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DESIGN AND USE OF NOVEL COMPRESSION DEVICE FOR MICROTOMOGRAPHY UNDER APPLIED LOAD

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Abstract: *This paper deals with modification and usage of custom-designed compression device, that allows real time X-ray tomography scanning of specimen under applied pressure. In this case microtomography is used to obtain data required to determine specimens morphology and to develop 3D material model (especially for cellular materials such as bones, metal foams and quasi-brittle materials or particle composites such as concrete or cementitious composites). Important design changes were made in the existing device frame to increase its load capabilities, stiffness and to accomodate a larger specimen. Finally device displacement measurements were conducted and calibration experiment was carried out.*

Keywords: ***X-ray, microtomography, compression device, optical strain measurements***

1. Introduction

X-ray tomography is a method that facilitates generation of reliable and accurate 3D models of solid bodies and also development of material models using scanning of loaded specimens [Jiroušek & Jandejsek et al., (2011)]. These models can be used to study material morphology and additionally to use the data for development of finite element (FE) model of a studied material, e.g. trabecular bone [Jiroušek & Zlámal et al., (2011)] and quasi-brittle materials (such as stones, concrete). According to these techniques many design requirements had to be met. Loading device has to be very compact to fit in the X-ray scanning device and simultaneously it has to be as X-ray transparent as possible. Such material testing method is specific and the testing device has to be constructed with utilization of a custom design. Significant upgrade of previously designed machine capable of performing material measurements in X-rays is described in this paper.

2. Original device design

Described machine was designed and built in 2008. Primary, it was designed for compressional loading of trabecular bone specimens during X-ray tomography [Zlámal et al., (2008), Jiroušek & Zlámal et al., (2011)]. Nowadays, it is used also as a general purpose material testing machine. The device is displayed in Fig. 1. The loading frame of the device has been fabricated using high tech polymer [Zlámal et al., (2008)]. Polymeric material used as a body of machine is transparent for X-ray. However, the machine has been equipped by two oval holes in the body (see Fig. 1) for better manipulation and fastening of the specimen. The main disadvantage of the holes inheres in complicated reconstruction of the object using the filtered back projection method. Further development of the device has led to significant change in the device design.

The following requirements had to be satisfied:

- to accomodate larger specimen (cube with edge length 100 mm)
- ability to perform tests with very high loading forces (up to 25 kN)
- to increase the overall stiffness of the device

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Following limitations had to be eliminated:

– diversion of upper jaw under large loading force applied to heterogenous porous material

– X-ray noise caused by existing openings in the machine's polymeric body

Fig. 1: Device design prior to the modification

3. Modified design

To avoid the problems with manipulation windows in the existing design, construction with bayonet lock has been introduced. Bayonet lock allows for better manipulation with specimen and easier change of machines experimental setup. Both bayonets as well as the upper body are made of high strength duralumin 7075 with Young's modulus 72 GPa and strength 480 MPa (according to manufacturer's material datasheet). Upper part of the bayonet is constructed as duralumin body with wall thickness 5 mm. This part is considered to be absolutely rigid (based on results of FE simulation with load 25 kN). Maximal displacement calculated in the FE simulation was $5\mu m$. Bottom part of the device consists of three parts: bottom bayonet, flange used for fastening to the base desk and a composite tube. The composite tube is made of carbon fibre composite MTM57/T700S(12k)-150-35. This material exhibits excellent mechanical characteristics in tension while quaranteeing very low X-ray absorbtion. According to the data provided by manufacturer the material was used for fabrication of medical sockets for commercial CT scanners. Young's modulus of MTM is 125 GPa in the fibre direction and its strength is 2481 MPa. Sufficient tube wall thickness has been calculated as 0.65 mm using FE simulation and analytical model. Bottom part of the body (lower bayonet, flange and composite tube) has been permanently glued together by PL20 epoxide with shear strength 45 MPa (according to manufacturer's measurements). First experiment have proved that device is very stiff and can be used for loading up to 25 kN. Overall view of the new machine design and its parts in detail are shown in Fig. 2.

Another problem that had to be resolved was connected to flexural rigidity of the upper jaw. To ensure perfect vertical movement of the upper jaw during loading, a slide assembly was inserted into the machine's mechanism. Its functionallity has been verified in a sequence of experiments up to 13.5 kN in which horizontal movement of the jaw was observed with high resolution CCD camera. Slide assembly consists of bearing made of alloy with 60% PTFE and 40% percent bronze and inner shaft made of stainless steel. Maximal effectivity and functionallity of the part has been calculated using appropriate formulas [Černoch, (1977)]. Slide assembly has been manufactured with maximal precision and with, theoretically, zero clearence. Slide assembly visualization is displayed in Fig. 3.

