Computational Multi-scale Constitutive Model for Wood Cell wall and its Application to the Design of Bio-inspired Composites

E. I. Saavedra Flores, M. S. Murugan, M. I. Friswell and E.A. de Souza Neto
College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP, United Kingdom

ABSTRACT
This paper presents a fully coupled multi-scale finite element model for the description of the dissipative mechanical response of wood cell walls under large strains. Results show the ability of the present model to capture the main phenomenological responses found typically in wood at the microscopic scale. In addition, the structural and mechanical concepts involved in wood cells are exploited further in order to design new wood inspired composites. Numerical tests are conducted in prototypes of bio-inspired composites and demonstrate substantial gains in terms of resistance to failure and in the control of the overall flexibility/stiffness balance in the material.

Keywords: Cell-wall, Multi-scale modelling, Wood, Bio-inspiration, Finite element method

1. INTRODUCTION
Wood microstructure can be understood as the result of an optimisation process developed by nature over millions of years. One of its main features is its hierarchical nature distributed across multiple spatial scales. This important feature has been widely investigated over the last few years by means of multi-scale finite element models1-6, bringing substantial progress to the understanding of this material. Until now, however, research on the multi-scale constitutive description of wood appears to have been focused exclusively on the study of the linear elastic response.

In an attempt to understand the highly irreversible processes in wood, our main objective in this paper is to investigate the dissipative mechanical response of wood cell walls by means of a finite element-based computational multi-scale approach. At the level of the cell-wall, the material response is described by a Representative Volume Element (RVE) composed of three basic constituents: hemicellulose, lignin and cellulose. Furthermore, at a lower scale the cellulose fibre is represented as a periodic arrangement of crystalline and amorphous portions, whose overall constitutive behaviour is modelled as a single material defined at each Gauss-point by means of a second RVE. We anticipate that key features of the mechanical behaviour of wood cell walls are reproduced by the proposed model, such as fibre reorientation-induced stiffening. The predictive capability of the present multi-scale model is demonstrated by comparing the numerical results with published experimental data.

In addition, the structural and mechanical concepts involved in wood cells are exploited further in order to design new wood inspired composites. Based on our results obtained from the numerical modelling of wood cell walls, we suggest a bio-inspired strategy to increase the resistance to failure and to control the balance between stiffness and flexibility in prototypes of new composites. This strategy is suggested by the strong influence of the proportion of volume fractions of crystalline and amorphous celluloses on the overall mechanical behaviour of wood cells.

The paper is organised as follows. Section 2 presents a brief review of wood cell-wall mechanics. The finite element-based multi-scale model of wood cell-wall and some numerical results are presented in Section 3. Finite element analyses on a wood-inspired composite are conducted in Section 4. Finally, Section 5 summarises the main conclusions.

Further author information: (Send correspondence to Erick Saavedra Flores)
E-mail: e.i.saavedra-flores@swansea.ac.uk, Telephone: + 44 (0)1792 513177


Proc. of SPIE Vol. 7975  79750D-1
2. WOOD CELL-WALL MECHANICS

The cell-wall contains three major chemical constituents: cellulose, hemicellulose and lignin as shown in Figure 1(a). Cellulose, hemicellulose and lignin approximately constitute 40–50%, 25% and 20–30%, respectively, of the weight of wood substance. The cellulose is a long polymer composed of glucose units which is organised into periodic crystalline and amorphous (non-crystalline) regions along its length and called crystalline-amorphous cellulose core as shown in Figure 1(b)). This periodic arrangement is further covered with an outer surface made up of amorphous cellulose. The (volumetric) degree of crystallinity, $e_v$, is defined as the ratio between the volume of crystalline cellulose and the total volume of cellulose. The high stiffness of the cellulose is due to its crystalline fraction whereas its flexibility is provided by the amorphous part.

Hemicellulose is a polymer with little strength built up of sugar units. Its structure is partially random with mechanical properties highly sensitive to moisture changes. Lignin is an amorphous polymer whose purpose is to cement the individual cells together and to provide shear strength. It is the most hydrophobic component in the cell-wall, with relatively stable mechanical properties under moisture changes. These three main constituents, cellulose, hemicellulose and lignin, form a complex network characterised by cellulose acting as a fibre embedded in a matrix composed of hemicellulose and lignin.

