Detailed Finite Element Modeling of Fiber-Reinforced Tissues

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Introduction

- Current finite element models describe fiber-reinforced tissues as either fibers embedded in matrix (**EMB**) [1,2] or a homogenized volume of fiber and matrix (**HOM**) [3,4].
- However, these methods cannot provide information about fiber-matrix interactions, which may be critical for understanding failure mechanics and stress distribution [5].
- *Therefore, we propose an alternative solution of modeling fiber bundles as a separate component from the extrafibrillar matrix* (**SEP**).
- The **objective** of this study was to compare three model descriptions for single- and double-lamella AF in uniaxial tension.
- We based the model architecture on the AF due to the complex fiber architecture, where collagen fibers are oriented at ±45-65° to the vertical axis (Figure 1). Therefore, we investigated the effect of fiber orientation on the stress-stretch response.

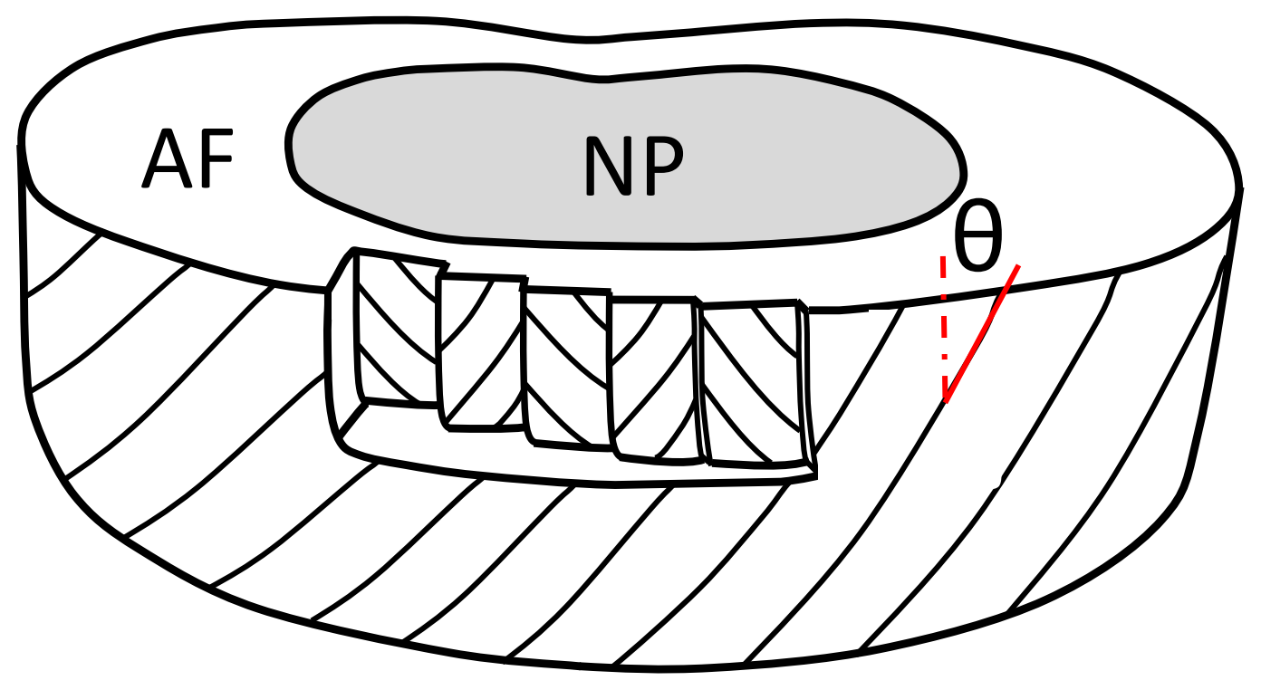

Figure 1. Anatomy of the disc. NP: nucleus pulposus; AF: annulus fibrosus. θ: fiber angle orientation.

