Fabric-Elasticity Property Relationships of the Human Cortical Femur

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ABSTRACT

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1. Introduction

Bone is a hierarchical material...

1.1. Bone structure

- Bone composition
- Mineralised collagen fibrils
- Lamellar bone
- Osteon
- Cortical bone

1.2. Mechanical testing

- Nanoindentation
- Resonant ultrasound spectroscopy

1.3. Imaging

- Micro-computed tomography

1.4. Bone Properties Estimation

- Micro finite element analysis
- Density and fabric
- Homogenised finite element analysis

The aim of the present study is to investigate the influence of the bone matrix properties and microstructure on the mechanical properties of human bone. The relationships between density, fabric and mechanics are presented from the bone matrix (bone of full density) down to the low density of trabecular bone with a strong focus on the cortical bone. Additionally to relationships description, the ojective is to provide material constants for bone properties estimation.

Abbreviations: ROI, region of interest; μCT, micro-computed tomography;

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2. Material and Methods

2.1. Bone Experimental Properties

Lamellar bone

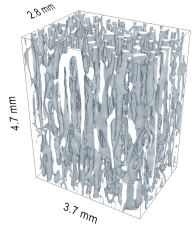
- Nanoindentation data
- Virtual fabric

Cortical bone

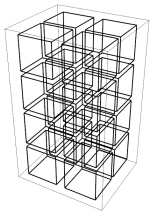
- Samples
- Micro-CT
- RUS data

In the present study:

- Downsampling factor 2
- 16x 1mm^3 Relationships
- Isotropic vs transverse isotropic material
- Average $\mathbb{S}$ per sample



(a) Typical sample with its porosities



(b) ROIs analysed

2.2. Theorical Model

- Density-elasticity relationships
- Fabric-elasticity relationships

Standard Model

$$\mathbb{S} = \lambda_0 \rho^k \mathbf{M} \otimes \mathbf{M} + \mu_0 \rho^k \mathbf{M} \underline{\overline{\otimes}} \mathbf{M} \tag{1}$$

with

$$\mathbf{M} = \sum_{i=1}^{3} m_i^l \mathbf{m}_i \otimes \mathbf{m}_i \tag{2}$$

Proposed Model

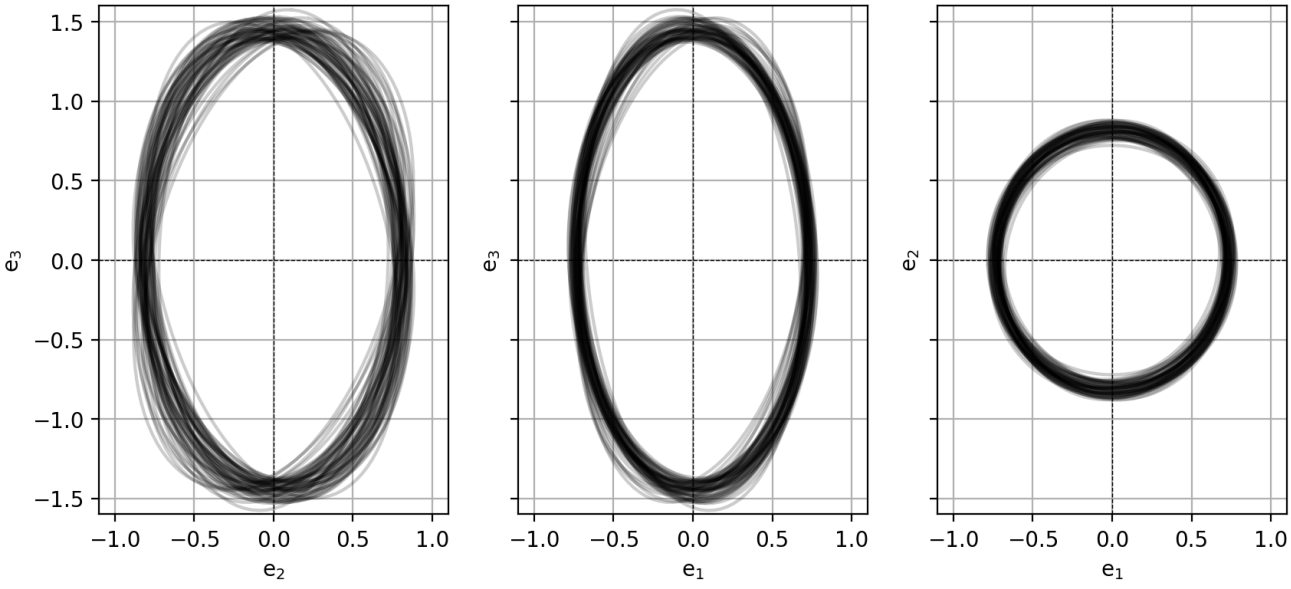
$$\mathbb{S} = \lambda_0 \mathbf{M} \otimes \mathbf{M} + \mu_0 \mathbf{M} \underline{\overline{\otimes}} \mathbf{M} \tag{3}$$

