27/28th International Conference
ENGINEERING MECHANICS 2022
Milovy, Czech Republic, May 9 –12, 2022
Paper **#111**, pp. 69–72, doi: 10.21495/51-2-69

ITERATIVE EVALUATION OF TRABECULAR BONE ANISOTROPIC APPARENT MECHANICAL PROPERTIES

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Abstract: *The trabecular bone, formed as a result of complex remodeling processes, is characterized not only by the heterogeneity of the mineral fraction distribution but also by its structure anisotropy. As a result of these processes, the mechanical properties of trabecular structures are also characterized by anisotropy. In the paper the orientation of the trabecular bone structure principal mechanical direction was iterative determined by univariate search method. Successive steps assumed the execution of mFE analyzes set for the iterated values of one of the angles defining the direction of the considerations. Constant angle of spatial orientation for volume of interest for each step of analysis was determined from results of previous step. Based on significant correlation between bones principal mechanical direction and principal structural direction accuracy of the numerically determined structure direction was evaluated by comparison apparent modulus characteristic for this direction with modulus referred to principal structural direction.*

Abstract: Apparent stiffness, mFE analysis, Univariate method.

1. Introduction

The process of trabecular bone tissue remodelling is strongly correlated with local tissue loading which means that together with the site of the body change, also the results of remodelling changes (Christen et al., 2014). The trabecular bone, formed as a result of complex remodelling processes, is characterized not only by the heterogeneity of the mineral fraction distribution but also by its structure anisotropy (Tassani et al., 2010). The degree of anisotropy (DA) indicator is commonly used to describe the structure anisotropy determined by Mean Intercept Length (MIL) method. The increased value of DA suggests that in the considered region of the bone its structure is optimized with regard to load transfer (Blok et al. 2013). Site-specific variation of DA of trabecular bone structure may indicate that the directions and types of forces acting in the considered bone regions were different (Kim et al., 2013). Although grouping DA with other principal component analysis (PCA) indicators increases their predictive effectiveness (Cichański et al., 2010), more complete information about the trabecular structure anisotropy carries the fabric tensor which combines anisotropy and orientation of bone structure (Moreno, Borga and Smedby, 2014). The degree of mechanical anisotropy DM is used to describe the anisotropy of the mechanical properties of bone structures. The DM index is based on the modulus of elasticity determined in mutually perpendicular directions (Nikodem, 2012). Magnitudes of the apparent structure modules are proportional to the bone volume fraction and principal mechanical direction are closely aligned to the principal structural direction (van Eijden et al., 2006). Degree of mechanical anisotropy is more sensitive to local changes in the trabecular bone structure compared to degree of structural anisotropy, which is based on an approximation of spatial distribution of tissue by an ellipsoid (Cichański and Nowicki, 2022).

The paper deals with the anisotropy of the mechanical properties of the trabecular bone structure. The aim of the study is determination of the orientation of the trabecular structure principal mechanical direction. A set of mFE analyses was carried out which VOI orientation ware changed according to univariate search method. For successive iteration calculations constant microstructure sample cutting angles was selected on the basis of the results previous step. Accuracy of the estimation of trabecular bone mechanical properties orientation was evaluated in relation to the principal structural direction.

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2. Materials and methods

Samples of the trabecular structure taken from the head of the human femur with coxarthrosis disease were studied. The method of obtaining material for research and preparation of samples has been described in the paper (Topoliński et al., 2012). The collected biological material was stored in such conditions that its mechanical properties were unchanged (Mazurkiewicz, 2018). From this material, cylindrical samples with a diameter of 10 mm and a height of 8.5 mm were cut. These samples were scanned on the µCT80 (SCANCO Medical AG) microtomograph with a resolution of 36 µm, and then their trabecular structure was reconstructed with the same resolution. (Cichański and Nowicki, 2019). Four samples selected from the set n = 33 were used for the study. The extreme values of the BV/TV and DA ratios were adopted as the selection criterion. Selected structural indicators for the analysed samples are presented in Table 1.

Tab. 1: Trabecular structure samples indicators.

