterized in this investigation. Tensile and interlaminar stress–strain plots have a bilinear nature with elastic proportionality limit being relatively smaller in the tensile plots. The average values of tensile and flexural moduli were found to be 6.7 GPa and 7.35 GPa, respectively. Hemp fiber, though it greatly improves the flexural capabilities of pure epoxy and is less expensive than glass fiber, was found to have much less desirable mechanical

Fig. 14 PDF and CDF plots of E_x of hemp/epoxy composite for combined stochastic analysis of tow center spacing X , tow minor radius and tow volume fraction

Fig. 15 PDF and CDF plots of E_x of hemp/epoxy composite for combined stochastic analysis of tow major and minor radii

Table 8 Optimum geometric parameters of unit cell considering value of E_x having maximum probability

Parameter (mm)	Value
Tow major radius	5.15
Tow minor radius	0.515
Tow center spacing X	11.7
Tow center spacing Y	11.7
Tow volume fraction %	57.5

properties than typical glass fiber/epoxy composites (ultimate tensile strength and Young's modulus). This shows that hemp may only be a suitable replacement in non-structural, low load-bearing applications to prevent early product failure and frequent replacement. Areas, where hemp is currently being used, include vehicle interiors, packaging, construction and horse bedding. The multiscale analysis was conducted on tensile behavior of hemp/epoxy composites by developing twill weave unit cell model and thereby considering the effects of fiber tows and matrix on the material response. Excellent

correlation was achieved by using a multiscale analysis approach. Stochastic analysis showed the dominance of different geometric parameters on E_x of composite with the considered standard deviation for these parameters.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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