Finite element analysis of osteoporotic lumbar vertebrae L1 under dynamic loading

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INTRODUCTION

Osteoporosis impacts the micro-architectural structure of bone tissue and increases fracture risk [1]. Vertebral fractures in particular result in a high mortality rate [2]. Although osteoporosis affects the entire skeleton, many fragility fractures occur in the lumbar spine [3]. The present study is aimed to investigate the influence of osteoporosis on the mechanical behavior of the vertebra L1.

MODELLING

Problem formulation

The three-dimensional static FEM analysis was performed in order to define the mechanical behavior of human lumbar vertebrae L1 model under the compression load. Theory of elasticity was applied.

The bone tissue is modelled as elastoplastic continuum, so the Von Mises-Hencky criterion is chosen to predict the failure of the model. The selection of this criterion is based on mechanical properties of the bone, which seem to behave as a ductile material [4], [5]. Also, the structure of model is continuous, so the Von Mises stress criterion is applied on research of stresses, which occur on cortical shell of the model.

Structure of the model

The inhomogeneous lumbar vertebrae body consists of two basic structural members – outer cortical shell fulfilled by inner bone tissue. The initial anatomical geometry of the developed vertebrae body model is illustrated in Fig. 3.

Material properties

Both cancellous trabecular bone and surrounding compact bone (cortical shell) are modelled as elastoplastic transversally orthotropic continuum. The stress-strain curve for cortical bone in main axial direction is presented in Fig. 1. Intervertebral disks were assumed isotropic and perfectly elastic. Mechanical properties of model members are presented in Table 1.