Sample	Description	BV/TV, -	Tb.Th, mm	TB.N, 1/mm	DA
1.	min of BV/TV	0.1513	0.1329	1.1381	1.9658
2.	max of BV/TV	0.3532	0.2360	1.4967	1.996
3.	min of DA	0.1851	0.1492	1.2405	1.5051
4.	max of DA	0.175	0.153	1.1441	2.2505

On the basis of the bone structure models obtained as a result of the reconstruction of the cylindrical samples, a hexahedral finite elements mesh was prepared (Cichański and Nowicki, 2020). The elements included in the volume of interest (VOI) in the form of a cube with side of 5.4 mm were selected from the FE mesh prepared in this way. (Fig. 1). The centre of the VOI was at the centre of gravity of the cylindrical sample. For the consideration of the orientation of the bone microstructure, the angles of the cube excision measured in the coordinate system assigned to the geometry of the cylindrical sample were adopted. The angle γ was measured with respect to the axial direction of the cylinder and the angle α with respect to the radial direction of the cylinder (Fig. 2). During the analysis of cubic samples, the boundary conditions were selected to obtain compression ε=1% for the considered direction (Cichański and Nowicki, 2022).

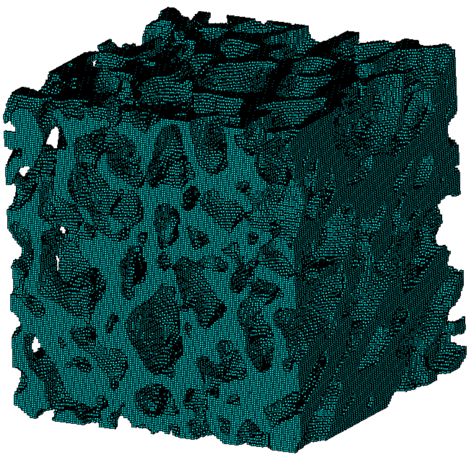

Fig. 1: Trabecular bone structure, sample BV/TV=0.3532.

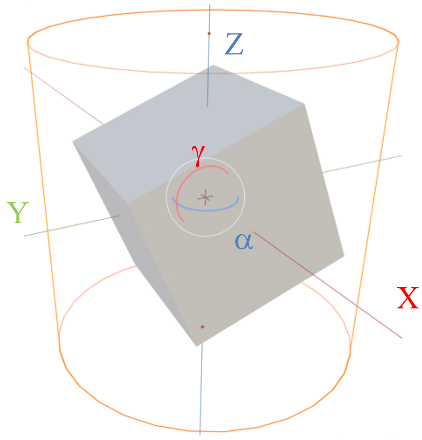

Fig. 2: Volume of interest cube in cylindrical bone sample

The orientation of the principal mechanical direction for analysed microstructure was determined during iteratively performed numerical analyses for alternately swapping rotation angles of VOI according to univariate search method. In the first step of search, analyses were carried out for which the direction of the considerations rotated with respect to the OX axis (Fig. 2). These analyses were carried out for directions described with $\alpha=1^o$angle and γ angles variable within the 180^o range with step 5^o. The results of the analyses were the values of the apparent module determined for the directions under consideration. Angle γ corresponding to the maximum of the apparent modulus was a constant value in the second step of search. In this step, the α angle was changed in range 360^o with step 5^o. In the third step of search, the angle α was again constant. Its value corresponds to the maximum of the modulus determined in the second step, and the γ angle was changed. In a similar manner, the angles for the fourth and fifth steps were alternated.

3. Results

As a result of iterative analyses, it was determined how the values of the apparent modulus change with the change of the consideration angle in individual step of search. The results obtained for the sample BV/TV = 0.3532 described in Table 1 as "max of BV/TV" are shown in Fig. 3a for the first and third steps, and in Fig. 3b for the second and fourth steps. One numerical analysis corresponds to a point in the result plot in Fig. 3. In each odd step, 36 iterations were performed and in each even-numbered step 72 iterations were performed. A total of five steps were performed, requiring a total of 252 analyses for each sample. In subsequent steps of search, the increase in the maximum value of the Young apparent modulus is noticeable. For the sample BV/TV = 0.3532, in the first step the maximum value of the module was 2440MPa and in the last step 3070MPa.