Method

Single-lamella models

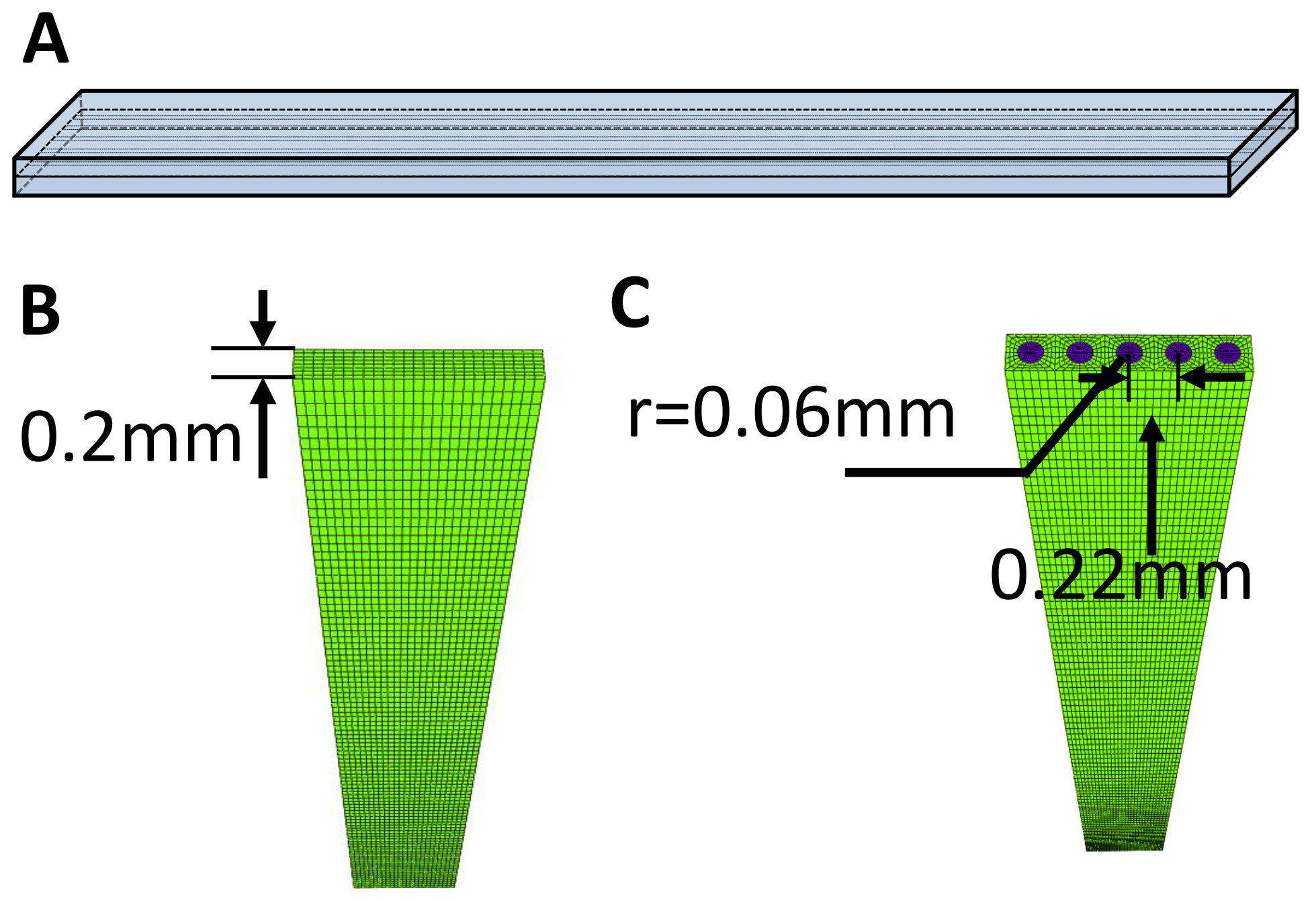

Figure 2. **A**. Embedded smeared (**EMB**). **B.** Homogenized hyper-elastic (**HOM**). **C**. Fiber-matrix separated (**SEP**).

Material coefficients

- Material properties for **HOM** and **SEP** were based on single lamellae tensile testing data (Table 1) [8]. Material properties for EMB were based on values reported in [1] (E = 500 MPa, ν = 0.3) [2, 6, 7].