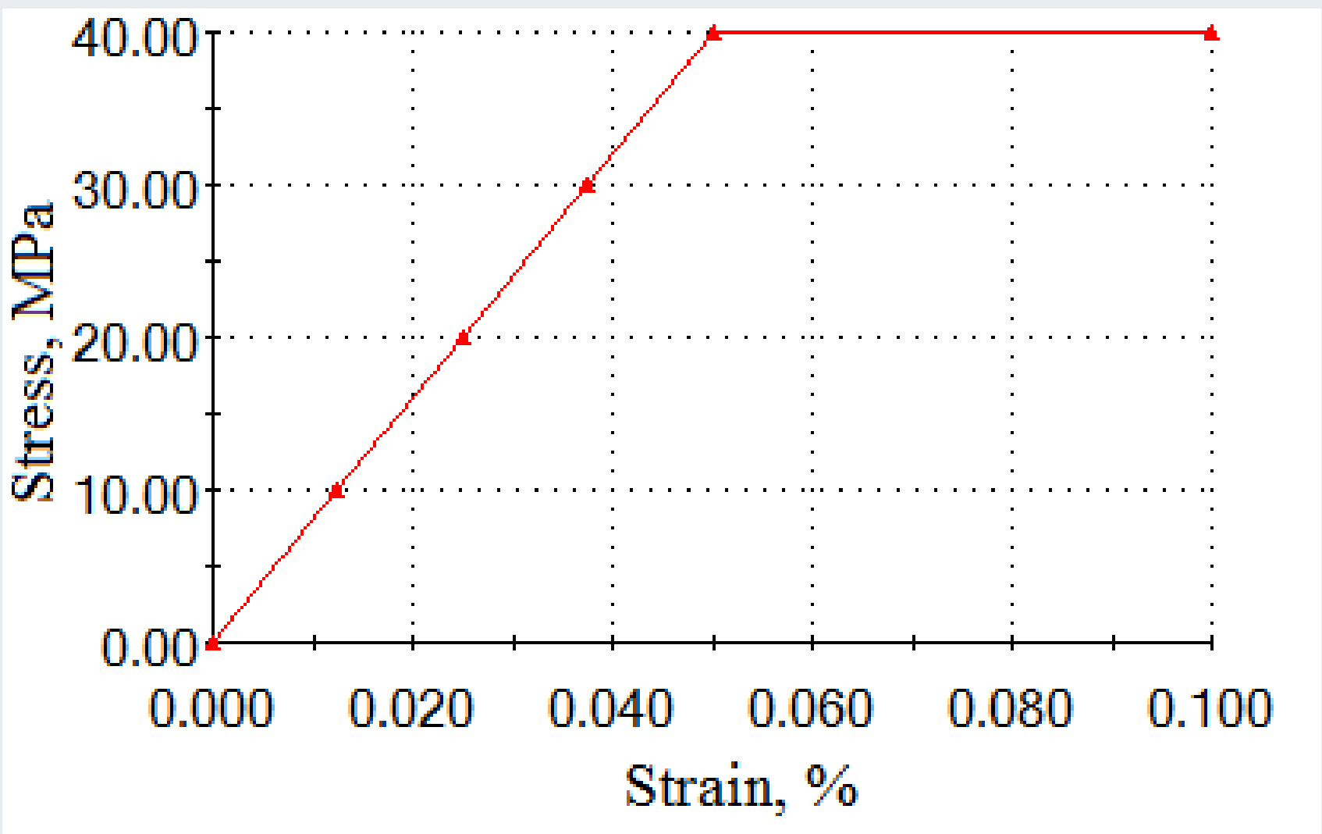


Fig. 1: Stress-strain curve for cortical bone

Osteoporotic influence for the vertebrae is characterised by decreasing modulus of elasticity of cancellous bone. Modulus of cancellous bone is determined according to power-law equations, which reflect the impact of apparent density. The selection of this equation is based on alignment of our research and data published by Helgason et. al.[6].

$$E_{cancellous} = 4.730\rho^{1.56}$$

where ρ is apparent density. In current research it is in range between 0.10 and 0.30 g/cm^3.

Table 1. Elasticity constants and density parameters

Component	E_z, MPa	E_x=E_y, MPa	ν_z	ν_x=ν_y	ρ, g/cm^3
Cortical shell	8000	2500	0.30	0.200	-
Trabec. bone	130-720	42-240	0.30	0.200	0.10-0.30
Inter. disk	10	10	0.495	0.495	-

Loads and boundary conditions

The bone is subjected by the physiological loads, which occur through daily activities. Generally, it presents the axially acting pressure load (Fig. 2). The model was meshed with tetrahedral finite elements due to its curvature. The number of finite elements of cortical shell was 7686 and the number of nodes – 16597, as for the most important part of the model. In order to accelerate calculations, the number of finite elements of cancellous bone was 12915, the number of nodes – 18313. The number of finite elements of intravebral disks was only 3224 and the number of nodes – 5677, for it‘s not the primary part of the model.