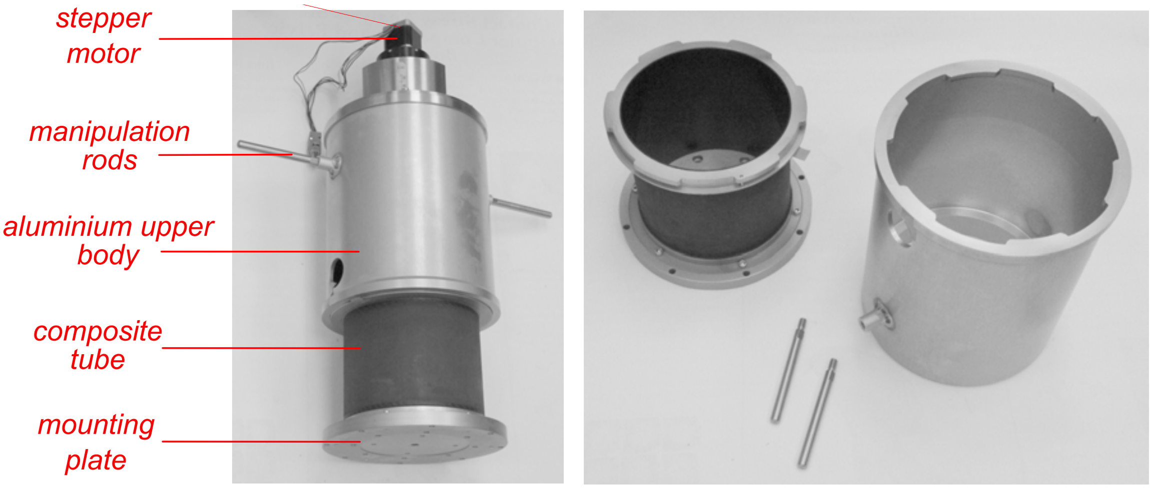

Fig. 2: Overall view of new design and description (left). Detailed view of assembly parts (right)

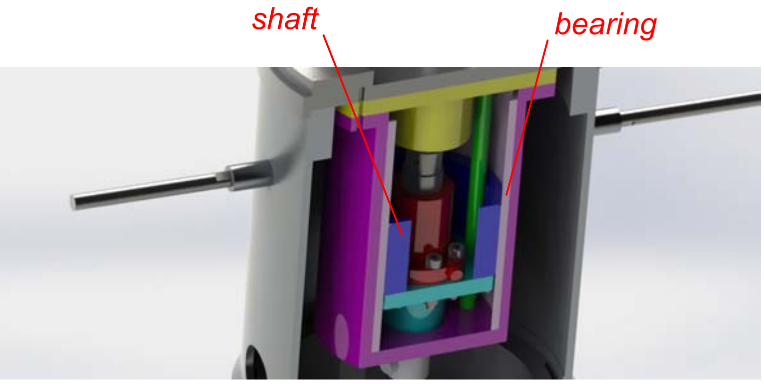

Fig. 3: Detail of slide assembly - bearing (light pink) and shaft (blue)

4. Initial testing and problems

Initial mechanical tests were performed to prove the stiffness and strength of the device. Loading force was increased in steps and device deformations were carefully observed by CCD camera. The only problem was caused by stepper motor that could not actuate the assembly due to its low performance. This problem appeared at load approximately 7 kN and was ad-hoc resolved by mounting of new stepper motor of higher torque capacity.

5. Experiment - displacement measurement

Manipulation and operation with the device is suitable for inserting in the shielded box of the micro-CT device. However, its stiffness had to be measured by a reliable method. Stiffness of the device is very important property. To capture the softening behaviour of loaded specimen the elastic strain was plotted to assess effects of device deformation tendency. Comparative experiment with both bodies (polymeric and composite) was carried out and measured deformations were confronted.

Displacements were measured optically using digital image correlation (DIC). DIC is reliable, precise, contactless method that enables measuremets of deformations without influencing the specimen. All image data were acquired using macro objective (Canon EF 180 mm f/3.5L Macro USM, Canon, Japan) mounted on a 15 MPix body (Canon EOS 7D, Canon, Japan). Composite tube was measured by DIC without any modifications to the surface because of its natural texture (see Fig. 4). Polymeric body was markered by dots required for correlation feasibility. Verification experiment was carried out by displacement driven loading with loading rate of 5 $\mu\mathrm{m/s}$ up to maximum force value 10 kN. Designated zone on device surface was captured in eqvuidistant time intervals. Images have been then processed by digital image correlation toolkit [Jandejsek et al., (2010)] based on Lucas-Kanade algorithm [Lucas & Kanade, (1981)]. Displacement and deformation in vertical direction were determined and the results were compared with numerical and/or analytical calculations. Experiment setup is shown in Fig. 5.

