Experimental investigation of the pig mandible fatigue behaviour

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Introduction. Analysis of compact bone tissue mechanical behaviour under cyclic loading is necessary for oral implantology and orthodontics. The problem of jaw bone-dental implant interaction regards, in particular, the effects induced in the surrounding bone tissue under the application of functional cyclic loading. The evaluation of stresses in bone can be the basis of an analysis of the efficiency and reliability of the shape or dimensions of endosseous implants.

The determination of fatigue life has been widely used for studies on cortical bone to investigate a variety of variables, including age [9], donor species [8], cyclic frequency, testing geometry [1, 7, 9], and loading mode [4, 6]. In all above-mentioned investigations human or bovine compact bone samples taken from the femur or tibia have been studied. In the available literature there was no information about the behaviour of jaw compact bone tissue under cyclical loads. Therefore, the aim of this work was to investigate the fatigue properties of jaw bone compact bone tissue in compression at the frequency of 2 Hz.

Methods and materials. Three fresh two years old pig mandibles were used for this study. After the sectioning of the mandible from the premolar and molar regions compact bone specimens of rectangular prismatic shape were prepared. Twenty six specimens were prepared to determine the ultimate compressive stresses, to find regression between density and yield strength and 30 specimens were prepared for fatigue tests. During the entire process of preparation, harvesting and testing, the test specimens were kept moist, since purpose of this study was to investigate the properties of wet bone. All tests were conducted at room temperature (approx. 20 °C).

Compressive fatigue tests and static experiments were carried out in an INSTRON 8872 servo-hydraulic testing machine equipped with a water bath with transparent acrylic walls. During testing the samples were immersed in water and placed to a specially designed holding tool (Fig. 1).

Before mechanical experiments for all specimens the density was measured using hydrostatic weighing method. Specimens were loaded to fracture at a deformation rate of 1 mm/sec. Compression load was applied to the specimen perpendicular to the occlusal plane. For each specimen there was determined the yield strength and recorded ultimate compressive stress. The regression analysis between density and yield strength revealed theoretical relationship:

$$\sigma_y = 228{,}73\rho - 377{,}74 \quad (1)$$

where σ_y – yield strength, MPa; ρ – density, g/cm^3 and r^2 = 0,922.

The expected yield strength for 30 fatigue test specimens was calculated using regression equation obtained in the previous step and then the level of loading for each specimen was defined. The fatigue properties of bone material were investigated under cyclic load with peak load levels 60%, 70%, 80%, and 90% from the compressive yield strength with a frequency of 2 Hz. Loading was used in this study with maximum cyclic stress – from 0.5 to 1.5 MPa, but the minimum stress value for each specimen was calculated using selected load level and theoretical yield strength.

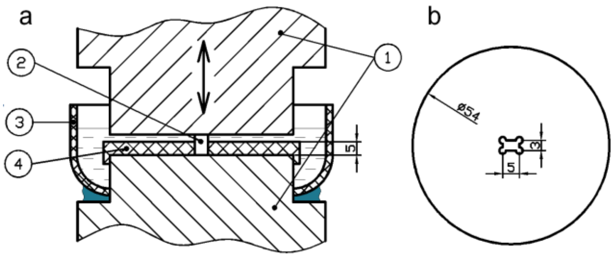

Fig. 1. a) Specimens holding tool and water bath: 1 – compression platens, 2 – specimen, 3 –bath with water, 4 – holding tool. b) Top view of holding tool

Results. Results from the fatigue tests of pig jaw cortical bone in compression are summarized as stress range versus cycles (S-N curve). The effect of applied cyclic loading on the number of cycles to failure has the form of an inverse power law:

$$N = F\Delta\sigma^G \quad (2)$$

where N – the number of cycles to failure, $\Delta\sigma$ – stress range (MPa), $\Delta\sigma = \sigma_{max} - \sigma_{min}$, F and G – empirical constants. Equation constants were determined from curve fits of fatigue data of pig jaw compact bone tissue: $F = 1.47 \times 10^{20}$; $G = -10.05$; $r^2 = 0.804$.

The fatigue properties of cortical bone in compression determined in this study were compared with previous studies from the literature. As illustrated in Fig. 2 the fatigue life of pig mandible compact bone material for the given stress magnitude was considerably less than fatigue life at similar stress magnitudes, determined for compact bone tissue specimens from human femur or bovine tibia. As it is obvious, the results of this study are very close to the results of cortical bone fatigue life in shear.