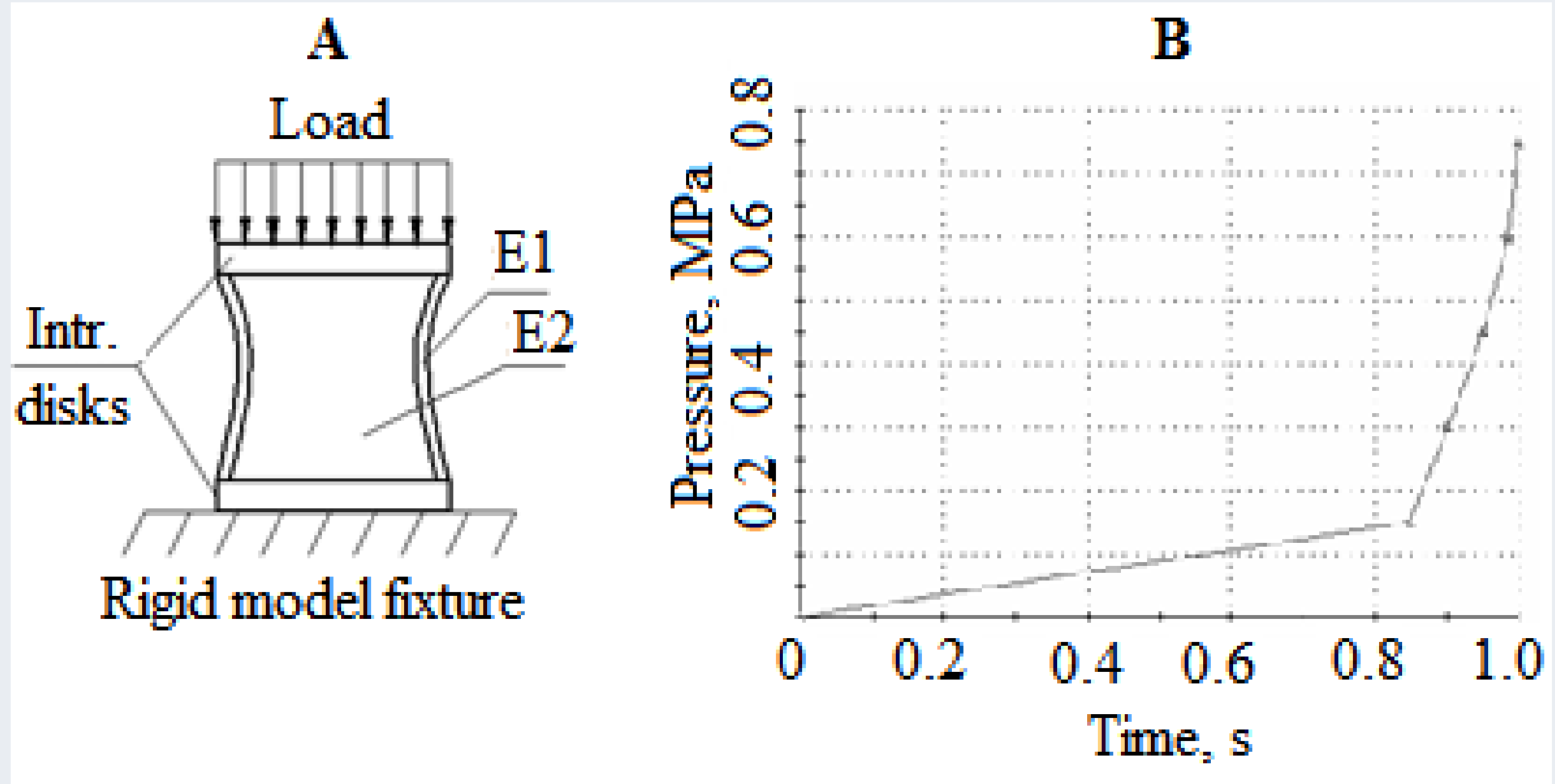


Fig. 2. A: Schematization of load due to compression test;
E1 – cortical shell;
E2 – cancellous bone; B: time variation of load

The Brigade/Plus software was used.