Double-lamella models

- ±65° orientation was compared to experimental tensile data [9].
- Fibers were arranged at ±45°, ±50°, ±55°, or ±60°, representing the change in fiber orientation from the inner to the outer AF.

	EMB(matrix)	HOM	SEP(Matrix)	SEP(Fiber)
C_1 (MPa)	0.7	0.5	0.75	0.75
C_2 (MPa)	0.2	0.1	0.1	0.1
K (MPa)	N/A	50	50	50
D	~0	N/A		
C_3 (MPa)	N/A	0.05	N/A	0.21
C_4		78		98
C_5 (MPa)		70		380
λ		1.017		1.025

Table 1. Material parameters for FEM models.

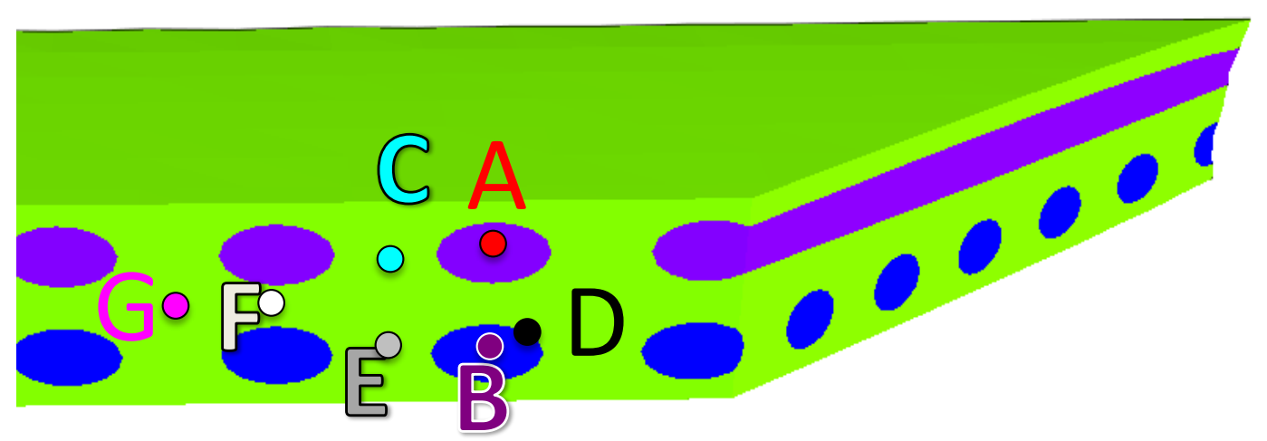

Figure 3. Double-lamella model with ±45° fiber bundles. A-G represent different locations. A and B on fibers, D on the boundary, and C, E, F, G on matrix.

References

[1] Ueno, K & Liu, Y.K., *J Biomech Eng*, 1987; [2] Adam, C. et al., *J Biomech*, 2015; [3] Nathan, T.J., et al., *J Biomech*, 2014; [4] Ayturk, U.M., et al., *J Biomech Eng*, 2010. [5] Latridis, J.C., *J Biomech*, 2004. [6] Little, J.P., et al., *CMBBE*, 2008; [7] Kiapour, A., et al., *Spine*, 2012. [8] Holzapfel, G.A. et al., *BMMB*, 2005; [9] Ebara, S. et al., *Spine*, 1996; [10] Mow, V.C., Huiskes R., *Basic ortho biomech & mechanobiology*, 2005. [11] Han W.M., et al., *Ann Biomed Eng, 2012.* [12] Guerin, et al., *J Biomech*, 2006.

