Prediction of Mechanical Performance of Natural Fibers Polypropylene Composites: a Comparison Study

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Abstract. The future trends of wind turbine blade materials are mostly centered around utilizing lighter materials with improved life cycle and low cost. In modern wind turbine blade, using green composite or biocomposite is a sustainable solution, especially for small wind turbine blade with natural fiber and biodegradable polymer. In this work, four natural fibers (Alfa, Flax, Sisal and Hemp) are used with Polypropylene (PP) thermoplastic polymer. The objective is to evaluate the elastic moduli of composite by two methods; Analytical Mori Tanaka theory and numerical with Digimat MF. The results show a good validation between the two methods. The comparison of the mechanical behaviour of the transversely isotropic of natural fibers indicate that the hemp have a good performance with high Young and shear modulus regarding to their low density, which can offer an excellent candidate for the manufacturing of small wind turbine blades in rural and isolated areas.

Keywords: Biocomposite, Small wind turbine, Natural fiber, Mori-Tanaka

1. Introduction

The biocomposites are fast growing attention in industries because of their excellent advantages such as cheap, recyclable, biodegradable and renewable which can be used in manufacturing of wind or tidal turbine blades [1–3]. Examples for the natural fibers are sisal, flax, hemp, jute and cellulose fiber. The advantages of natural fibers are: low costs, available and environmental friendly. However, their disadvantages are the quality variations, high moisture uptake and low thermal stability of the raw fibers [4]. An interesting option for developing countries is small turbines, producible on-site, and made from bioresources [5]. Most blades are simply cut or shredded for incineration before being permanently buried in landfills, which poses environmental problems since the blades are made from glass and carbon fibres that are not biodegradable [6].
Nevertheless, research interests on natural fiber reinforced composites happened much later in time than high-strength synthetic fibers. Relevant analytical solutions for the prediction of the mechanical properties of natural fiber composites are relatively limited in the reported studies. Several papers therefore present more specialized analytical expressions based on the Mori-Tanaka method for the elastic stiffness of nanocomposites. These expressions are then established for specific composites, containing inclusions with isotropic or anisotropic material properties, with a specific geometric shape, and with either aligned or random orientations. Qiu and Weng [7] have presented a general model for spherical inclusions with anisotropic material properties, also for random oriented needles (or circular fibres), thin discs and spherical inclusions with anisotropic material properties. Tandon and Weng [8,9] have presented a model for the elastic moduli of a composite with unidirectionally aligned isotropic and 3D random oriented inclusions applicable for spheroidal, fibre-like and thin discs with an aspect ratio $\alpha$.

Several homogenization techniques are used in profit of composite in renewable energy production [10–12], and in order to evaluate the mechanical properties of the fiber-reinforced composite. The required quantities are the isotropic mechanical properties of the matrix ($E_m$, $\nu_m$, $\rho_m$) and reinforcing fibers ($E_f$, $\nu_f$, $\rho_f$) which can be isotropic or transversely isotropic. Chamis approach [13] defines the elastic properties of a unidirectional lamina made of anisotropic fibers in an isotropic matrix. Hahn approach [14] allows to obtain the transversely isotropic mechanical properties of a fibrous composite made by fibers with circular cross-section randomly distributed in a normal plane to the direction of the oriented fibers. Hashin–Rosen approach [15] represents a simple approach to compute the mechanical properties of a unidirectional fiber-reinforced composite with an isotropic properties of the fiber and matrix. Halpin–Tsi approach [16,17] evaluates the mechanical properties of the three-phase multiscale composite by using the Hill’s elastic moduli and a semi-empirical approach.

2. Mathematical model

The homogenization concept used in this work is the Mori Tanaka (MT) approach, in order to evaluate the effective transversely isotropic properties of two-phase polymer and fiber composite. There are four natural fibers used in this numerical simulation by Digimat MF (version 2019). Also, the obtained numerical results by Digimat are completely agreed with the analytical model based on Eshelby tensor theory as described below.

Representative volume element (RVE) was constructed maintaining a fiber volume fraction rang (10% - 50%) embedded in polymeric matrix. In the current model, the natural fibers and the polypropylene were treated as isotropic material. The properties of the natural fibers and polypropylene used as inputs are summarized in Tables 1 and 2.