MODEL STRUCTURE

Fig. 3. The initial geometry derived from DICOM data

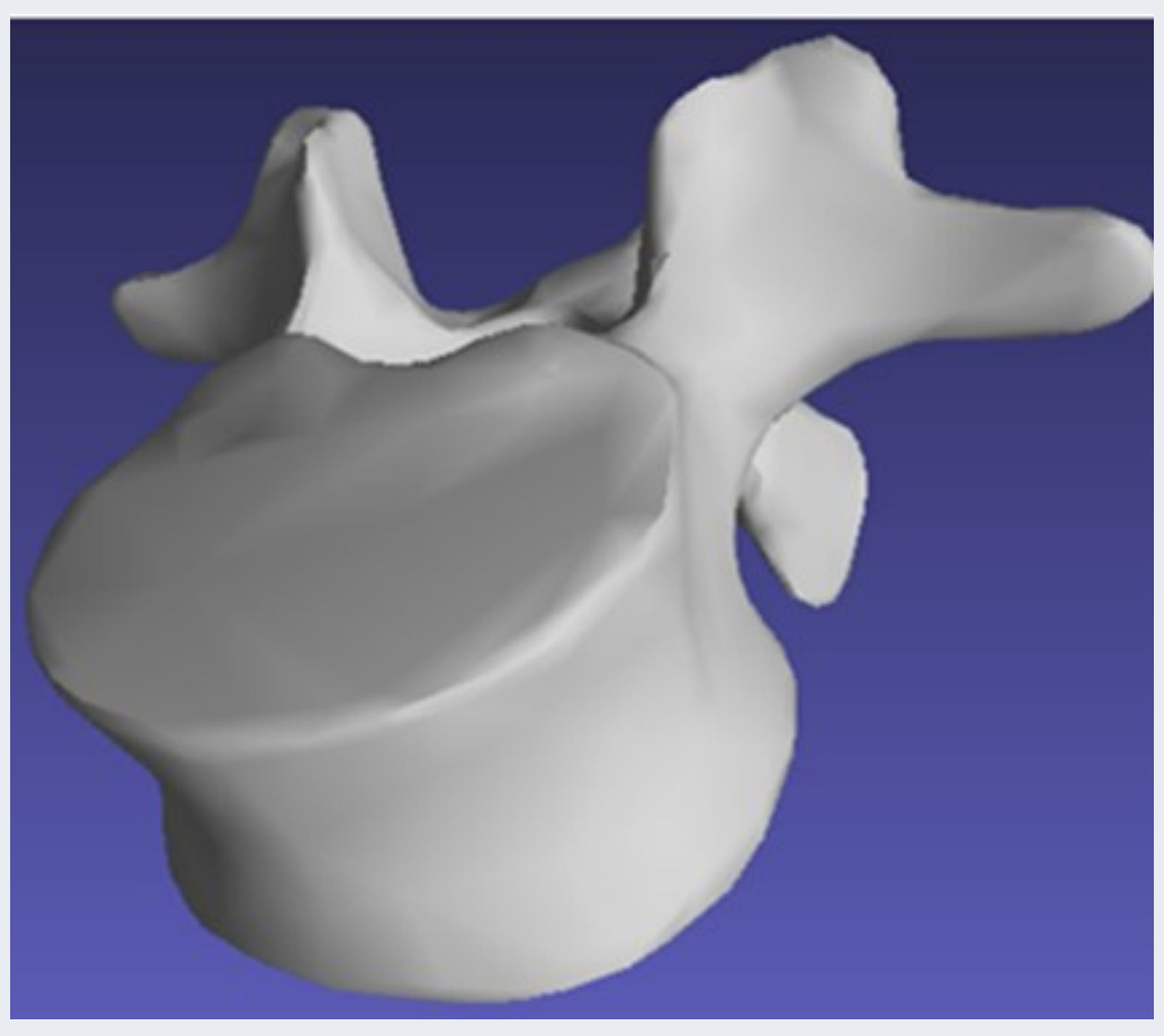