The spatial arrangement of the components discussed above is known as microfibril, and can be considered as a periodic unit building block of rectangular cross-section with infinite length (see Figure 1(a)). The specific orientation of microfibrils with respect to the longitudinal cell axis is called the microfibril angle (MFA) and is one of the most important parameters controlling the balance between stiffness and flexibility in trees.

Depending on the proportions of constituents and the microfibril angle, wood cell-walls can be divided in different layers. In all these layers, the microfibril takes different orientations throughout the cell-wall, generating a mechanical locking effect and consequently, an increase in the overall stiffness in the cell. Among all these, the S2 layer is the thickest and most influential factor in the mechanical behaviour of wood cells. It comprises about 80 – 90% of the total volume of the cell-wall and concentrates a high content of cellulose of about 50% in weight.

3. FINITE ELEMENT MODELLING OF WOOD CELL-WALL AND NUMERICAL RESULTS

3.1 Finite element modelling of wood cell-wall

A compression wood of Norway spruce (Picea abies (L.) Karts.) is selected in this work to study the complex mechanical interactions at the level of chemical constituents in wood. The compression wood, at natural moisture...
In order to study the wood cell-wall mechanical behaviour, a fully coupled three-scale model is presented here, corresponding to a periodic boundary displacement fluctuations model. This type of model is described in further detail, for instance, in Refs. 13–16. The overall mechanical response of the cell-wall composite (large scale) is obtained by the computational homogenization of the microfibril–RVE at the nanoscopic level (intermediate scale). The mechanical response prediction of the microfibril–RVE, in turn, involves the homogenization of the cellulose core–RVE at the level of the crystalline and amorphous portions of cellulose (small scale). That is to say, each microfibril–RVE equilibrium problem is solved simultaneously with a large number of cellulose core–RVE equilibrium problems at the Gauss-point level of the microfibril–RVE finite element mesh. In the present model, volume fractions of 30, 32.5 and 37.5% are adopted for cellulose, hemicellulose and lignin, respectively\(^\text{17}\). The modelling discussed here takes into account non-linear kinematics and dissipative response of the material under finite strains regime.

In the following, we present a brief description about the modelling of the basic constituents present in wood. Further details can be found in Ref. 18.

(i) **Constitutive description of hemicellulose and lignin**

Hemicellulose structure is partially amorphous. It is considered that certain fraction of its structure is aligned along the microfibril and consequently, its general behavior can be modelled as orthotropic\(^\text{19}\). However, the principal mode of deformation in hemicellulose during tension of the cell-wall is related exclusively to shear, with little contribution of the degree of anisotropy in the mechanical response\(^\text{20}\). Hence, the hemicellulose is assumed as isotropic in this study. Similarly, lignin is also assumed to be isotropic due to its amorphous nature.

Hemicellulose and lignin materials are modelled with a visco-elastic/visco-plastic response\(^\text{21–24}\). To capture the rate-dependent behavior of hemicellulose and lignin, a constitutive model based on the combined action of two rheological models, a visco-plastic Prandtl model and a visco-elastic Maxwell model in a parallel arrangement\(^\text{25}\), is used.

In Table 1, the mechanical properties of all the constituent materials used in the current study and their corresponding sources are summarised.

(ii) **Constitutive description of cellulose**

The cellulose structure is described as a periodic alternation of amorphous and crystalline domains with an additional outer sheeting made up of amorphous cellulose. In order to model the whole cellulose (including

<table>
<thead>
<tr>
<th>Constituent</th>
<th>(E_A)</th>
<th>(E)</th>
<th>(G_A)</th>
<th>(\nu)</th>
<th>(\eta_p)</th>
<th>(\eta_m)</th>
<th>(\sigma_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline cellulose</td>
<td>134.00</td>
<td>27.2</td>
<td>4.4</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Amorphous cellulose</td>
<td>10.42</td>
<td>10.42</td>
<td>4.24</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>4e-2</td>
<td>4e-2</td>
<td>1.67e-2</td>
<td>0.2</td>
<td>8.5</td>
<td>3.1</td>
<td>1.9e-2</td>
</tr>
<tr>
<td>Lignin</td>
<td>1.56</td>
<td>1.56</td>
<td>0.6</td>
<td>0.3</td>
<td>20.0</td>
<td>6.5</td>
<td>1.9e-2</td>
</tr>
</tbody>
</table>
its crystalline and amorphous fractions), in the following we adopt the considerations made in Ref. 30. The average thickness of cellulose (which includes the core and the outer layer of amorphous cellulose) is 3.6 nm\textsuperscript{31}. Furthermore, the average thickness of the central (crystalline-amorphous) cellulose core is 3.2 nm\textsuperscript{32} in Norway spruce. Consequently, a 0.2nm thick layer of amorphous cellulose is determined for the outer layer. Additionally, if a 52\% degree of crystallinity\textsuperscript{32} is considered, along with a mean length of the crystalline fraction of about 36.4 nm\textsuperscript{30}, there should be a length of 18.9 nm\textsuperscript{30} of amorphous cellulose between two consecutive crystalline units. The above considerations define the geometry of the cellulose to be taken into account in the multi-scale finite element modelling which will be presented later.