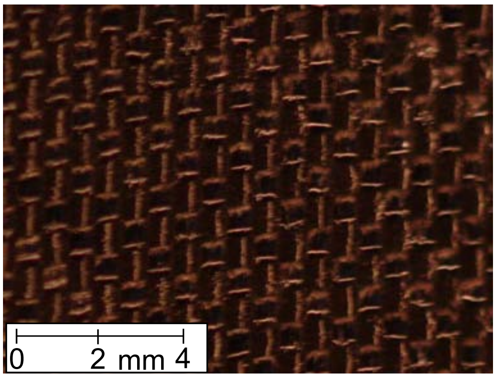

Fig. 4: Detailed view of the surface of the composite loading frame

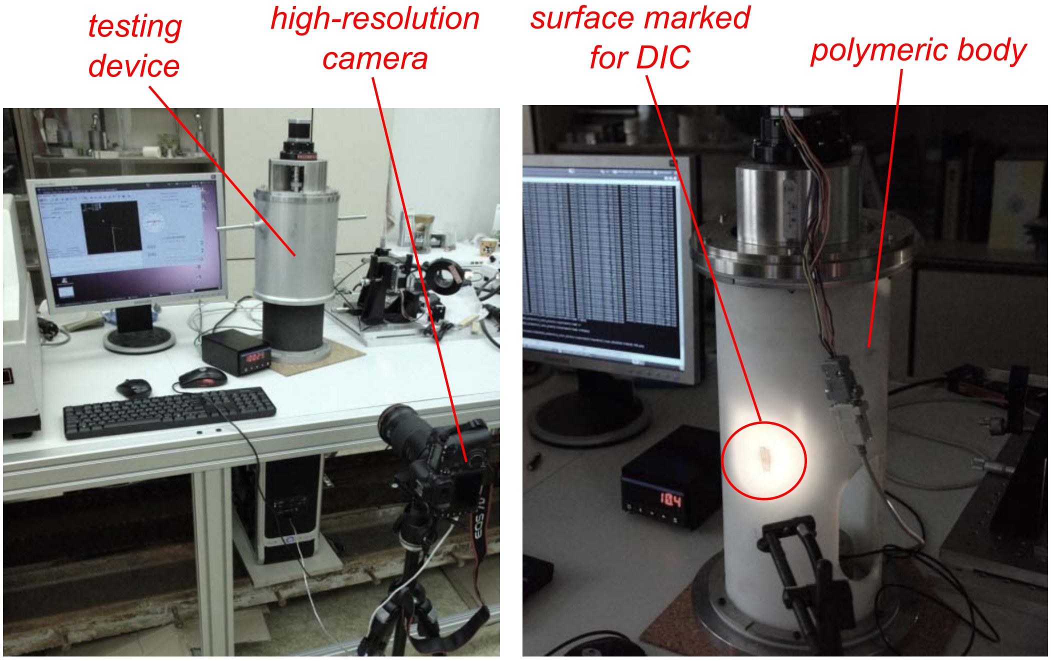

Fig. 5: Both device designs during experiment - optical measurement of displacements and deformations

Composite tube consists of 5 layers with fibre orientation 0, 45, 90, -45, 0 (orientation to force direction) and shows mechanical anisotropic behaviour. Overall Young's modulus was calculated using following equations [Meyers & Chawla, (2009), Meissner & Zilvar, (1987)] (updated for 5 layers):

$$E = \frac{2 \cdot E11 + E22 + 2 \cdot E45}{5} \tag{1}$$

$$\frac{1}{E45} = \frac{\cos^4\left(\frac{\pi}{4}\right)}{E11} + \frac{\sin\left(\frac{\pi}{4}\right)}{E22} + \left(\frac{1}{G12} - \frac{2 \cdot \nu}{E11}\right) \cdot \sin^2\left(\frac{\pi}{4}\right) \cdot \cos^2\left(\frac{\pi}{4}\right) \tag{2}$$

Material properties of MTM composite (according to manufacturer's datasheet) are shown in Tab. 1. Numerical solution has been done using ANSYS software with 8-noded shell elements. Results and comparison with digital image correlation data are displayed in Tab. 2. Linear behaviour of device was proved and it is graphically shown in Fig. 6.