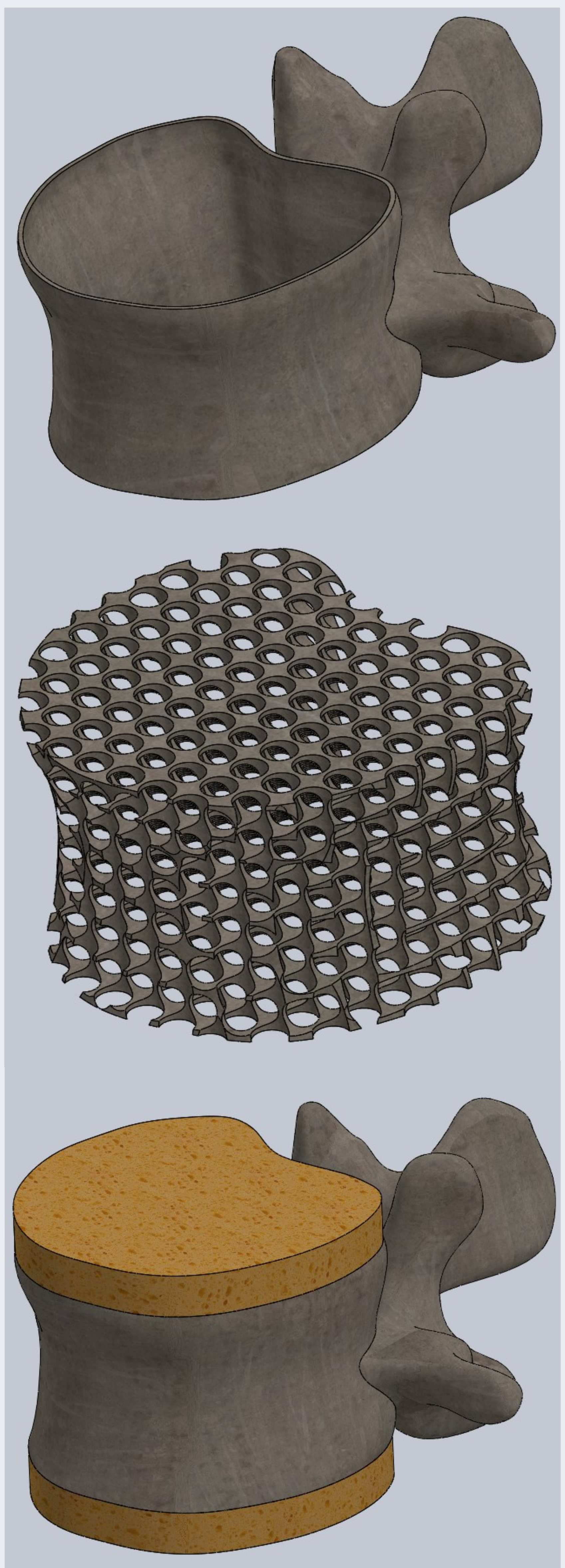
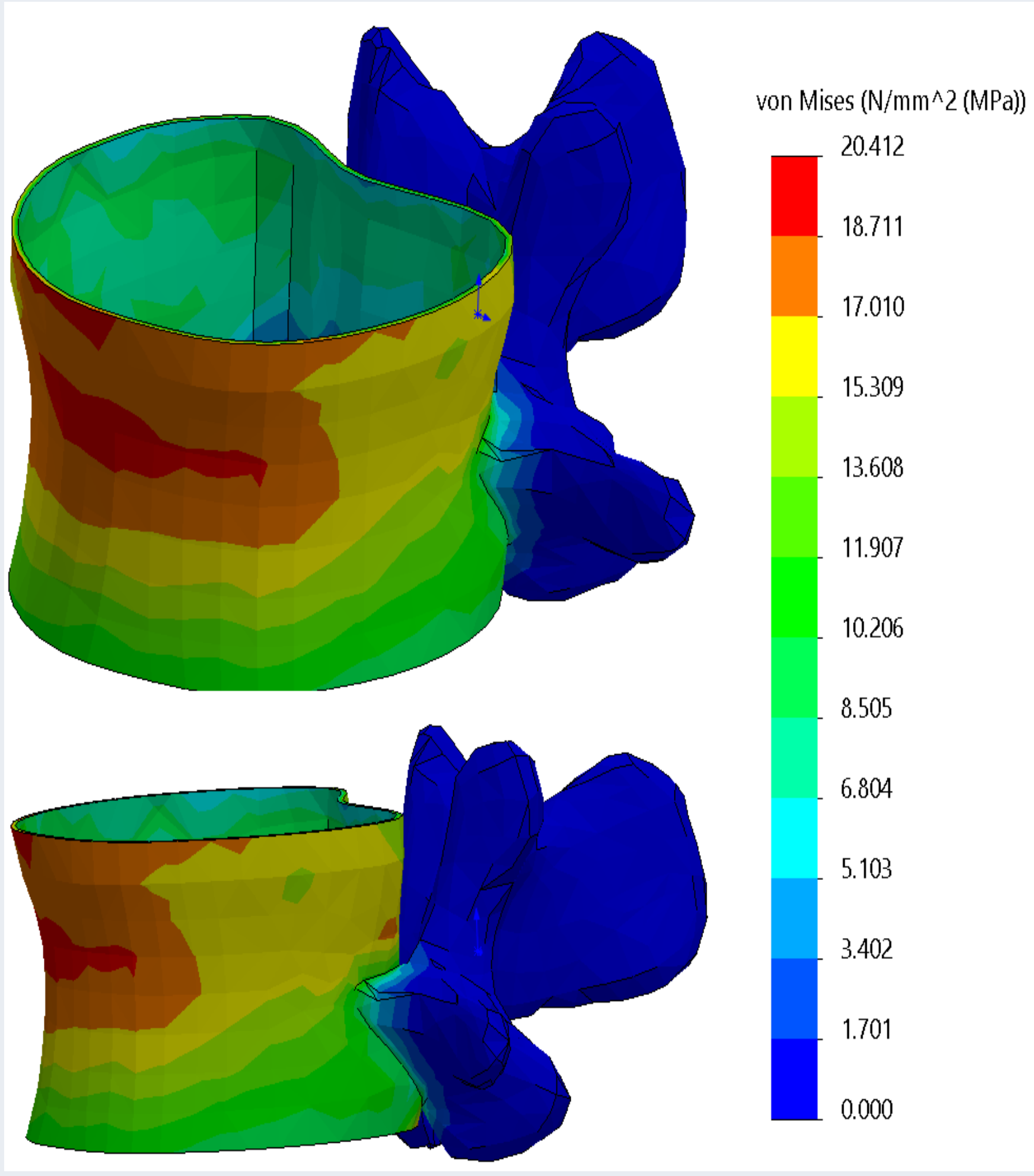