The deformation of amorphous and crystalline cellulose is very small as a consequence of its interaction with the weak hemicellulose-lignin matrix. Thus a compressible version of the isotropic Neo-Hookean strain-energy function is considered. The amorphous cellulose assumes a conventional von Mises elastic-perfectly plastic law. The mechanical properties assumed here are given in Table 1.

The crystalline fraction is assumed to be elastic\textsuperscript{33}, consisting of a transversally isotropic material. A generalisation of the compressible version of the isotropic Neo-Hookean strain-energy function is adopted to capture this type of constitutive response at large strains\textsuperscript{34}. The linear elastic mechanical properties for the crystalline cellulose are given in Table 1.

### 3.2 RVEs Finite element meshes

**Microfibril–RVE:** In order to reduce computational requirements, the point symmetry condition present in the geometry was taken into consideration\textsuperscript{35,36}. That is, only one half of the full RVE domain is modeled as shown in Figure 2(a). Furthermore, to avoid the possible shear locking problems, the final microfibril–RVE mesh used was obtained after a convergence analysis. To eliminate volumetric locking, the F-Bar methodology is used in all of the FE meshes\textsuperscript{37}. The microfibril–RVE mesh contains 1008 F-bar eight-noded hexahedral elements with a total of 2136 nodes.

![(a) Finite element microfibril–RVE mesh. By taking advantage of symmetry conditions, only half of the domain is modelled.](image1.png)

![(b) Finite element cellulose core–RVE mesh.](image2.png)

Figure 2. Finite element RVE meshes utilised in the present multi-scale model.

**Cellulose core–RVE:** The optimal finite element mesh for the cellulose core–RVE, after a FE convergence study, consists of 24 F-bar eight-noded hexahedral elements and a total of 100 nodes as shown in Figure 2(b).
3.3 Numerical results

In order to better understand the mechanical interactions present at the level of the wood cell-wall, we investigate the strain state in the cell-wall when it is subjected to tensile loading in the direction of the cell axis. In what follows, the cell-wall is assumed to be defined on the $x$-$y$ plane, with $y$ denoting the cell axis direction, and $x$, its corresponding normal direction. The $z$ direction is defined perpendicular to the $x$-$y$ plane, along the cell-wall thickness.

Here, we investigate the strain state in the cell-wall resulting from a tensile load applied in the direction $y$ of the cell axis. By assuming an inextensible cellulose fibre and considering a uniform microfibril angle MFA, referred to as $\mu$, it is possible to obtain a simple expression that relates the applied strain, $\varepsilon_{yy}$, in the direction $y$, with the resulting variation, $\Delta \mu$, of the MFA. If we consider a rectangular material element of cell-wall in the $x$-$y$ plane, with dimensions $lx$ and $ly$, in the corresponding $x$ and $y$ directions, it follows that $\cos(\mu)$ is proportional to $ly$ under the assumption of inextensible cellulose. Then, the relationship between the applied strain and the variation of MFA can be expressed as $\varepsilon_{yy} = -\tan(\mu_o)\Delta \mu$, with $\mu_o$ denoting the initial microfibril angle. Similarly, a second relationship can be obtained in the $x$ direction. Here, the length $lx$ in the portion of the cell-wall considered, is proportional to $\sin(\mu)$ under the assumption of inextensible fibre. In this case, the strain in the direction $x$ can be calculated as $\varepsilon_{xx} = \cot(\mu_o)\Delta \mu$. Moreover, if we relate the expressions for $\varepsilon_{xx}$ and $\varepsilon_{yy}$ by means of the in-plane Poisson’s ratio of the cell-wall, $\nu = -\varepsilon_{xx}/\varepsilon_{yy}$, we can obtain the relationship $\nu = [\cot(\mu_o)]^2$. By taking an initial microfibril angle in compression wood, equal to $23 \, 45.7^\circ$, we can estimate an in-plane Poisson ratio $\nu = 0.95$ for the cell-wall.