Results

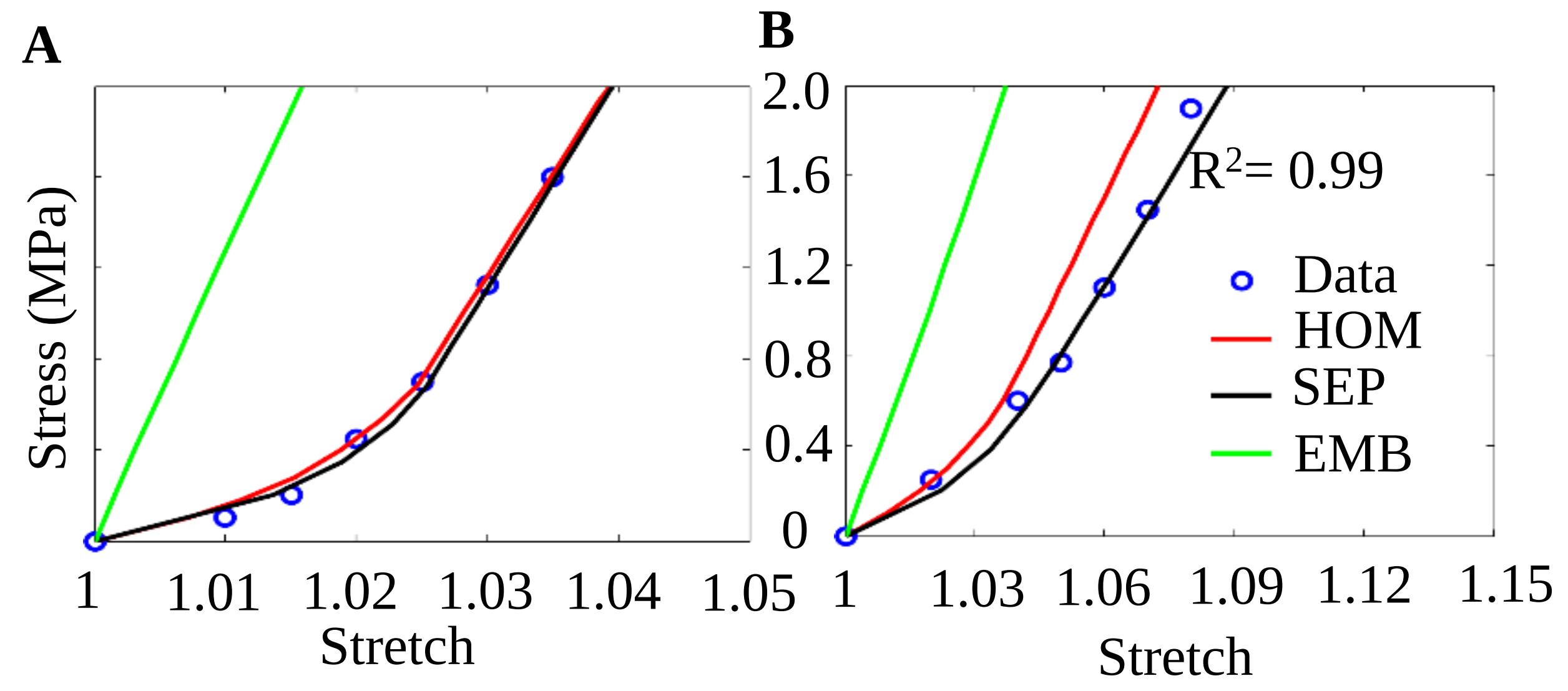

Figure 4. Stress-strain response in uniaxial tension for (A) single-lamella models and (B) double-lamella models (fiber orientation = ±65°) compared to data reported in the literature [9].