with

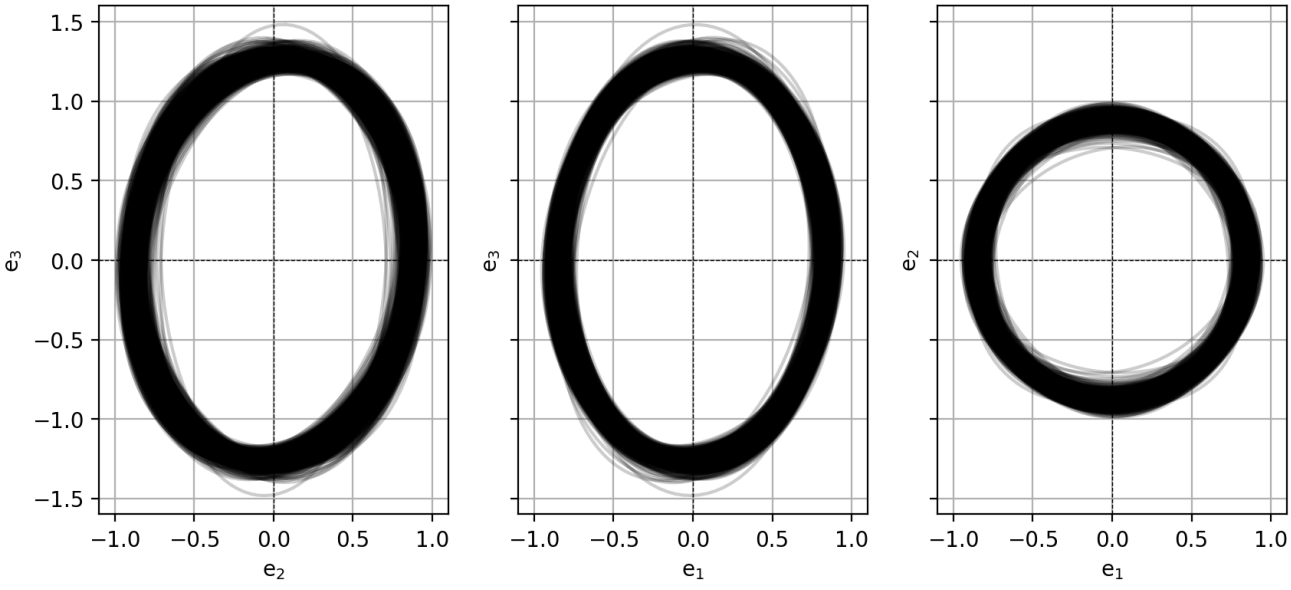
$$\mathbf{M} = \sum_{i=1}^{3} \rho^{k_i} m_i^l \mathbf{m}_i \otimes \mathbf{m}_i \tag{4}$$

Table 1
Nanoindentation - cortical bone matrix properties

Study	E1	E2	E3	Nu12	Nu13	Nu23	Mu12	M13	Mu23
Dall'Ara Fanzoso Present	14796.9	14796.9	21175.8	0.34	0.284214	0.284214	5521.23	6604.96	6604.96