With the above estimated in-plane Poisson’s ratio in the cell-wall, we proceed to define a prescribed incremental strain array to be applied in the microfibril–RVE of the cell-wall. If we assume a strain history whose final state in the direction of the cell axis is $\varepsilon_{yy} = 0.2$, a corresponding lateral strain $\varepsilon_{xx} = -0.19$ is obtained under the consideration of $\nu = 0.95$. Also, since compression wood cells present thick cell-walls, and considering that the existing load acts only along the axis of the cell, it is reasonable to assume $\varepsilon_{xz} = \gamma_{xz} = \gamma_{yz} = 0$. In addition, the interaction between two or more adjacent cells in wood tissue severely constrains torsion about the cell axis, so that we can assume $23 \, \gamma_{xy} = 0$ in the cell-wall. Similarly, for single cells under tensile loading, the torsional rotation is prevented by the tensile testing device and in this case it is also reasonable to take $\gamma_{xy} = 0$. Finally, the end strain state in the cell-wall, to be prescribed incrementally to the microfibril-RVE in the analyses presented in the following, is chosen as

$$\varepsilon = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}\}^T = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}\}^T = \{-0.19, 0.2, 0, 0, 0, 0\}^T,$$

in standard engineering strain array format.

Then, we proceed to apply the prescribed strain array, $\varepsilon$, in 20 time steps of 10s each and we focus our attention on the variation of the microfibril angle MFA with the applied strain $\varepsilon_{yy}$.

Figure 3 shows both the experimental information reported in Ref. 23 during a tensile test of compression wood tissue, and the result obtained from the analysis of the microfibril–RVE. The general trend of the numerical curve is almost linear, showing an increase of the slope at the end of the complete deformation process of 3.5% (though not visible in the graph) with respect to the initial slope. This slight increase is due mainly to the geometric non-linear relationship between the prescribed strain and the variation of the MFA.

From numerical experiments (not shown here), we also note that the changes in the in-plane Poisson’s ratio can lead to substantial variations in slope in the graph of Figure 3. In addition, a relatively constant in-plane Poisson ratio during the deformation process results in a general linear trend. Therefore, the good agreement between numerical and experimental results suggests that a suitable Poisson’s ratio has been obtained when the expression $\nu = [\cot(\mu_o)]^2$ is used along with an initial microfibril angle $\mu_o = 45.7^\circ$.

The reduction of the MFA is a characteristic feature of the mechanical behaviour of wood cells under straining and results from the alignment of the cellulose fibres in the direction of the cell axis when the cell-wall composite (microfibril–RVE) is stretched in this direction. As we shall see in the following section, this alignment results in a fibre reorientation-induced stiffening of the (cell-wall) composite when the level of straining becomes large.
4. BIO-INSPIRED COMPOSITE

In this section we explore the design of a prototype bio-inspired composite when some of the structural and mechanical concepts involved in wood cells are exploited further.

Based on the characteristics present in wood cell walls, we suggest a bio-inspired strategy to increase the resistance to failure and to control the balance between stiffness and flexibility in a new composite. This strategy is suggested by the strong influence of the proportion of volume fractions of crystalline and amorphous celluloses on the overall mechanical behaviour of wood cells.

In order to endow this composite with similar mechanisms of deformation found in the wood cell, we establish a one-to-one correspondence between each of the constituents present in wood and those existing in the new composite, and therefore the role performed by each of the cell-wall constituents is replicated in the new wood-inspired material. Thus, the reinforcing fibre of the new composite is assumed to be made up of two phases. The first phase is considered to be a very rigid elastic material (in the wood cell-wall composite, the stiff crystalline cellulose fibre), called here RF (Rigid portion of the Fibre). The second phase of the fibre is assumed to have a softer elasto-plastic response (the softer amorphous cellulose fraction in wood cell-wall), called SF (Softer fraction of the Fibre). Furthermore, the matrix is assumed to be formed by two phases, a very soft portion (in wood, the hemicellulose) called SM (Softer phase in the Matrix) and a relatively more rigid fraction (lignin in the cell-wall), called here RM (more Rigid fraction in the Matrix). Refer to Figure 4 for further details.