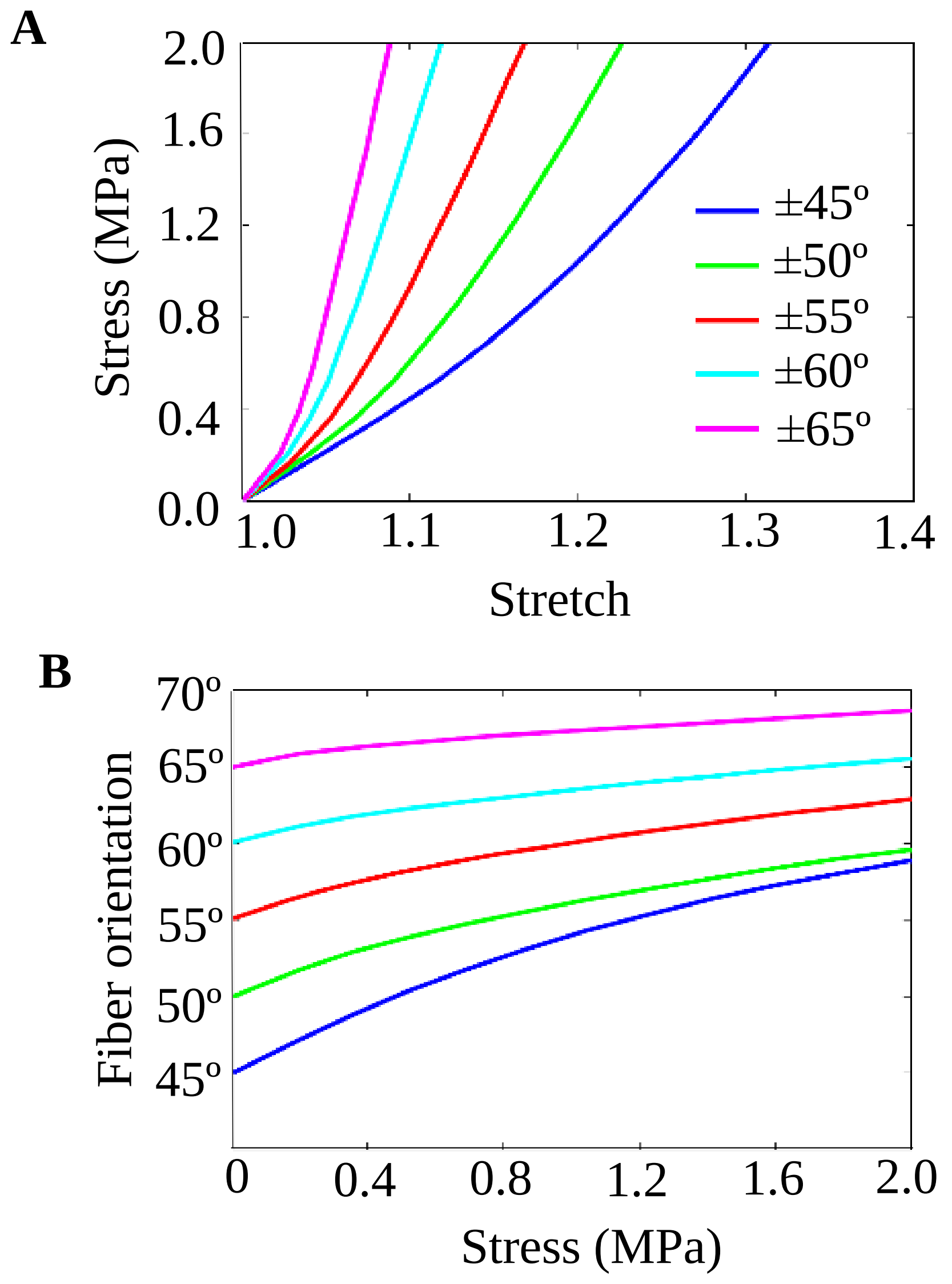

Figure 5. SEP model: (A) Stress-stretch response with fiber orientation. (B) Fiber re-orientation under tension.