| Natural fibers | Alfa | Flax | Sisal | Hemp |
|----------------|------|------|-------|------|
| Young modulus, $E_f$ (GPa) | 19.4 | 27.6 | 22 | 70 |
| Poisson ratio, $\nu_f$ | 0.34 | 0.45 | 0.32 | 0.4 |
| Density, $\rho_f$ (g/cm$^3$) | 1.52 | 1.38 | 1.2 | 1.35 |

| Properties | Value |
|------------|-------|
| Elastic modulus, $E_m$ (GPa) | 1.6 |
| Poisson’s ratio, $\nu_m$ | 0.4 |
| Density, $\rho_m$ (g/cm$^3$) | 0.92 |
The Eshelby tensor theory is based on considering a homogenous linear elastic solid with volume $v$ and surface area $S$, with an inclusion volume $v_0$ and a surface area $S_0$, as shown in Figure 1. The volume $v$ outside the inclusion is called the matrix. The Eshelby tensor $S_{ijkl}$ expresses the constrained strain inside the inclusion $\varepsilon_{ij}^c$ to its eigenstrains $\varepsilon_{ij}^e$:

$$\varepsilon_{ij}^c = S_{ijkl} \varepsilon_{kl}^e$$ (1)

Since this tensor relates two strain tensors, the Eshelby tensor satisfies the minor symmetry condition, i.e. $S_{ijkl} = S_{jilk} = S_{klij}$, and does not satisfy the major symmetry condition, i.e. $S_{ijkl} \neq S_{jikl}$ [24].

Moreover, for fibre-like spheroidal inclusions the Eshelby tensor can be expressed as follows [8],

$$S_{ijkl} = \frac{1}{2(1-v_0)} \left\{ \frac{1 - 2v_0 + \frac{2R^2 - 1}{\alpha^2 - 1}}{1 - 2v_0 + \frac{3R^2 - 1}{\alpha^2 - 1}} \right\} g$$ (2)

Where

$$g = \frac{1}{(\alpha^2 - 1)^{1/2}} \left[ \frac{\alpha (\alpha^2 - 1)^{1/2} - \cos^{-1} (1/\alpha)}{\alpha^2 - 1} \right]$$ (3)

And $\alpha = l/d$ is the aspect ratio of the fibre length $l$ and the fibre diameter $d$. Note that the aspect ratio is applied for indicating the size of the inclusion in this case. The aspect ratio is explicitly included in several models for fibre-like inclusions in a matrix.

Figure 1. Representative volume element RVE of natural fiber reinforced polymer
2.1 Tensor notation

The original paper by Mori and Tanaka, describing their method, is from 1973 [25]. However, in the derivation of the Mori-Tanaka method presented in this work, we follow the derivation by Fisher and Brinson [26]. In the Mori-Tanaka method, it is assumed that the composite is comprised of \( N \) phases. Phase 0 is the matrix, and the remaining \( N-1 \) phases are inclusion phases. The matrix phase has stiffness \( C_0 \) and a volume fraction \( V_0 \), whereas the \( r \)th inclusion phase has stiffness \( C_r \) and a volume fraction \( V_r \). The quantities \( C_0 \) and \( C_r \) are generally fourth-order elasticity tensors, with certain symmetry properties. The elasticity tensors satisfy the minor symmetry condition, i.e.

\[
C_{ijkl} = C_{jikl} = C_{ijlk}
\]

In addition, the elasticity tensor will satisfy the major symmetry condition, i.e.

\[
C_{ijkl} = C_{klij}
\]

Figure 2 shows a multi-phase composite with inclusions, as well as a comparison material. The average stress for the comparison material is given by Hooke’s law,

\[
\sigma_0 = C_0 \varepsilon_0
\]

Whereas for the composite with inclusions, the average stress is given as

\[
\overline{\sigma} = C \overline{\varepsilon}
\]

Due to the inclusion, the average strain of the matrix of the composite will be perturbed, reading

\[
\overline{\varepsilon}_0 = \varepsilon_0 + \varepsilon_0^{\text{pr}}
\]

Where the over-score represent the volume average of the quantity, and \( \varepsilon_0^{\text{pr}} \) is the perturbation strain.

The average strain of the \( r \)th inclusion is perturbed by the amount \( \varepsilon_r^{\text{pr}} \),

\[
\varepsilon_r = \varepsilon_r + \varepsilon_r^{\text{pr}} = \varepsilon_r + \varepsilon_r^{\text{pr}} + \varepsilon_r^{\text{pr}}
\]

Given that the stress in the \( r \)th inclusion can be given as \( \overline{\sigma}_r = C_r \overline{\varepsilon}_r \), and using the equivalent method, the stress can be expressed in terms of the matrix stiffness,

\[
\overline{\sigma}_r = C_r \overline{\varepsilon}_r = C_0 (\varepsilon_0 - \varepsilon_r^{\text{pr}})
\]

The perturbed strain and the eigenstrain for a single ellipsoidal inclusion, can be related using the Eshelby tensor, reading

\[
\varepsilon_r^{\text{pr}} = \varepsilon_r \varepsilon_r^{\text{pr}}
\]