(a) 2.8x3.7x4.7 mm^3 samples

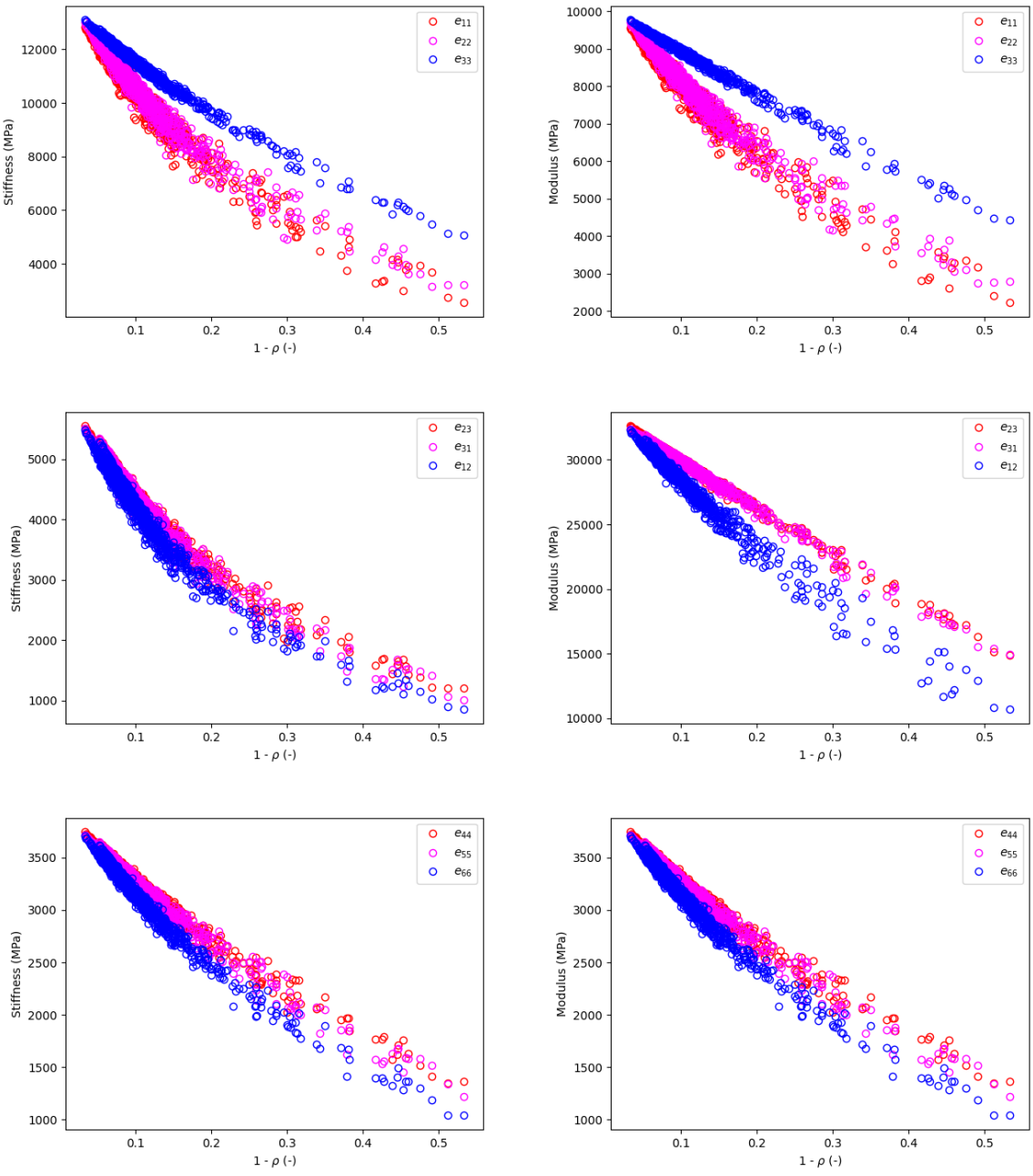


(b) 1x1x1 mm^3 ROIs

3. Results

3.1. Nanoindentation

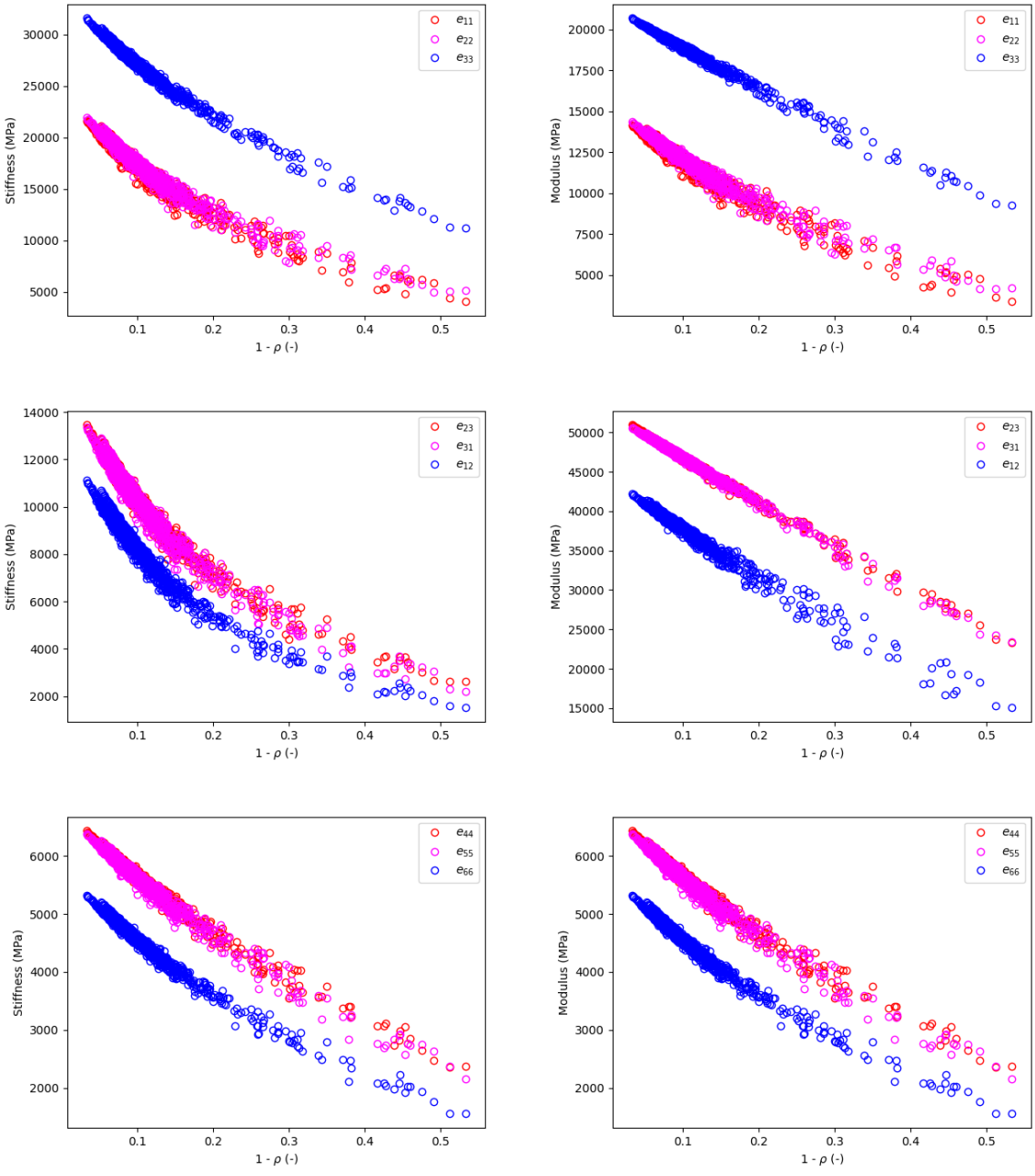
3.2. Cortical Bone Fabric



(a) Stiffness (b) Modulus