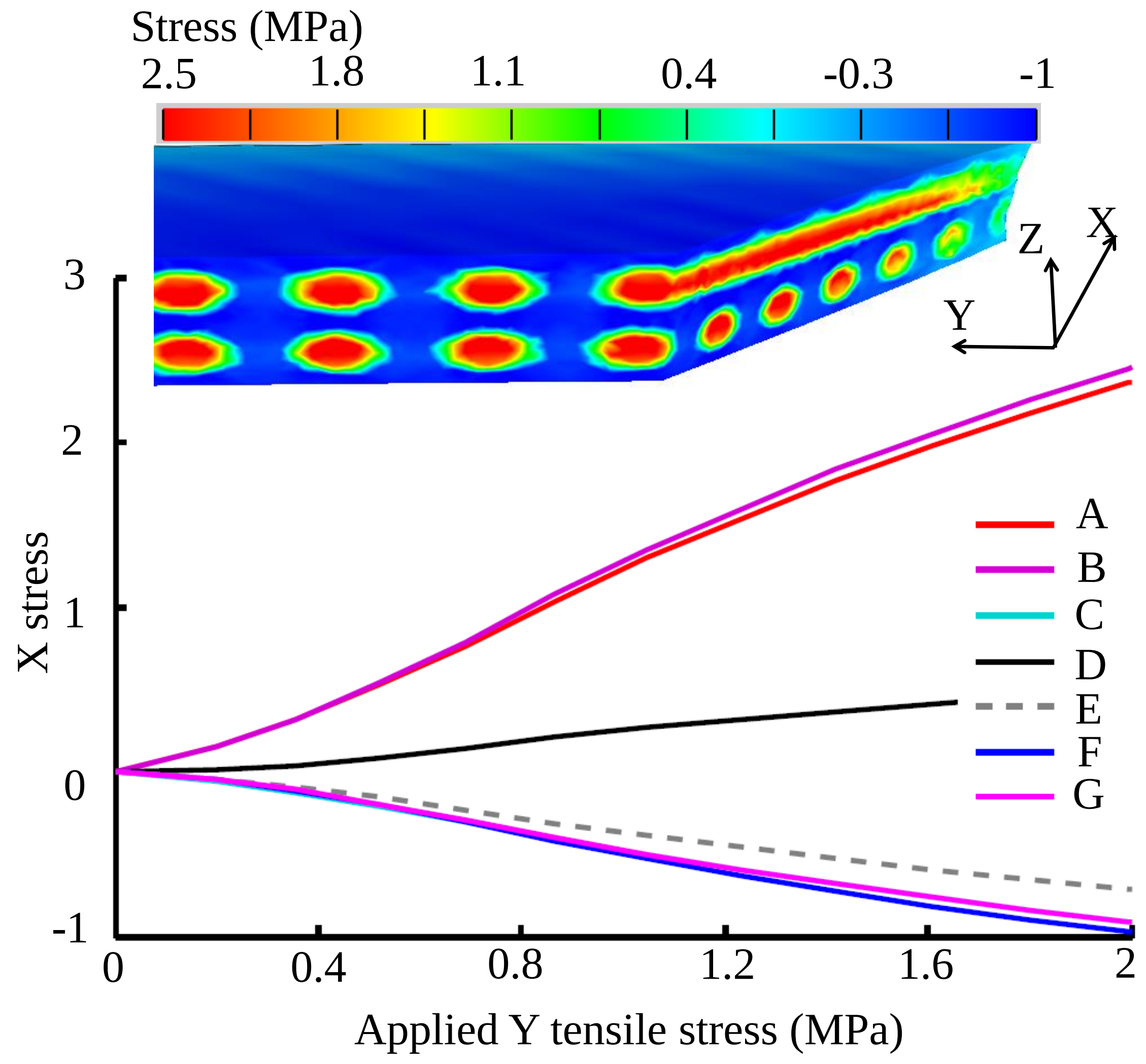

Figure 6. SEP model: X stress at different locations (see Figure 3).

