1. INTRODUCTION

1. Hierarchical structure of soft tissues

Soft collagenous tissue features many hierarchies of structure, starting from tropocollagen molecules that form fibrils, and proceeding to a bundle of fibrils that form fibers.

2. Summary of the work

- We present a continuous damage model with regularized softening (smeared crack models) for fiber reinforced soft tissues.
- Material parameters of the continuous models derive from the mesoscopic scale.
- We want to study the continuum-level response as a function of the nanoscale properties of the collagen and the adherent forces between the tropocollagen molecules.

2. METHODS

2.1 Regularized damage model

1. Strain energy function

Dissipation is modeled independently in the matrix and in each family of fibers:

\[ W = 3.5 \frac{1}{1} \left( 1 - 3(1) \right) - \frac{1}{1} \left( 1 - 3(1) \right) \]

\[ + 1 \left( 1 - 3(1) \right) \]

\[ (1 - 3(1)) \frac{(3(1) - 1)}{1} \]

\[ \psi = \psi(\varepsilon, \varepsilon) \]

\[ \varphi = \varphi(\varepsilon, \varepsilon) \]

2. Softening regularization

Model dissipation

\[ D_{\text{int}} = \sum_{\alpha=g, f, 1, 2} \left( \dot{q}_\alpha - \dot{q}_\alpha \right) \]

Stress-like internal variable rate

\[ \dot{q}_\alpha = -A_{\text{softening}} \]

Energy dissipation given by a material parameter

\[ W_{\text{int}} = \sum_{\alpha=g, f, 1, 2} \left( \dot{q}_\alpha \right) \]

Regularized softening modulus

\[ H_{\alpha}(q_\alpha(t)) = A_{\text{softening}} \]

\[ \dot{q}_\alpha(t) \]

2.2 Mesoscopic characterization of inelastic behaviour

1. Fibre mesoscopic characterization

(a) Elastic stretch threshold

(b) The two dimensional Hodge-Petruska model.

(c) Fibre mesoscopic model

2. Fibre and tissue characterization

3. Mesoscopic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Tropocollagen molecule length</td>
<td>180 nm</td>
</tr>
<tr>
<td>Proteoglycan-rich matrix width</td>
<td>200 nm</td>
</tr>
<tr>
<td>Tropocollagen molecule length</td>
<td>180 nm</td>
</tr>
</tbody>
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3. RESULTS

1. Fibre analysis

2. Fibre analysis

3. Tissue analysis

4. CONCLUSIONS

- Softening in damage models must be regularized in order to ensure the objectivity of the results.
- Energy dissipation in soft tissues should be considered as a needed material parameter and should be estimated.
- There is a dependence of the continuum response as a function of nanoscopic structural features.
- A hierarchical multi-scale approach is needed in order to define atomistically-informed continuum-scale mechanical properties of the soft tissues.