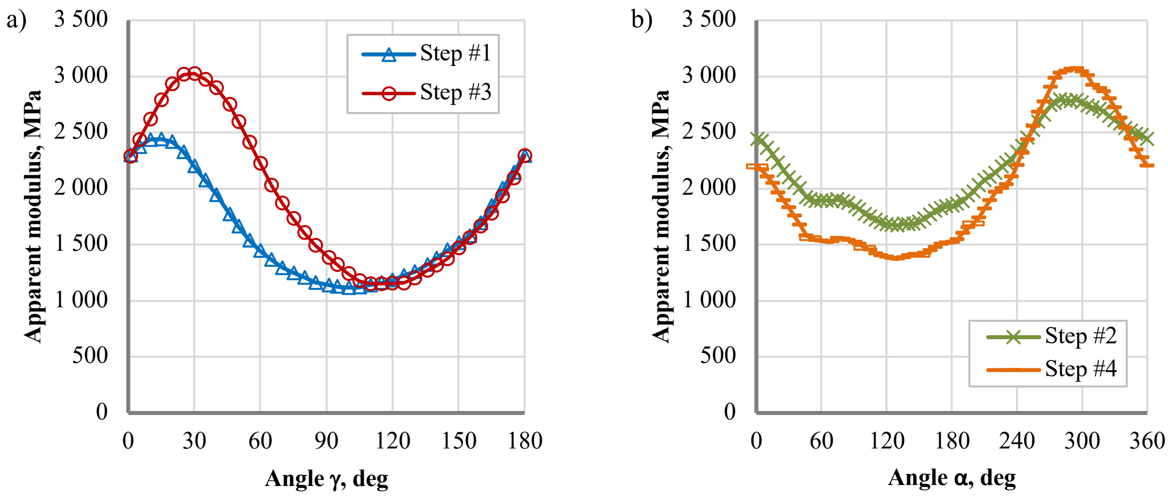

Fig. 3: Apparent modulus E, sample BV/TV=0.3532: a) α= const, γ=var, b) α=var, γ=const.

As a result of iterative searches, angles α and γ were determined for each of the considered samples, describing the principal mechanical direction of trabecular structure and the corresponding value of the apparent modulus. For each of the samples, in addition to the mFE analyses, MIL analyses were also performed, leading to the determination of the principal structural direction and the apparent modulus was calculated for this direction. With use of the value of the module calculated on the basis of structural analyses, the accuracy of the iterative determination of the module was estimated. Changes in the relative error of the apparent module in the subsequent iteration steps are shown in Fig. 4.

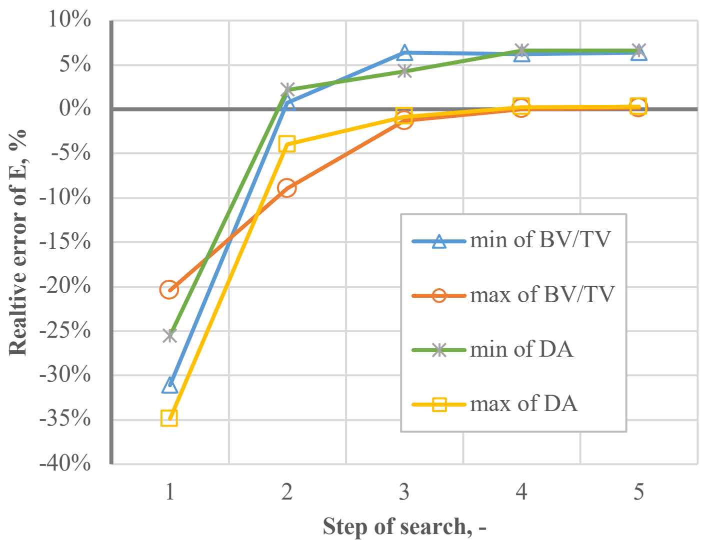

Fig. 4: Relative error of apparent modulus maximum determination.

4. Conclusions

In the course of computer analyzes, the values of the apparent Young's modulus were determined in orientations described by variable angular positions laying in mutually perpendicular consideration planes. The iterative calculations led to the determination of the orientation of the trabecular structure principal mechanical direction for which the apparent module reaches its maximum.

Determining the microstructure principal mechanical direction by univariate search method requires checking 252 combinations of sample cutting angles measured in 3D space. Another method of selecting angles should be considered, based on known algorithms of multivariate optimization. The analysis of the obtained results shows that performing more than three steps of search in the proposed approach does not lead to a significant decrease in the error value.

By indicating the structure principal mechanical direction for trabecular bone, it is possible to prepare a numerical model that more reliable describes the mechanical behaviour of the structure. The model thus calibrated can be used to determine the degree of mechanical anisotropy used as a measure of a preferential alignment of microstructures along a particular directional axis as a response to external load.

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