Figure 3: Isotropic matrix

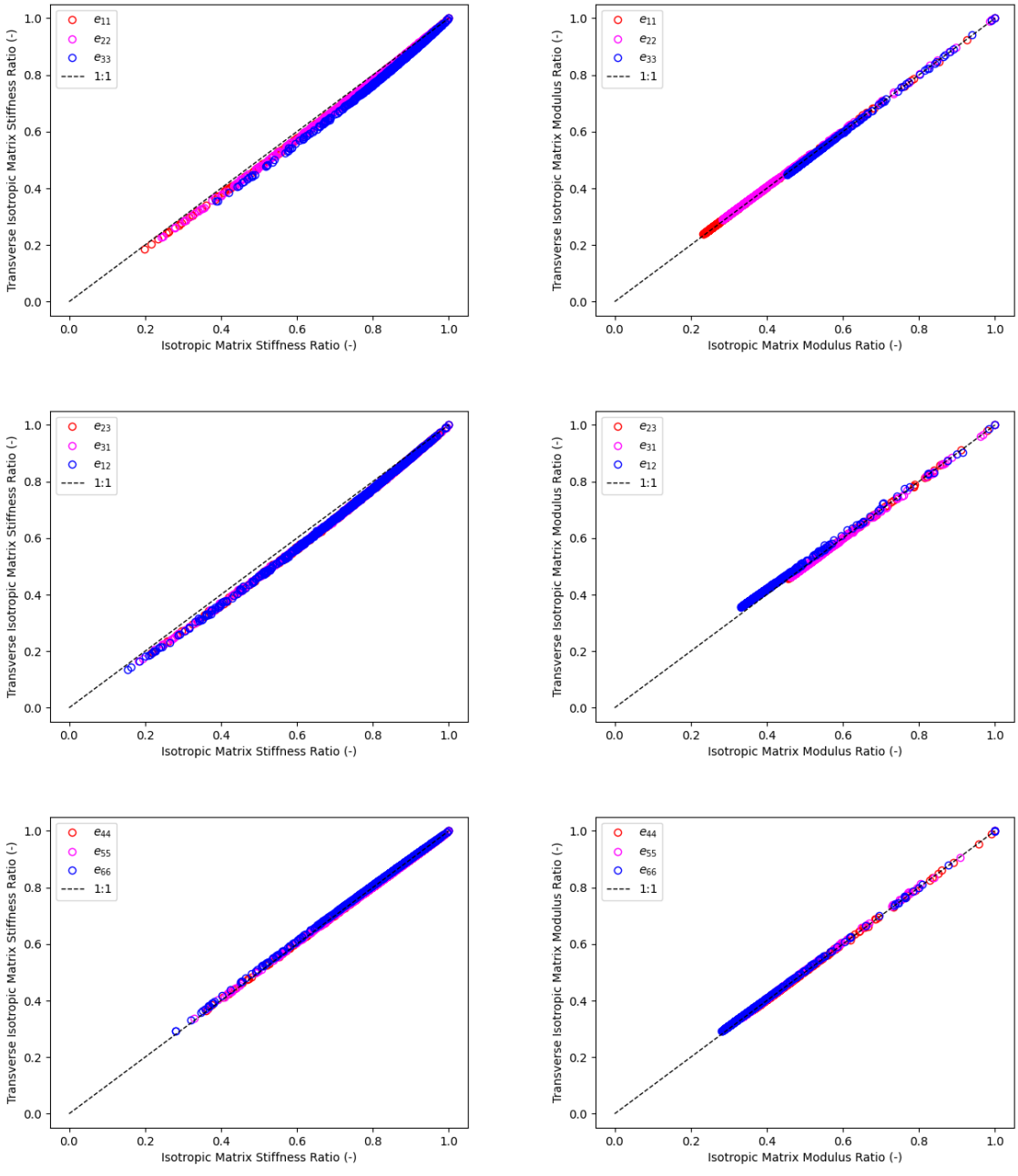
3.3. Cortical bone simulations



(a) Stiffness

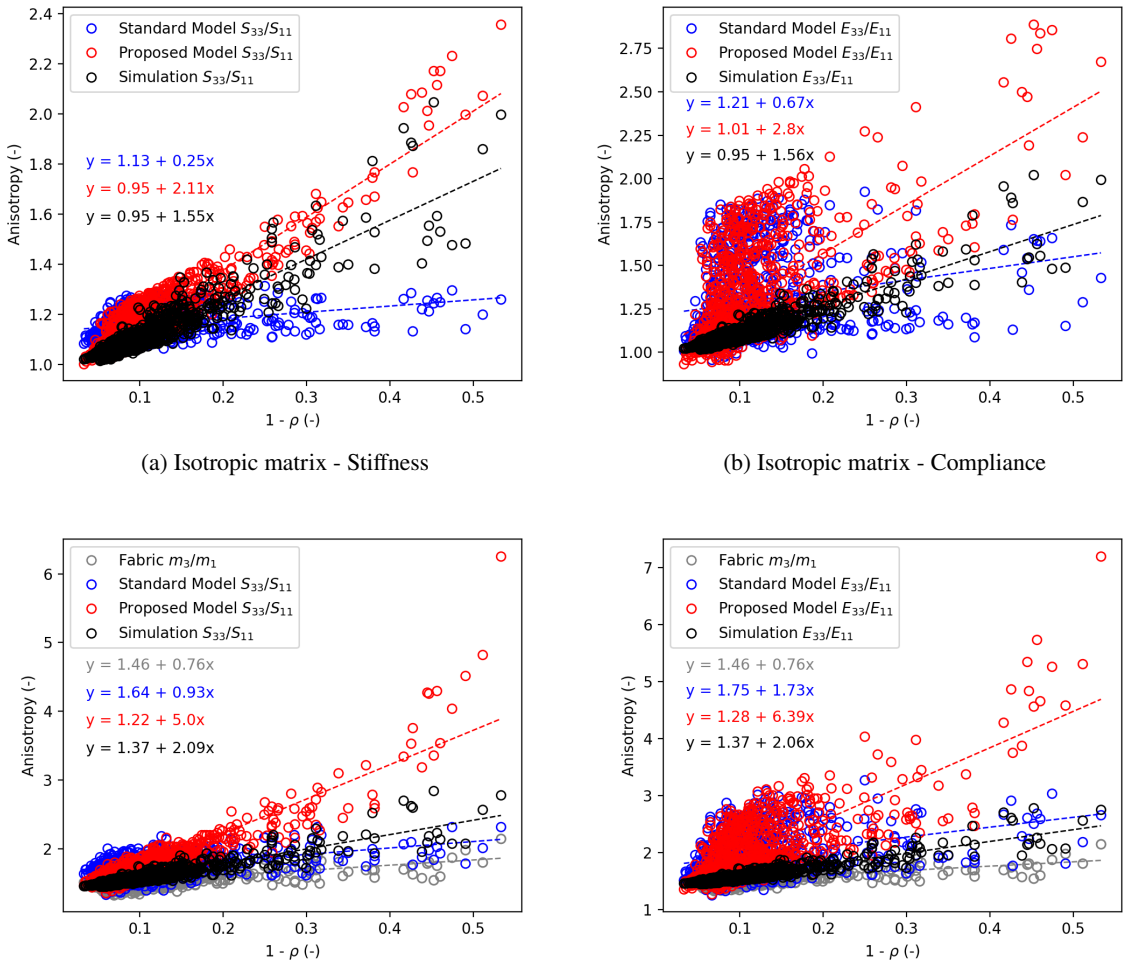
(b) Modulus

Figure 4: Transverse isotropic matrix



(a) Stiffness (b) Modulus

Figure 5: Values relative evolution with ρ



(a) Isotropic matrix - Stiffness

(b) Isotropic matrix - Compliance

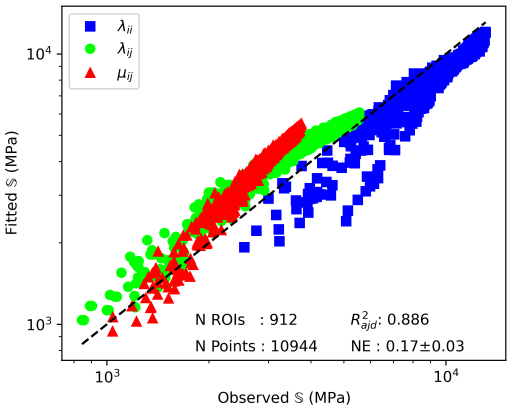
(c) Transverse isotropic matrix - Stiffness