Tab. 1: Material properties of MTM composite

Young's modulus in fibre direction (E11)	127 GPa
Young's modulus perpendiculary fibre direction (E22)	7.9 GPa
Poisson's ratio	0.3
Shear modulus (G12)	3 GPa

Tab. 2: Comparison of overall z-direction displacement calculated and measured

	Composite tube	Polymeric body
Analytic solution	0.0697 mm	not calculated
Numerical solution	0.0694 mm	0.141 mm (relevant to measured place), max. 0.188 mm
Digital image correlation	0.0741 mm	0.764 mm

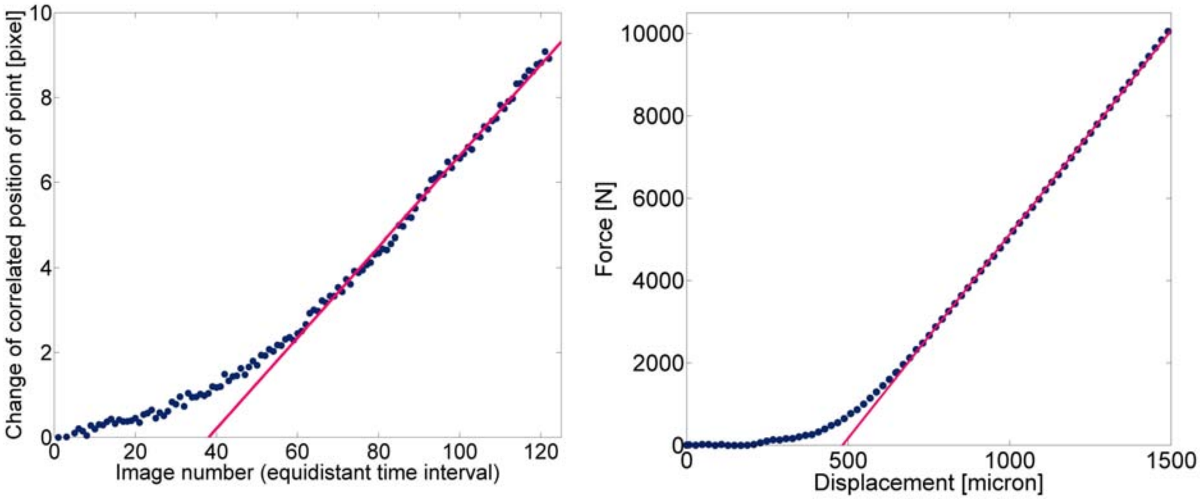

Fig. 6: Displacement and force diagram

Displacement and strains in the original (polymeric) body has been calculated in ANSYS software using solid elements. Results and comparison is summarized in Tab. 2. Numerical solution for displacement in vertical direction is shown in Fig. 7. Measured overall displacement of composite tube is very close to the analytical and numerical solution. High load capability of the redesigned device was verified and is realeased to loads up to 25 kN. On the contrary, the polymeric body was designed for loads up to only 2 kN and measured results confirmed that displacement and deformation at higher loads are too large for material testing.

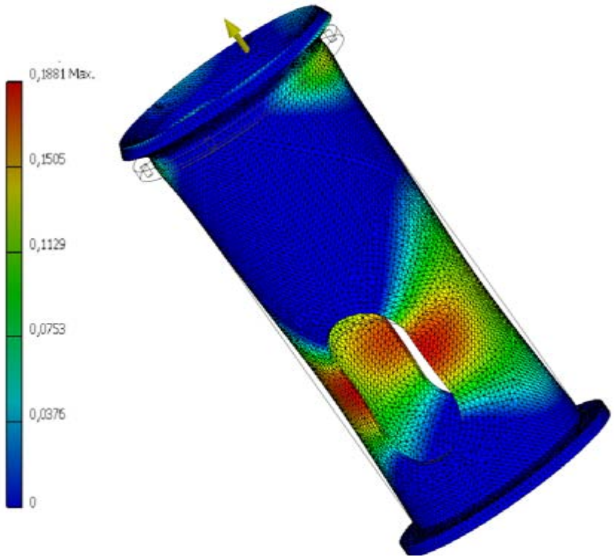

Fig. 7: Displacement in vertical direction [mm]

6. Conclussion and discussion

New upgraded design of device has been constructed. New design makes the device significantly stiffer which is important not only for higher loads but also for fracture toughness tests. Material more transparent for X-rays has been used to obtain more precise, more relevant and more accurate data. Linear behaviour of the device and its stiffness was measured and was considered as adequate to calculations and expectations. To conclude, prospective behaviour of device has been verified and device is suitable for considered experiments.

7. Acknowledgements

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