ON THE X-RAY MICRO-TOMOGRAPHY MEASUREMENTS OF BIOLOGICAL SAMPLES UNDER COMPRESSIVE LOADING

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Summary: *In this paper, compact loading device for micro-CT measurements under applied load was used in a series of instrumented compressive test of bone sample. Tested bone samples were loaded in several deformation steps and micro-CT scanning was carried out in each step. Reconstructed three-dimensional data of intact bone sample were used to develop 3D model of the specimen. Data from each deformation step were processed by DVC method for identification of displacement and strain fields and thus for evaluation of deformation response of human trabecular bone sample.*

Keywords: *micro-tomography, trabecular bone, compressive test, medical imaging, finite element modelling*

1 Introduction

X-ray computed micro-tomography (micro-CT) is widely used as a method for inspection and visualization of inner structure of advanced engineering and also natural materials [1] (particularly those with complex and heterogenous micro-structure). Moreover, three-dimensional micro-CT data can be also used for development of detailed finite element (FE) models suitable for inverse assessment of microstructure deformation behaviour.

In biomechanical applications, such a FE model can be used to assess bone quality. This approach has been proven to be more reliable than quality assessment using bone mineral density (BMD) with dual X-ray absorptiometry [2]. Furthermore, micro-CT measurements carried out in a time-lapse sequence during discrete loading of the bone sample can be used to evaluate displacement and strain fields using digital volumetric correlation (DVC) [3].

In this paper series of time-lapse radiographical and micro-tomographical measurements of specimens of human trabecular bone were performed. Specimen was incrementally compressed to several deformation steps using compact custom-design loading device. Tomographical scan was taken in each deformation step. Results of tomograhy reconstruction of undeformed specimen was used for development of 3D model of specimen. Results of tomography reconstructions of deformed specimen were used for evaluation of displacement fields in specimen's volume using DVC technique. Results of displacements evaluated by DVC were used for calculation of strain using Green-Lagrangian strain tensor and for overall analysis of trabecular bone deformation response under compressive loading.

2 Materials and methods

2.1 Specimen

Cylindrical sample of trabecular bone drilled from human femoral head was delipidated and cleaned in ultrasonic bath with distilled water and by sensitive air-flow cleaning. Both ends of the sample were trimmed and

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embedded into methylacrylat filler (VariKleer, Buehler GmbH, Germany) to ensure proper boundary conditions of experiment (elimination of influence of imperfect and non-parallel edges of the sample). Overall dimensions of prepared specimen were $5\,\mathrm{mm}$ in diameter and $17.2\,\mathrm{mm}$ in length. Prepared sample is depicted in Fig. 1a.

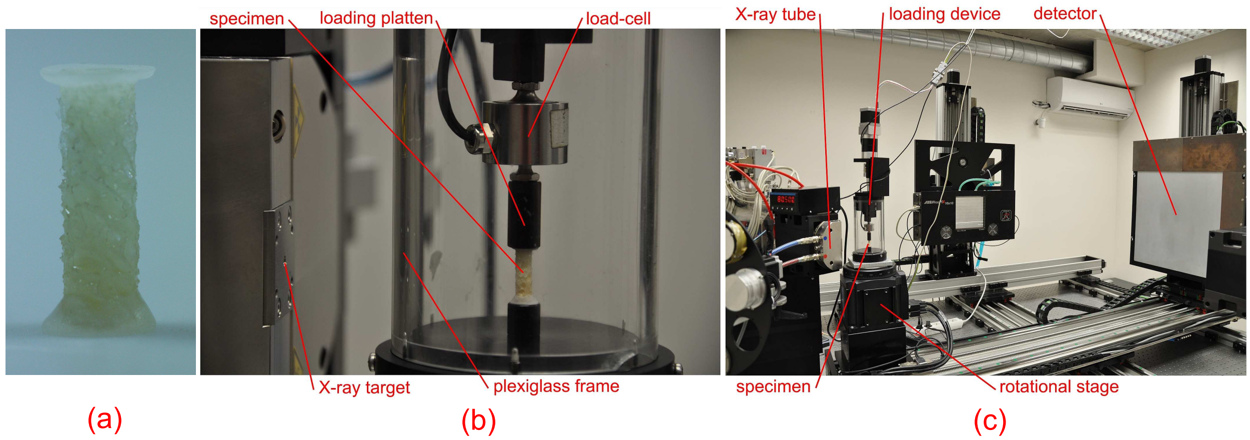

Figure 1: (a) Specimen prepared for experiment, (b) Part of the loading device with inserted specimen, (c) Experimental setup with loading device in tomographical assembly