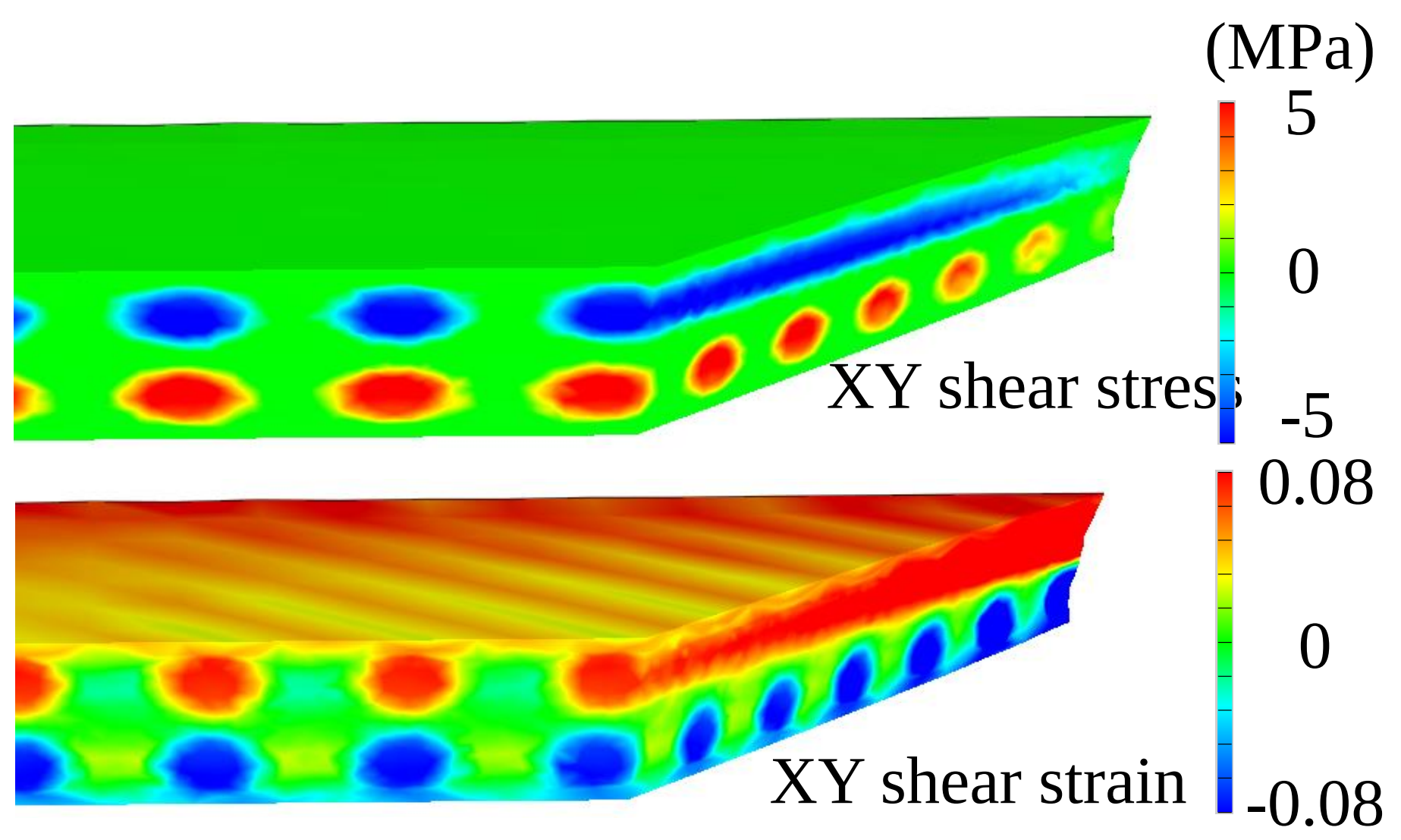

Figure 7. SEP model: XY shear stress and strain.

- Fibers showed tension in the transverse direction, while the matrix experienced compressive stresses (Figure 6). Fibers experienced much higher XY shear stress and strain than the extrafibrillar matrix (Figure 7).

Discussion

- *We developed a separated fiber-matrix model description (**SEP**), allowing for investigation of fiber-matrix interactions, which is not possible with more commonly used FEM for fiber-reinforced tissues (**EMB** and **HOM**).*
- The tissue-level response of the EMB model was linear (Figure. 4), suggesting that geometric nonlinearity is not sufficient for bulk nonlinearity.
- Decreasing the initial fiber orientation (±65° to ±45°) reduced the effective Young's modulus from 21.8 MPa to 7.5 MPa, which agrees with experimental data from outer and inner AF (17.2 ± 7.7 MPa and 2.6 ± 1.0 MPa, respectively) [10,11]. However, differences in the inner AF may be due to differences in collagen type and amount (Figure 5).
- Fiber reorientation in the ±45° SEP model was more pronounced than fiber reorientation in ±65° model, which agrees with previous data on human AF fiber reorientation [12].
- *In conclusion, fibers experience much higher stresses and strains than the matrix.*
- Future work will investigate tissue failure mechanism using the SEP model.

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