(d) Transverse isotropic matrix - Compliance

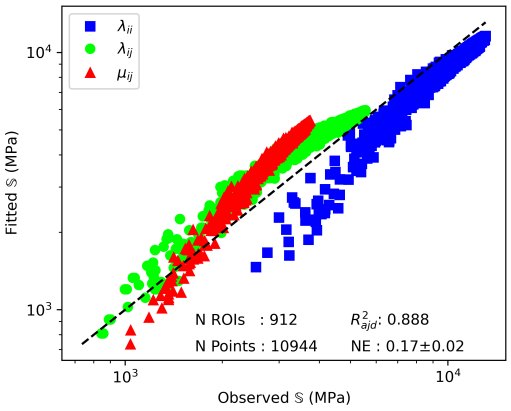
Figure 6: Anisotropy ratios

Matrix	M	Model	λ_0	μ_0	k1	k2	k3	l
Isotropic	Variable	Standard	6406	2912	2.28	2.28	2.28	0.14
Isotropic	Variable	Proposed	6414	2916	2.78	2.65	1.61	0.00
Isotropic	Average	Standard	6412	2915	2.29	2.29	2.29	0.14
Isotropic	Average	Proposed	6414	2916	2.78	2.65	1.61	0.00
Isotropic	Matrix	Standard	6409	2914	2.29	2.29	2.29	0.15
Isotropic	Matrix	Proposed	6414	2916	2.78	2.65	1.61	0.00
Transverse	Variable	Standard	14165	4879	2.47	2.47	2.47	0.66
Transverse	Variable	Proposed	14468	4977	2.92	3.48	1.82	0.48
Transverse	Average	Standard	14121	4865	2.44	2.44	2.44	0.65
Transverse	Average	Proposed	14446	4969	2.98	3.50	1.72	0.46
Transverse	Matrix	Standard	14088	4852	2.44	2.44	2.44	0.72
Transverse	Matrix	Proposed	14398	4953	3.27	3.14	1.74	0.51