Fig. 4. Components of the numerical model



NUMERICAL RESULTS

Fig. 5. Stress distribution on the cortical shell



NUMERICAL RESULTS

Fig. 6. Von Mises stress for 0.5 mm cortical shell thickness

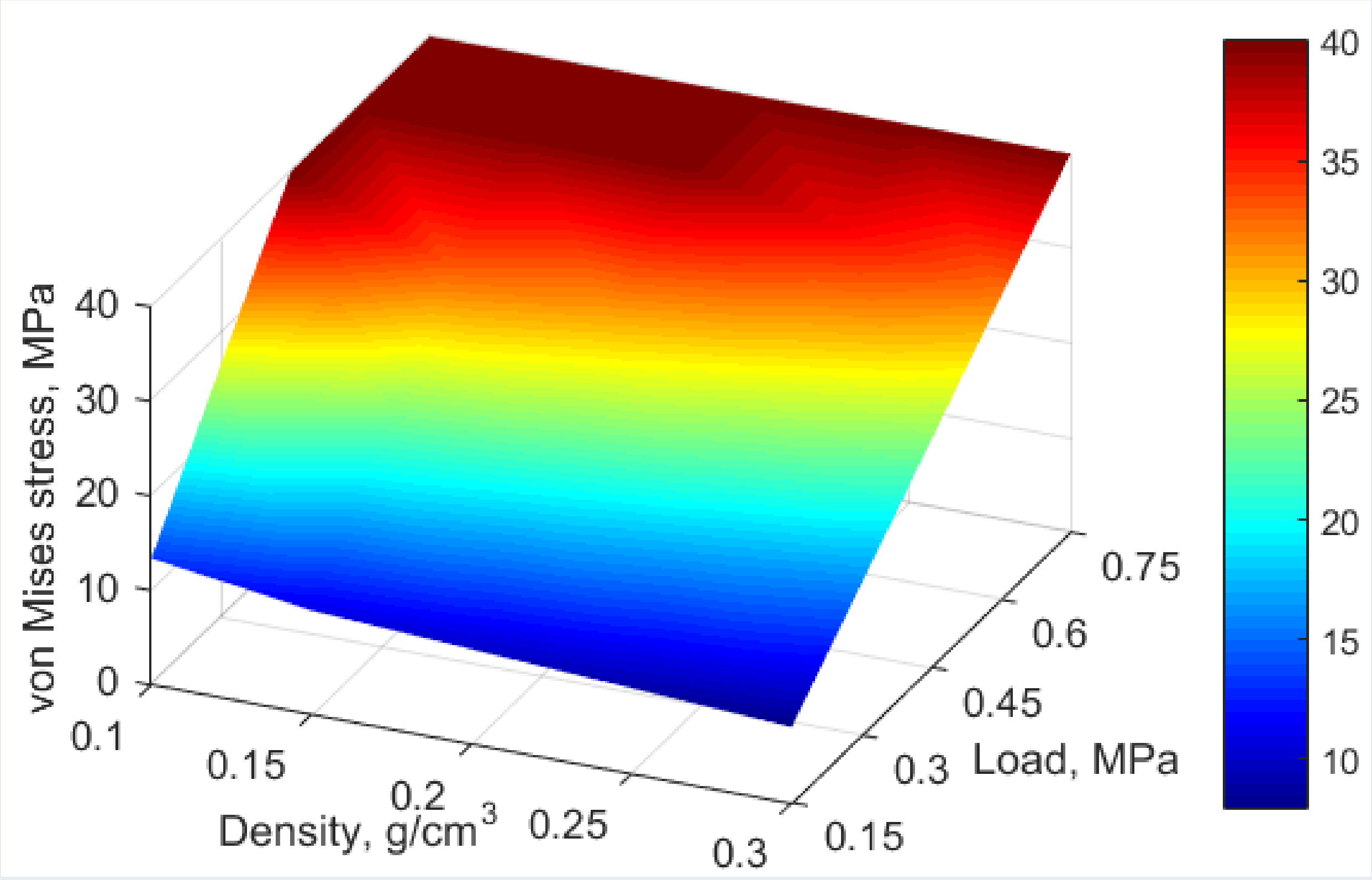


Fig. 7. Von Mises stress for 0.4 mm cortical shell thickness

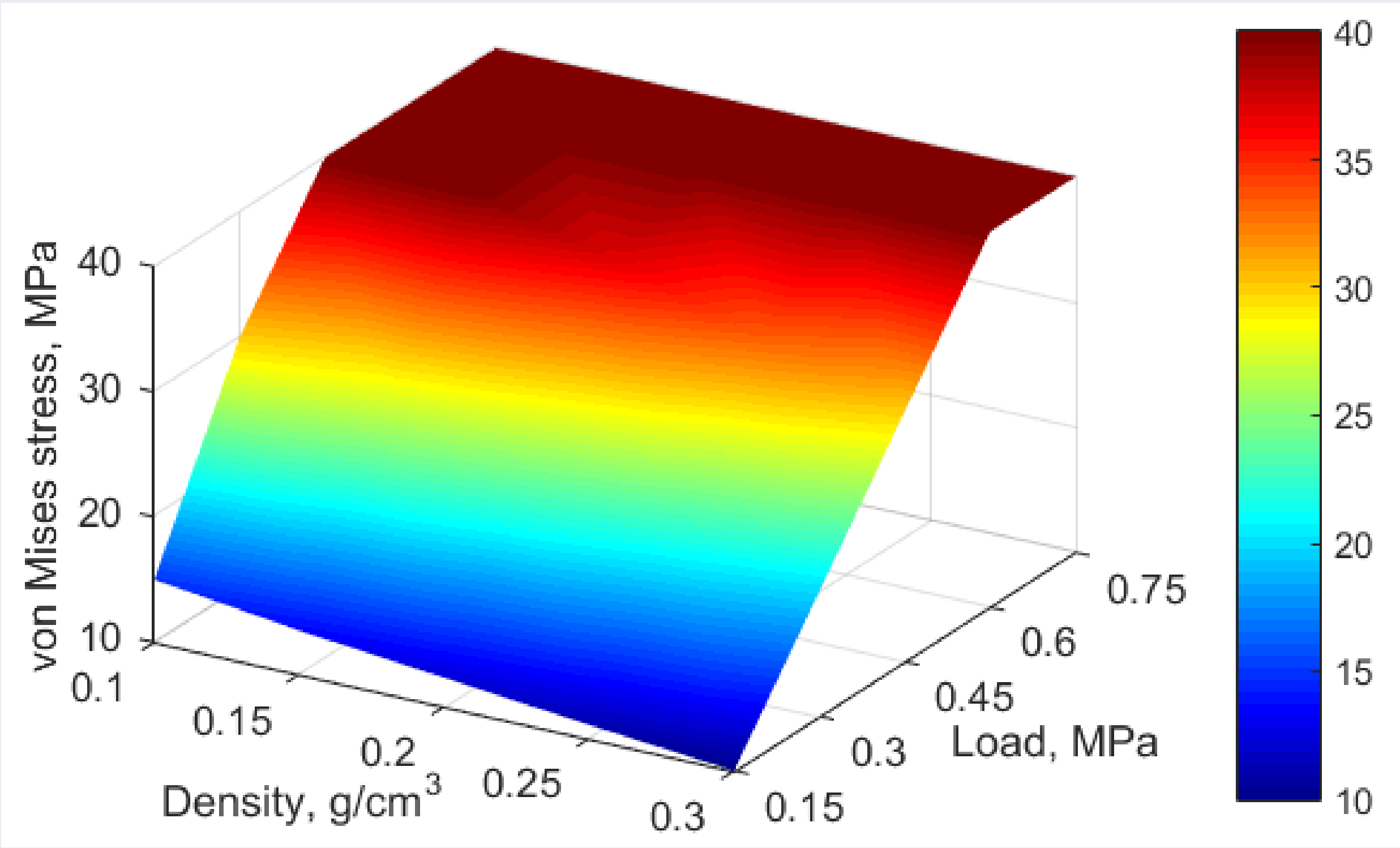
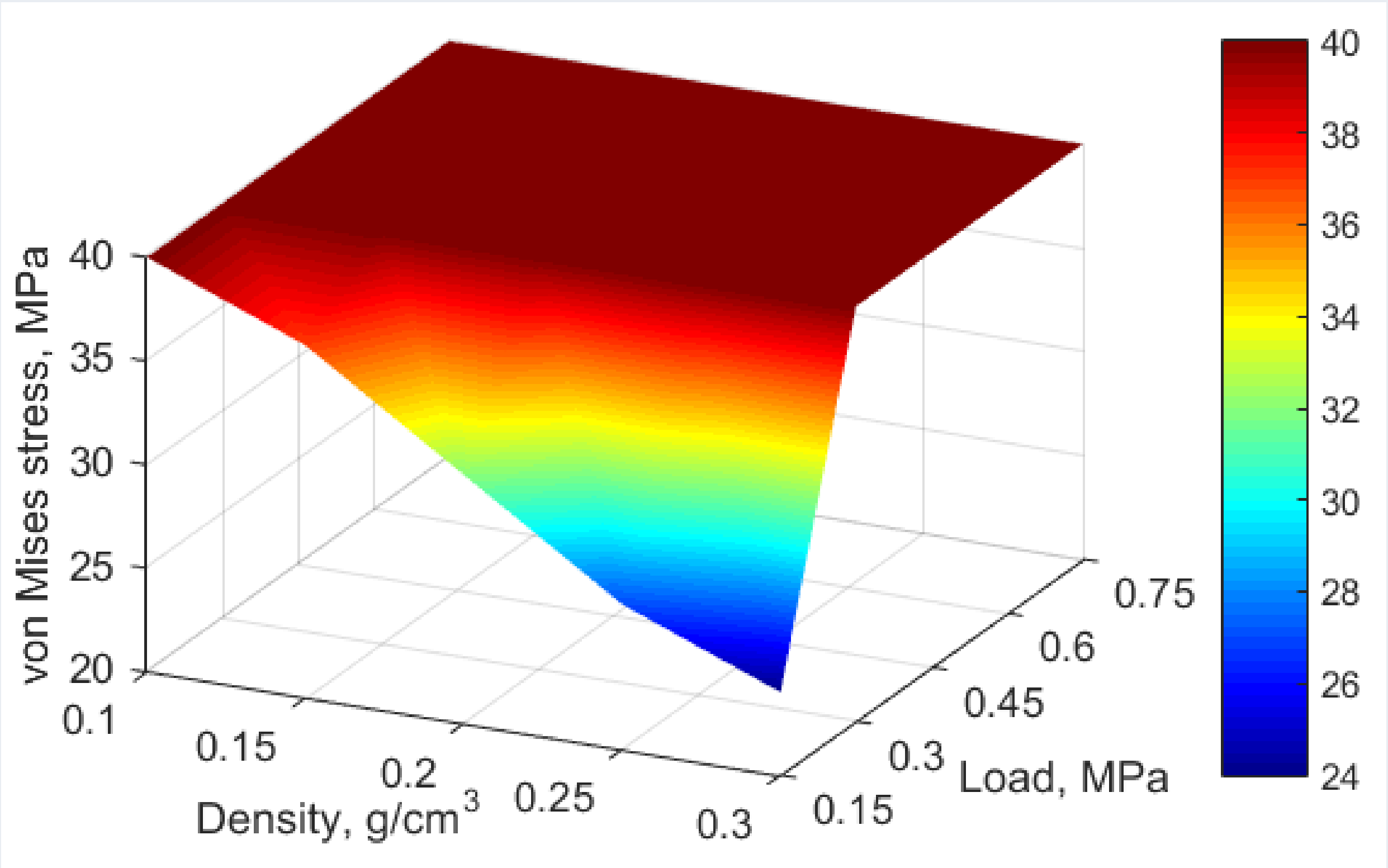


Fig. 8. Von Mises stress for 0.2 mm cortical shell thickness



CONCLUSION

We developed the L1 vertebra model, which consisted of cortical shell, cancellous bone and intervertebral disks. The model was treated for three grades of degenerative diseases. The model was investigated using finite element method. The von-Mises stress, which was assumed to predict the risk of fracture, was determined for three different thicknesses of cortical shell and different apparent density of cancellous bone (in range of 0.1—0.3 g/cm^3). The results showed that the von-Mises stress was substantially higher under relatively low levels of apparent density, and critical due to thinner cortical shell, which suggests that patients with degenerative bone diseases should be cautious of fracture risk even during daily activities.

In addition, this model could be easily individualized according to the anatomical peculiar properties of patients.

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