2.2 Experiment

Bone sample was inserted in loading device designed for compression tests of biological samples in micro-tomography setup [4]. The device consists of polymethyl metacrylate cylindrical frame transparent for X-rays, loading plattens, load-cell HBM U9B (Hottinger Baldwin Messtechnik, Germany) with load capacity $500\,\mathrm{N}$, precision translation stage 7T173-20 (Standa, Lithuania) with $1\,\mu\mathrm{m}$ sensitivity and propulsion system (planetary gear, flexible coupling and stepper motor). Minimal loading rate is $0.5\,\mu\mathrm{s}^{-1}$ with precision better than $5\,\mu\mathrm{m}$ (evaluated experimentally). Part of the device with inserted specimen is depicted in Fig. 1b.
Used tomography setup consisted of microfocus X-ray source XWT-240 (X-RayWorx, Germany) with minimal focal spot size $5\,\mu\mathrm{m}$, large area flat panel detector XRD1622 with active area $41\,\mathrm{cm} \times 41\,\mathrm{cm}$ and high-precision rotary stage APR-150 (Aerotech, USA). Setup geometry was adjusted to source-detector distance $1335\,\mathrm{mm}$ and source-object distance $75\,\mathrm{mm}$ (magnification $17.8\times$ and pixelsize $11.2\,\mu\mathrm{m}$). X-ray tube voltage $70\,\mathrm{kV}$ with target current $340\,\mu\mathrm{A}$ (target power $23.8\,\mathrm{W}$) were used for scanning. Tomographical measurements were performed with 800 projections and integration time $1000\,\mathrm{ms}$ per projection. Experimental setup is depicted in Fig. 1c.
Experiment consisted of 7 tomographical measurements in 7 deformation steps of the sample. First, undeformed specimen was tomographically scanned for development of geometrical model to be used in as reference model for evaluation of displacements using DVC. Then, the specimen was incrementally loaded to 6 predefined deformation steps ($1\,\%$ to $6\,\%$ of initial specimen length) and tomography measurement was performed in each step. Specimen loading was driven by upper platten displacement with constant loading rate $1\,\mu\mathrm{m\,s}^{-1}$. Prior to the tomography scan $20\,\mathrm{min}$ pause for material relaxation was held. During loading (between tomography measurements) the specimen was scanned using simple (non-tomographical) X-ray projections with acquisition time $1000\,\mathrm{ms}$.

2.3 Digital volumetric correlation, Strain calculation

Results of tomography reconstructions were used for development of full-scale 3D voxel model of the specimen. Full scale model had 50,736,191 voxels (spatial pixels) and its resolution had to be progressively

reduced to 431,626 because of computational complexity of DVC method. Voxel model was rescaled using discrete cosine transformation method. Displacement fields were calculated using custom DVC algorithm implemented in MATLAB toolkit [3] based on modified Lucas-Kanade tracking procedure [5]. Due to computational complexity of the task displacements were calculated only in two planes perpendicular to each other with their intersection in vertical axis of the sample. Initial coordinates of each voxel were assessed from 3D model of undeformed specimen and changes of their positions were evaluated from 3D model of relevant deformation step. The task was carried out using high-performance computing station with $4\times$ Intel(R) Core(TM) i7-3820 3.6 GHz CPUs.
Results of displacements were used for evaluation of deformation gradient tensor that was used in calculation of Green-Lagrangian strain tensor using following formulas:

$$\mathbf{E} = \mathbf{F^T F} - \mathbf{I} = \frac{1}{2}\left[(\nabla_{\mathbf{X}}\mathbf{u})^T + \nabla_{\mathbf{X}}\mathbf{u} + (\nabla_{\mathbf{X}}\mathbf{u})^T \cdot \nabla_{\mathbf{X}}\mathbf{u}\right] \tag{1}$$

where $\nabla_{\mathbf{X}}\mathbf{u} = \nabla_{\mathbf{X}}\mathbf{X} - \mathbf{I} = \mathbf{F} - \mathbf{I}$ is the material displacement gradient tensor

3 Results and discussion

Graphs of measured force-time and force-displacement dependencies are shown in Fig. 2a, b. Bone relaxation is clearly visible after each loading step. Visualization of tomography reconstruction (3D model) is depicted in Fig. 2c. Results of evaluated displacements and strains in two perpendicular planes are shown in Fig. 3a