The ultimate compressive stress of cortical bone determined in this study (mean value is 68±1.8 MPa) is lower than longitudinal compressive strength for femoral bone. The strength of mandible in current study is similar to the one measured for shear test of human femur (51.6 MPa) [5]. Low compressive strength of pig mandible is possible because during normal activities jaw bone is subjected to less loading than bones of lower limbs and has much weaker structure than femur or tibia. There is possible effect of such factors as specimens' surface condition and precision of the dimensions and geometric accuracy of the shape of the test specimens. The comparison of results of the studies from different investigations may be misleading due to variations in testing conditions: temperature and frequency.

For further comparison the S-N curves were normalized by cortical bone strength. After normalization, there were no significant differences between the S-N curves (Fig. 3), suggesting that fatigue behaviour is similar for human, bovine and pig cortical bone both in compression and shear.

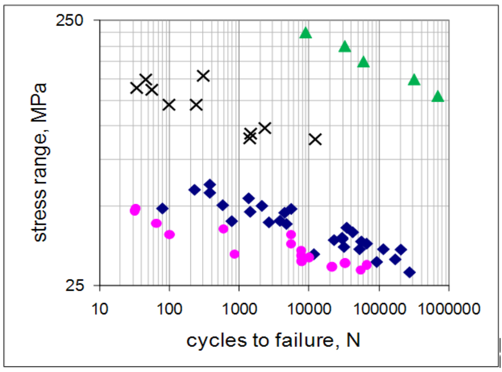

Fig. 2. S-N curve comparing fatigue of cortical bone in compression with fatigue measured in shear. Diamonds (compression determined in this study); closed triangles [2] (compression); oblique cross [3] (compression); closed circles (shear) [5]

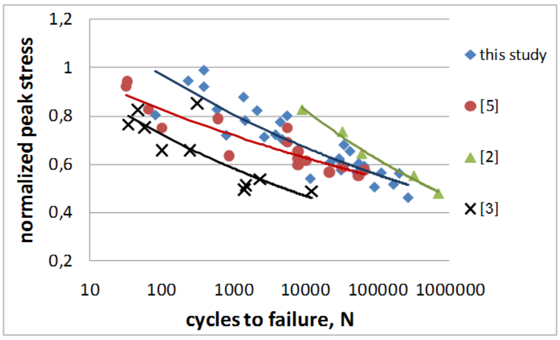

Fig. 3. S-N curves comparing fatigue properties after peak stress were normalized by the ultimate strength. This study fatigue data were were normalized by 68 MPa, shear fatigue data [5] were normalized by 52 MPa, compressive fatigue data [2] – by 272 MPa, fatigue data [3] – by 182 MPa

Conclusions. From compression tests of jaw compact bone tissue samples the fatigue stress-life data were obtained which characterise the material behaviour in a cyclic load stress range from 30.82 to 57.56 MPa. The experimental S/N curves of pig mandible compact bone material were approximated with reversed power function (r^2 = 0.80). This study S/N curves and previous studies fatigue data were normalized by ultimate strength. Analysis of the results showed that human, bovine and pig cortical bone fatigue behaviour is similar in compression and shear notwithstanding that specimens were taken from different bones. Obtained results may aid in understanding of mechanism of cortical bone fatigue and they should be taken into account in the design of treatment programs and in improvement of mechanical parameters of endosseous implants.

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The objective of this investigation was to study the fatigue behaviour of pig jaw compact bone material specimens subjected to compression tests. Samples for experiments were prepared from three 2 years old pig lower jaws. Specimens were tested under cyclic load with peak load levels that were 60%, 70%, 80%, and 90% of the compressive yield strength with a frequency of 2 Hz. For all specimens the density was measured using hydrostatic weighing method. Twenty six specimens were loaded to fracture to determine the ultimate compressive stress and to find a correlation and regression between density and yield strength. The level of loading for 30 specimens was calculated using regression equation obtained in previous step. Fatigue tests of pig jaw cortical bone in compression were conducted and results were summarized as peak stress versus cycles. Experimental data were approximated using reversed power function. The fatigue properties of cortical bone determined in this study were compared with previous studies from the literature.