In order to mimic wood, we design this prototype with the same features found in wood. That is to say, we keep the same volume fractions of basic constituents. This means that we adopt a 30% volume fraction for the whole fibre, including RF and SF; and 32.5 and 37.5% for the two phases in the matrix, SM and RM, respectively. Similarly, we choose 52% for the percentage of volume of RF with respect to the entire volume of fibre (degree of crystallinity in the cellulose).

In this study, we adopt Alumina as the rigid elastic fraction of fibre, RF. Its mechanical properties are obtained from Ref. 39 and correspond to an isotropic material with Young’s modulus $E = 379$ GPa and Poisson’s ratio $\nu = 0.25$. Its tensile failure strain is 0.4%. To keep the same ratio present in the wood cell-wall composite, between the Young’s modulus of the crystalline cellulose, $E = 134$ GPa, and its amorphous counterpart, $E = 10.42$ GPa, we proceed to define the Young’s modulus of the softer fraction of fibre SF with a value $E = 29.4715$ GPa, resulting in the same ratio $379/29.4715 = 134/10.42 = 12.86$. In order to endow this new composite with similar mechanisms of deformation found in the wood cell, we adopt the value of Poisson’s ratio $\nu = 0.23$ and failure strain $\varepsilon_f = 0.03838$ (onset of plastic yielding) of the amorphous cellulose fraction for the softer fraction of fibre SF in the new composite. With the above Young’s modulus $E = 29.4715$ GPa and failure strain $\varepsilon_f = 0.03838$, we calculate a yield stress $\sigma_y = 1.131$ GPa for SF.
Table 2. Summary of the mechanical properties adopted in the constituents of the present bio-inspired composite. The units adopted here are those used in Table 1. Mechanical properties of Alumina are obtained from Ref. 39.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>$E$</th>
<th>$\nu$</th>
<th>$\eta_p$</th>
<th>$\eta_m$</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF (Alumina – Rigid fraction of Fibre)</td>
<td>379.00</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF (Softer fraction of Fibre)</td>
<td>29.471</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
<td>1.131</td>
</tr>
<tr>
<td>SM (Softer fraction in Matrix)</td>
<td>0.1131</td>
<td>0.2</td>
<td>8.5</td>
<td>3.1</td>
<td>5.37e-2</td>
</tr>
<tr>
<td>RM (more Rigid fraction in Matrix)</td>
<td>4.4122</td>
<td>0.3</td>
<td>20.0</td>
<td>6.5</td>
<td>5.37e-2</td>
</tr>
</tbody>
</table>

For the definition of the mechanical properties of the matrix with its two phases, SM and RM, we follow the same considerations explained above. In addition, we adopt the same viscosity-related properties found in the hemicellulose and lignin for the softer and more rigid phases in the matrix, SM and RM, respectively. The resulting material constants for SM and RM along with those determined for RF and SF are summarised in Table 2.

The mechanical response of the composite is defined by a single material whose constitutive description is obtained by the computational homogenisation of the same RVEs described in Section 3.2 and shown in Figure 2. That is to say, we use the same periodic multi-scale model presented in Section 3 (originally proposed to investigate the wood cell-wall mechanics) to analyse this composite material. To avoid confusion, in this Section we rename the microfibril–RVE and cellulose core–RVE as RVE 1 and RVE 2, respectively (refer to Figure 4).

The end strain state to be prescribed incrementally on the corresponding RVE 1 is calculated under the same assumptions made in Section 3.3. If the initial orientation of the fibre with respect to the $y$-direction (stretching axis) is $45^\circ$ (in all analyses), then the in-plane Poisson’s ratio can be estimated as $\nu = [\cot(45^\circ)]^2 = 1$. Therefore, if the strain component applied in $y$-direction is 0.20, then the final strain state can be expressed as

$$\varepsilon = \{-0.2, 0.2, 0, 0, 0, 0\}^T,$$

in standard engineering strain array format.

In order to investigate the material response, we explore the influence of the volume fraction (Vf) of the constituent RF (with respect to the total volume of fibre) on the overall mechanical response of the new material. We compare the material response predicted for four different fractions: 0.45, 0.50, 0.55 and 0.60. Furthermore, we analyse the traditional condition in which the fibre is considered to be fully rigid, made of one single elastic material (in other words, Vf=1.0). The adopted strain rate is $1.25e-3s^{-1}$.