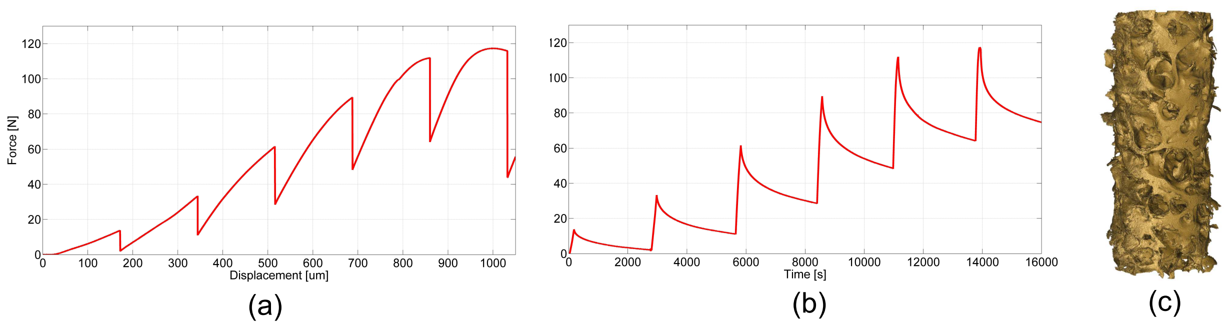

Figure 2: (a) Graph of force-displacement dependency, (b) Graph of force-time dependency, (c) Result of tomography reconstruction - 3D model of sample visualization

and Fig. 3b. Based on DVC strain results it can be seen that strain occured predominantly in higher third of the specimen length on the most thin beams of the bone microstructure. Results from all deformation steps show not only the compressive behaviour of beams but also their bending.

4 Conclusions

Experimental procedure for evaluation of strains in biological samples using computed tomography and digital volumetric correlation method was introduced. Sample of human trabecular bone was loaded to 6 deformation steps and tomographical measurement in each step was used for development of bone's 3D models. Evaluation of displacements and strains in two selected planes of the models was performed using DVC technique and calculation of Green-Lagrangian strain tensor. Evaluated strain fields were used for analysis of deformation response in the bone microstructure and thus for identification of location with maximal strain and bending effects in bone microstructure.

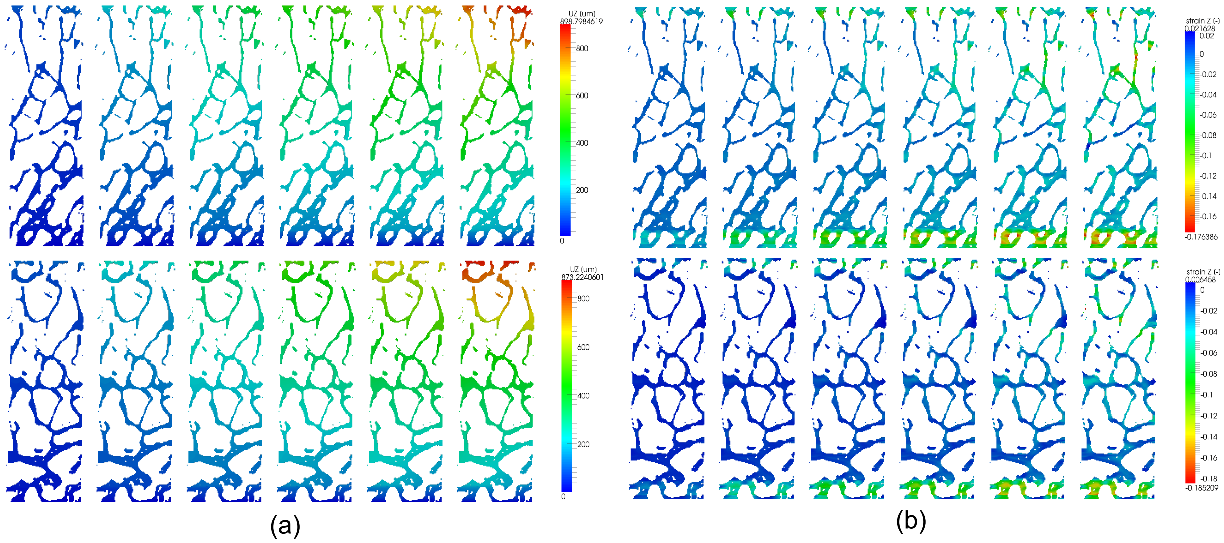

Figure 3: (a) Visualization of DVC results for displacements in two selected planes and all deformation steps, (b) Visualization of DVC results for G-L strains in two selected planes and all deformation steps

5 Acknowledgement

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