Using the above expressions, one finds that

\[
\varepsilon_r = \varepsilon_0 + \varepsilon_r^{\text{pr}} = \varepsilon_0 + \varepsilon_r \varepsilon_r^{\text{pr}}
\]
Now, solving for $\varepsilon_{rr}$ in (8)

$$\varepsilon_{rr} = C_0^{-1} (C_0 - C^0) \varepsilon^0$$

(11)

And inserting into (10),

$$\varepsilon' = \varepsilon^0 + \varepsilon_{rr} C_0^{-1} (C_0 - C^0) \varepsilon' \rightarrow \varepsilon' = A^d \varepsilon^0$$

(12)

Where

$$A^d = [I + S r C_0^{-1} (C_0 - C^0)]^{-1}$$

(13)

Hence, the quantity $A^d$ for the $r$th inclusion contains the Eshelby tensor, which depends on the shape of the inclusion.

Furthermore, it is required that the volume-weighted average phase strain must equal the far-field applied strain. From this, a strain-concentration factor can be established, that accounts for the inclusion interaction by relating the average matrix strain in the composite to the uniform applied strain. The factor reads

$$A_r = \left[V_0 I + \sum_{r=1}^{N-1} V_r A^d_r \right]^{-1}$$

(14)

In the $r$th inclusion, the strain concentration factor in the non-dilute composites can be written as

$$A_r = A^d_r A_0$$

(15)

An effective stiffness for the composite for a unidirectionally aligned composite, can then be defined as

$$C_{\text{effective}} = V_0 C_0 A_0 + \sum_{r=1}^{N-1} V_r C_r A_r = \left(\frac{V_0 C_0}{V_0 I + \sum_{r=1}^{N-1} V_r A^d_r} \right)^{-1}$$

(16)

### 2.2 Matrix notation

Since the previous expressions include fourth-order tensors, it will be advantageous to reduce the size of the involved quantities for implementation and calculations. Considering the involved quantities, the stress and strain second-order tensors are symmetric. Moreover, the fourth-order tensors have at least minor symmetry properties (e.g. the Eshelby tensor), or both minor and major symmetry properties (e.g. the elasticity tensors for the matrix and the inclusions). Applying the symmetry properties of the strain tensors and the Eshelby tensor, we find that

$$
\begin{pmatrix}
    \varepsilon_{11} \\
    \varepsilon_{22} \\
    \varepsilon_{33} \\
    \varepsilon_{12} \\
    \varepsilon_{23} \\
    \varepsilon_{13}
\end{pmatrix}
= 
\begin{pmatrix}
    S_{1111} & S_{1122} & S_{1133} & 2S_{1112} & 2S_{1113} & 2S_{1123} \\
    S_{2222} & S_{2233} & 2S_{2223} & 2S_{2212} & 2S_{2213} & 2S_{2233} \\
    S_{3333} & S_{3311} & S_{3322} & 2S_{3312} & 2S_{3313} & 2S_{3323} \\
    S_{1222} & S_{1233} & 2S_{1212} & 2S_{1213} & 2S_{1223} & 2S_{1233} \\
    S_{2311} & S_{2322} & S_{2333} & 2S_{2312} & 2S_{2313} & 2S_{2323} \\
    S_{3111} & S_{3122} & S_{3133} & 2S_{3112} & 2S_{3113} & 2S_{3123}
\end{pmatrix}
\begin{pmatrix}
    \varepsilon_{11} \\
    \varepsilon_{22} \\
    \varepsilon_{33} \\
    \varepsilon_{12} \\
    \varepsilon_{23} \\
    \varepsilon_{13}
\end{pmatrix}
$$

(17)

Using engineering shear strains in the above relation, we obtain the expression...
The coefficients of the Eshelby tensor in the two latter expressions are dependent on the geometry of the inclusion. In a similar way, the general Hooke’s law for linear elastic solids can be expressed [2],

\[
\begin{pmatrix}
E_{11} \\
E_{22} \\
E_{33} \\
E_{12} \\
E_{13} \\
E_{23}
\end{pmatrix}
= \begin{pmatrix}
S_{1111} & S_{1212} & S_{1313} & 0 & 0 & 0 \\
S_{1212} & S_{2222} & S_{2323} & 0 & 0 & 0 \\
S_{1313} & S_{2323} & S_{3333} & 0 & 0 & 0 \\
0 & 0 & 0 & S_{1212} & S_{1313} & S_{2323} \\
0 & 0 & 0 & S_{1313} & S_{2323} & S_{3333} \\
0 & 0 & 0 & S_{2323} & S_{3333} & S_{1111}
\end{pmatrix}
\begin{pmatrix}
E_{11} \\
E_{22} \\
E_{33} \\
E_{12} \\
E_{13} \\
E_{23}
\end{pmatrix}
\]