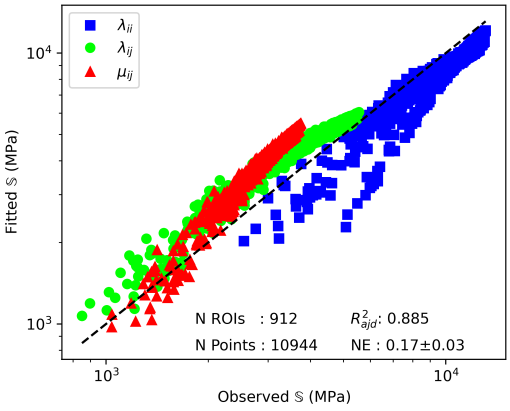
3.4. Fit to model



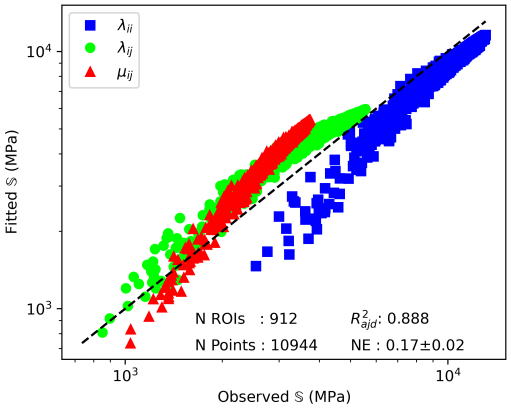
(a) Standard model variable M



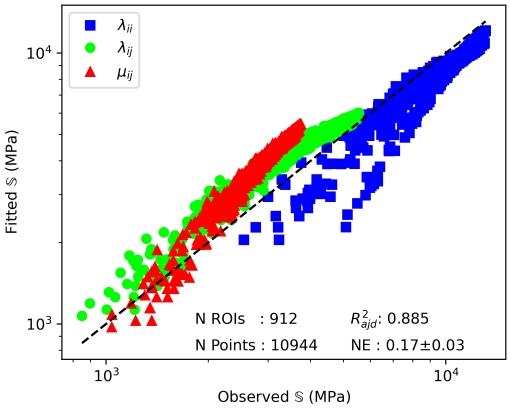
(b) Proposed model variable M



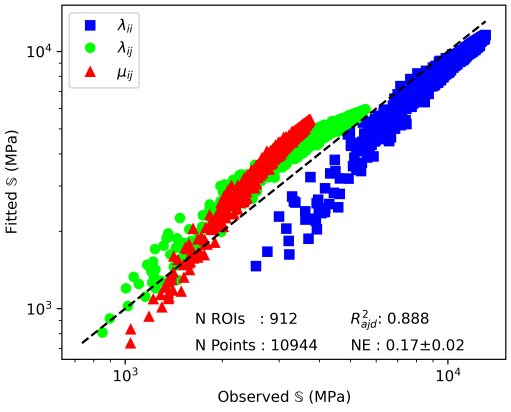
(c) Standard model average M



(d) Proposed model average M

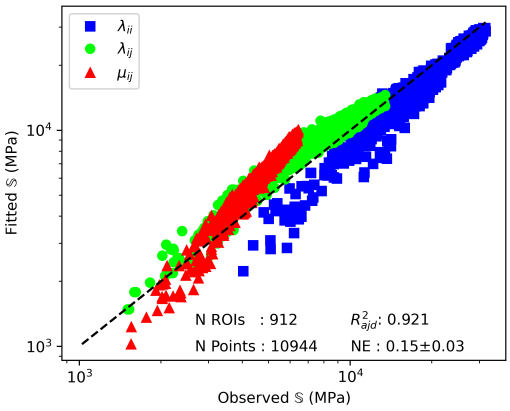


(e) Standard model matrix M

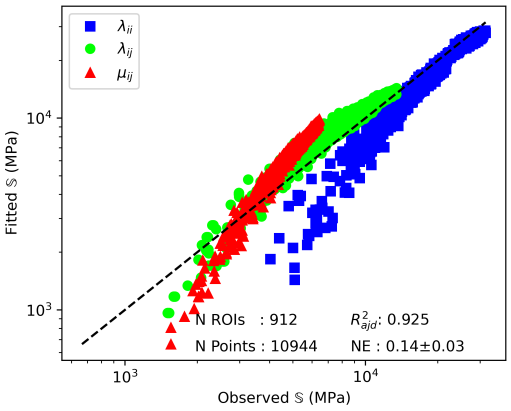


(f) Proposed model matrix M

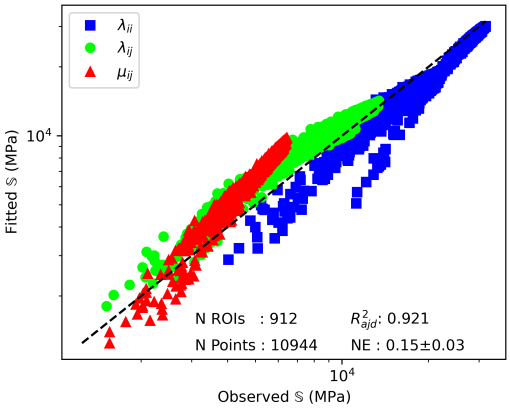
Figure 7: Isotropic matrix properties



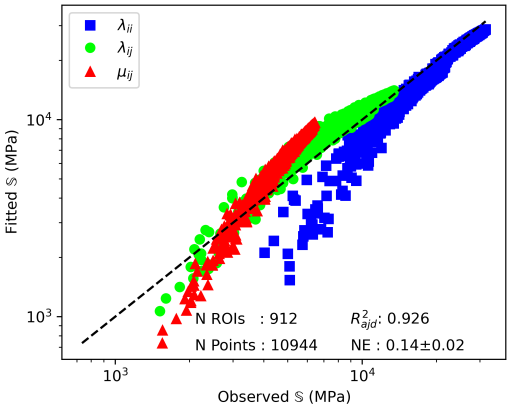
(a) Standard model variable M



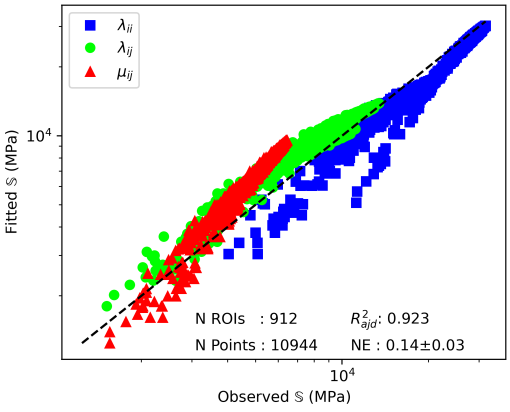
(b) Proposed model variable M



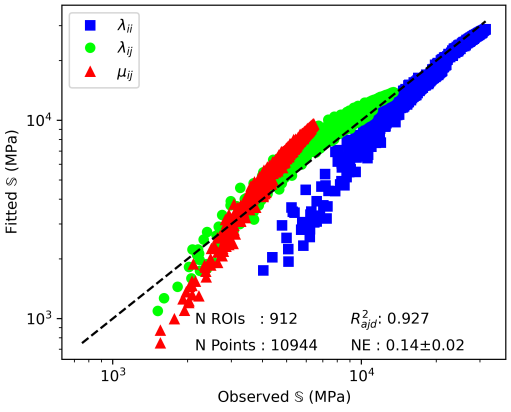
(c) Standard model average M



(d) Proposed model average M

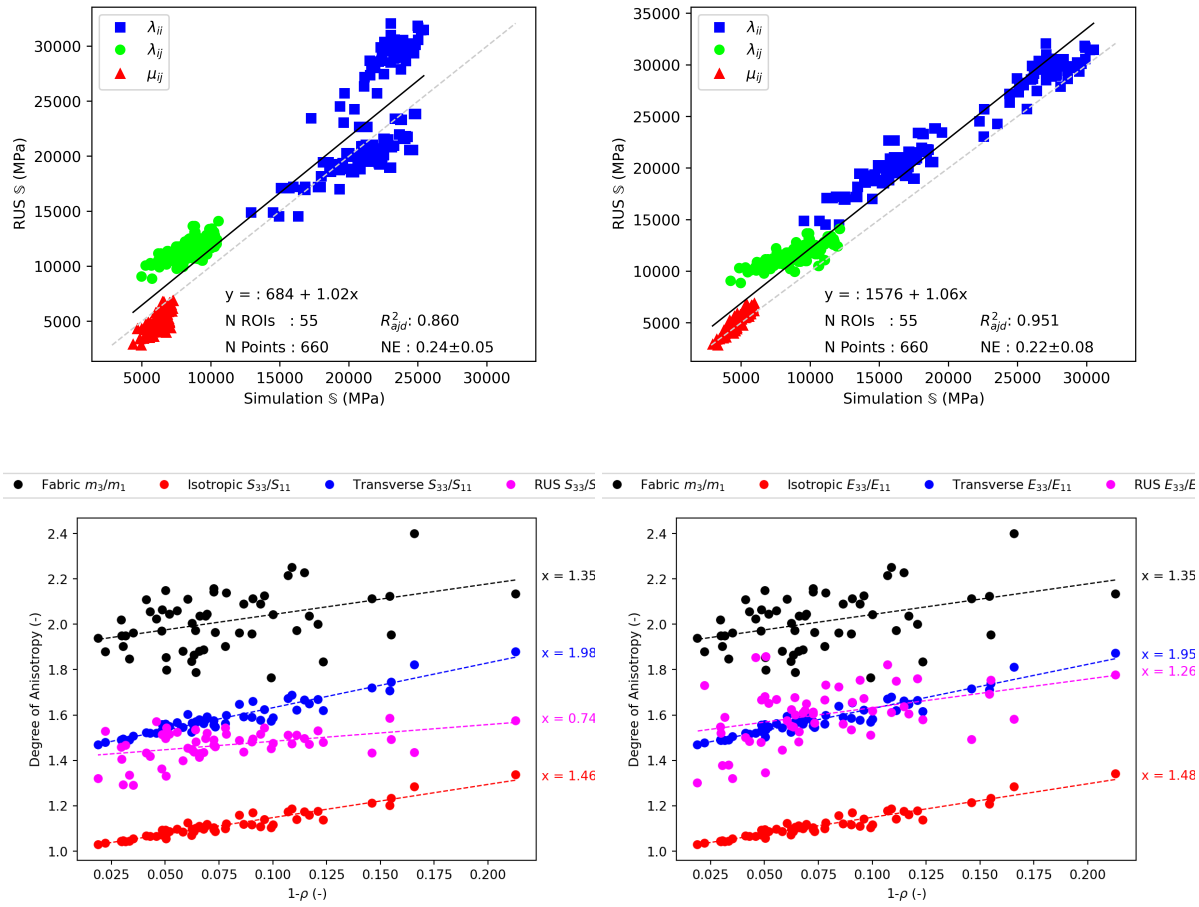


(e) Standard model matrix M



(f) Proposed model matrix M

Figure 8: Transverse isotropic matrix properties



3.5. Comparison to RUS

4. Discussion and Conclusion

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Data availability statement

The data that support the findings of this study are available on request. The data are not publicly available due to privacy/ethical restrictions. The scripts used for the analyses performed in the present study are available on Github: https://github.com/artorg-unibe-ch/FABTIB

Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

CRediT author statement

Mathieu Simon: Data Curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. **Philippe Zysset:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review and editing.

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[1] Simon, M., Indermaur, M., Schenk, D., Hosseinitabatabaei, S., Willie, B.M., Zysset, P., 2022. Fabric-elasticity relationships of tibial trabecular bone are similar in osteogenesis imperfecta and healthy individuals. Bone 155, 116282. URL: https://www.sciencedirect.com/science/article/pii/S8756328221004488, doi:https://doi.org/10.1016/j.bone.2021.116282.