Overview of ModelSteelComp ICON project incl. insight on micro-mechanical modeling of short wavy reinforced composites
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Micro-mechanical & Fatigue modeling of short steel fiber reinforced composites

Project goal
Development of a validated predictive model of mechanical behavior and electromagnetic properties (EM) of steel fiber RFRC
Project Summary

Achievements in Micro-mechanical Modeling
Industrial situation
- Generic model to predict the EM properties of a material is not available.

Problems
- Existing models (mainly effective medium theory) are only valid for low volume fraction of steel fibers and short fiber length.
- For higher volume fractions interactions between fibers become relevant; EM properties change drastically (percolation theory)
- Direct modeling only possible for small amount of fibers.

Solution
- Efficient EM property prediction based on fiber topology and distribution
Fatigue of Composites

- **Industrial situation**
  - More and more different types of fiber-reinforced composites are used in load-containing components for automotive, energy, and aero applications.
  - Fatigue is an issue for these parts.

- **Problem**
  - Today a lot of extra testing is applied for those parts compared to metals.

- **Solution:** Fatigue simulation for composites
  - Interface to manufacturing processes
  - Interaction with material modeling software for local fatigue behavior
  - Accurate fatigue analysis using local material behavior
How to reach the project goals?

- Basic Models
  - Geometrical and micro-structural characterization of Steel Fiber Reinforced Composites

- EM Modeling
  - Understand a link between the microstructure and the EM properties
  - Establish tools for predicting critical EM parameters (conductivity, permittivity) with precision inside the experimental scatter
  - Thin wire approximation
How to reach the project goals?

- Fatigue Simulation
  - Micro-mechanical definition of the fatigue behavior on meso level
  - Fatigue behavior determined based on micro-level (only material testing needed)
  - Feedback loop to include pre-damage into micro-mechanical model
  - Fatigue simulation on component level under realistic loading conditions
- Validation
  - Steel fibers
  - Glass fibers
Project Summary

Achievements in Micro-mechanical Modeling
Short wavy steel fiber composites

- Short steel fiber composites are novel material combining outstanding properties of stiffness and ductility.
- Processing of injection molded short steel fiber composites leads to significant fiber waviness.

![Stress vs. Strain Graph for Steel Fiber]

**Steel fibre**

\[ E = 193 \text{ GPa} \]
\[ \sigma = 660 \text{ MPa} \]
Geometrical characterization and modeling of short steel fiber composites

Micro-CT characterization for determination of geometrical parameters

Model:

\[ r(s) = A \left( r_1 \sin \left( n_1 \frac{\pi s}{L} + \psi_1 \right) + r_2 \sin \left( n_2 \frac{\pi s}{L} + \psi_2 \right) \right) \]
Micro-Mechanical Modeling of Short Steel Fibers Composites

- Geometrical Model (MOSCO.GEO)
  - $\Psi(L)$
  - $\Psi(\theta,\varphi)$
  - waviness

- Interfacing
  - For each segment $i$
    - $X_c(i)$, $Y_c(i)$, $Z_c(i)$
    - $L(i)$
    - $\Theta(i)$, $\varphi(i)$

- Micro-Mechanical Model (MOSCO.MICRO)
  - $C_{eff}$
    - $\langle \sigma(i) \rangle$, $\langle \varepsilon(i) \rangle$

- Damage
  - Plasticity of matrix
  - Plasticity of fibers
  - Debonding
  - Breakage

Validation needed for Micro-Mechanical model for:
- Accurate prediction of overall composite effective response
- Accurate prediction of the local stress and strain states in inclusions $\langle \sigma(i) \rangle$, $\langle \varepsilon(i) \rangle$
Wavy fiber validation case

Transformation of a wavy fiber into an equivalent ellipsoidal inclusion system

Model based on Eshelby solution for ellipsoidal inhomogeneities and Mori-Tanaka mean-field averaging scheme

\[ E_m = 1.500 \text{ GPa, } \nu = 0.4 \]
\[ E_f = 193 \text{ GPa, } \nu = 0.25 \]
Poly Inclusion Model

- Each wavy fiber is subdivided into a sufficiently large number of straight segments.
- Each segment is replaced by an imaginary equivalent ellipsoid such that volume fraction of equivalent ellipsoid is equal to volume fraction of the segment it represents.
- The elongation of the equivalent ellipsoid is proportional only to the radius of curvature of the segment and related by an Elongation Factor $\beta$.

A higher radius of curvature ($R$) leads to higher equivalent ellipsoid length ($2b$).

$\beta$ typically $= \pi/2$ for textile yarns
FE models for validation

Calculation of $C_{eff}$

Calculation of $\langle \sigma \rangle$ in segments

Calculation of $\langle \sigma \rangle$ in modelled equivalent inclusions with different $\beta$

Tension $Y - Y$ Strain = 1%

$\beta = \pi/2$

$\beta = \pi/4$
Homogenized properties: PI against FE PBC

- PI mean field model leads to fair prediction of overall elastic constants.
- It is observed that the PI model generally leads to underestimation of effective composite properties.
- Elastic constants show a slight difference in values with different $\beta$. Higher constants obtained with higher $\beta$.

FE model done with Periodic boundary conditions
Comparison PI model with FE-PBC

- PI model with $\beta = \pi/2$ leads to very good predictions of stresses inside equivalent inclusions.
- Predictions are closer to FE full solution for the cases of segments more aligned to global axes and less accurate for misaligned segments.

$$\beta = \pi/4$$

FE full solution

$\beta = \pi/2$

Representation of PI models

Composites Materials Group
Validation of P-I concept

- Figure shows plots of FE models of equivalent ellipsoids compared to PI model and full FE solution.
- PI model (with $\beta = \pi/2$) compared to FE models of equivalent ellipsoids.
Investigation of effect of Waviness of SF -1

Scheme by Fisher et al., 2002 for including effect of waviness in Mean field homogenization models

- Performing FE analysis on single nanotubes at different waviness values.
- Back calculating stiffness of wavy nanotube.
- Incorporating reduced stiffness of each wavy nanotube in mean field algorithm

\[
E_{\text{wavy}} = \frac{E_{\text{cell}}^{\text{FEA}} - (1 - c_{\text{NT}})E_{\text{matrix}}}{c_{\text{NT}}}
\]

NRP micrograph (a)  NT waviness distribution  Multiphase wavy NT model
Investigation of effect of Waviness of SF -2

- FE models built with difference waviness ratios $W = A/L$
- Comparison with PI model to be performed
- The purpose is to investigate the accuracy of PI model with varying waviness of the fibers.

$W = 0.1$

$W = 0.3$

$W = 0.5$
Investigation of effect of Waviness of SF -3

- Comparison between P-I and FE made based on stresses in wavy fiber (iso-strain assumption cannot be assumed for short fiber models).
- P-I model results in excellent agreement with FE.
- Effect of waviness can be predicted using P-I model without the need to perform FEA on single wavy fibers.

\[ y = a \cos\left(\frac{2 \pi z}{L}\right) \]
Summary

- Geometrical model developed for generation of short steel fiber composites.
- Validation of geometrical model against micro-CT observations.
- Mean-field based model implemented for wavy fibers.
- Validation of the micro-mechanical model for elastic constants and stress state in inclusions.
- Model able to predict effect of variation of waviness parameter.
Thank You