The five transversely isotropic constants of unidirectional natural/polypropylene ply can be predicted analytically through the Mori-Tanaka theory as:

\[
E_{11} = \frac{1}{S_{1111}} , \quad E_{22} = E_{33} = \frac{1}{S_{2222}}
\]

\[
\nu_{12} = \nu_{13} = -\frac{E_{11}S_{2222}}{S_{1111}} , \quad \nu_{23} = -\frac{E_{11}S_{3333}}{S_{1111}}
\]

\[
G_{12} = G_{13} = \frac{1}{S_{1111}} , \quad G_{23} = \frac{1}{S_{3333}}
\]

Where \(E_{11}\) is the axial Young modulus, \(E_{22} = E_{33}\) is the in-plane Young modulus, \(\nu_{12}\) is the transverse Poisson ratio, \(\nu_{23}\) is the in-plane Poisson ratio, \(G_{12}\) and \(G_{13}\) are the transverse shear modulus, \(G_{23}\) is the in-plane shear modulus.

Then these expressions are implemented in Matlab program.

3. Results and discussions

From the isotropic properties of natural fibers (Alfa, Flax, Sisal and Hemp) and polypropylene resin, the analytical model of Mori Tanaka calculate the transversely isotropic with six elastic constants: \(E_{11}\) the axial Young modulus, \(E_{22} = E_{33}\) the in-plane Young modulus, \(\nu_{23}\) the in-plane Poisson ratio, \(\nu_{12} = \nu_{13}\) the transverse Poisson ratio, \(G_{23}\) the in-plane shear modulus, \(G_{12} = G_{13}\) the transverse shear modulus, and finally the density \(\rho\). The natural fiber is considered as aligned fibre-like inclusions, the analytical results are compared with the mean field homogenization MFH of Digimat 2019, the comparison shows very well agreement as seen in Table 3.

| Table 3. Comparison between the elastic moduli obtained by Matlab code and Digimat MF |
|---------------------------------------------|
| \[V_f\] | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
| \(E_{11} \) (GPa) | Digimat MF | 3.3807 | 5.1612 | 6.9416 | 8.7218 | 10.502 |
| | Matlab code | 3.3804 | 5.1607 | 6.9409 | 8.7210 | 10.501 |
| \(E_{22}=E_{33} \) (GPa) | Digimat MF | 1.9986 | 2.3791 | 2.8172 | 3.3546 | 4.0433 |
| | Matlab code | 1.9986 | 2.3791 | 2.8172 | 3.3545 | 4.0433 |
Figure 2 shows the composite elastic constants for the four material systems considered. As observed, the longitudinal and transversal Young modulus \( E_{11}, E_{22} \) of composite increase linearly with the fibre volume fraction (10% - 50%) with an order of hemp, flax, sisal and then Alfa. The curves of flax, sisal and Alfa are closely, but for hemp fiber which have high value of \( E_{11} \). The same remarks have been found for longitudinal and transversal shear modulus \( G_{12}, G_{13} \). In figure 2-e) the transverse Poisson ratio \( v_{12} \) increase for flax fiber, and decrease for Alfa and Sisal fibers, but the variation remains constant for Hemp fiber. This is due to the Poisson ratio 0.45, 0.4, 0.34 and 0.32 for Flax, Hemp, Alfa and Sisal fibers respectively. In figure 2-f) the transversal Poisson ratio increase with volume fraction from 10% to 30%, and then decrease slowly, and have a maximum value at 30%. In figure 2-g) shows the linear increase of density of natural fibers with volume fraction. As demonstrated, the lightest natural fiber is the sisal, and the heaviest natural fiber is the Alfa. Flax and hemp fibers have close values between sisal and Alfa fibers.
Figure 2. Transversely isotropic constants of natural fibers (Alfa, flax, sisal and hemp) in function of fiber volume fraction $V_f$. a) Axial Young modulus $E_{11} \,(GPa)$. b) In-plane Young modulus $E_{22} \,(GPa)$. c) Alfa fiber, d) Flax fiber, e) Sisal fiber, f) Hemp fiber.
c) Transverse shear modulus \( G_{12}(\text{GPa}) \), d) In-plane shear modulus \( G_{22}(\text{GPa}) \), e) Transverse Poisson ratio \( v_{12} \), f) In-plane Poisson ratio \( v_{22} \), g) density \( \rho(\text{g/cm}^3) \).

4. Conclusion

In conclusion, continuous efforts are needed for the development of numerical and analytical models suitable for the prediction of various behaviors of natural fiber composites before their practical applications. From Mori Tanaka and Digimat, we found that the natural fiber of hemp has good mechanical properties according to their light weight in comparison to other fibers, which can be used for fabrication of small wind turbine blades in rural and isolated zone; but the mechanical behavior is not the only important parameter in manufacturing process. The availability and ease of fiber processing plays a fundamental role, which Alfa and Sisal natural fibers offers, especially in Morocco.
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