Figure 5 shows the stress-strain curves for the different volume fractions Vf considered. In the corresponding graph, we see that for volume fractions Vf between 0.45 and 0.60 the mechanical response is virtually independent
of Vf for strains under 4-5%. From the numerical results, it can be concluded that up to this level of strain, the whole fibre remains almost inextensible. After 8-9% of strain, however, the dependence of the response on the volume fraction Vf varies. When these curves (Vf=0.45, 0.50, 0.55 and 0.60) are compared to the condition Vf=1, the response becomes practically independent of Vf only for strains under 1.25%.

The small influence of Vf on the overall mechanical response at lower strain levels is attributed to the large angle (near 45°) between the fibre and the stretching axis at this stage. Here, only a small portion of the axial load is carried by the fibre. In addition, the main mechanism of deformation in the composite is shear, localised in the matrix, due to the relative displacements among fibres undergoing rigid body rotation and alignment in the stretching direction. Therefore, any increase of the stiffness in the fibre due to a rise in the volume fraction of the stiff portion RF will not affect significantly the overall mechanical response of the composite under low strain levels since the fibre will experience predominantly changes in its orientation rather than straining along its own axis. If the straining process continues, the angle between the fibre and the stretching axis will reduce considerably and the fibres will begin to take larger portions of axial loads and the corresponding alignment will result in a fibre reorientation-induced stiffening, as shown in Figure 5. Consequently, for only moderate to large strains the choice of different volume fractions Vf in the fibre will lead to different levels of stiffness in the material. On the contrary, for smaller strains (possible during service conditions) the amount of rigid fraction in the fibre will have virtually no influence on the overall response of the material.

Importantly, the curve shown in Figure 5 for Vf=1 has been truncated for a maximum strain of the (single material) fibre equal to 0.4% (the failure strain of Alumina). Similarly, the remaining four curves for Vf between 0.45 and 0.60 have been truncated at failure. However, the mechanism of failure in this case is represented by the onset of plastic strain in the softer fraction of the fibre (SF) rather than failure in the rigid portion RF. This redistribution of the failure from the rigid constituent of the fibre to its softer counterpart allows the composite to increase substantially the strain to failure, from almost 9% (for the classical solution Vf=1) to 20% strain (Vf=0.45), without showing significant loss in the maximum stress (just a drop from 0.285 to 0.25 GPa).

It is important to note that in Ref. 23 it was shown how wood tissue and individual cells are able to undergo large deformations without apparent damage in the hemicellulose-lignin matrix. This process is interpreted as a stick-slip mechanism at the molecular level of the matrix which results in a plastic response similar to crystallographic sliding in polycrystalline metals. Therefore, inspired in this feature, the proposed matrix in this composite does show plastic response but does not jeopardize the integrity of the entire unit.

We also remark that the main mechanism of failure in the wood cell-wall under straining has been demonstrated to be the onset of inelastic yielding in the amorphous fraction of the cellulose fibre which is consistent
with the deformation mechanism shown by the proposed composite.

The features presented above have been replicated from wood and represent a natural mechanism to control the overall flexibility/stiffness balance in the material and to increase its resistance to failure by means of a natural adaptation to the development of large strains.

5. CONCLUSIONS

The irreversible behaviour of wood cell-walls has been investigated by means of a finite element-based computational multi-scale approach. Numerical material tests have been carried out and the results have been compared to published experimental data, demonstrating the predictive capability of the present model. In particular, the model is able to capture phenomena such as the reorientation of the fibre during stretching and the consequent stiffening in the overall response of the material.

In addition, fundamental concepts involved in wood cell mechanics have been exploited in order to design a new bio-inspired material. Numerical tests have been conducted on a prototype and have demonstrated substantial gains in terms of resistance to failure and in the control of the overall flexibility/stiffness balance in the material. We have shown here that the introduction of a very simple wood-inspired strategy allows the composite to increase substantially its strain to failure, from 9% (for the classical engineering solution considering a single material fibre) up to 20% strain (when almost half of the original rigid fibre is replaced with a softer fraction), without showing significant loss in the maximum stress (just a drop from 0.285 to 0.25 GPa).

ACKNOWLEDGMENTS

The authors acknowledge funding from the European Research Council through Grant No. 247045 entitled "Optimisation of Multiscale Structures with Applications to Morphing Aircraft".

REFERENCES


