UNIAXIAL AND TRIAXIAL MECHANICAL TESTING OF BIOMATERIALS FOR BONE REPLACEMENT

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1. Introduction

A wealth of bone replacement materials, based on a multitude of different chemical compositions, is available nowadays. All these materials are designed as to mimic bone as closely as possible. In other words, the bone biomaterials are required to be biocompatible [2], i.e. they should smoothly fit into the biological, chemical, and mechanical environment inside the body of the patient. As regards the mechanical aspect, a certain stiffness and strength is mandatory, in order to effectively carry the loads imposed onto the skeleton. In addition, the biomaterial should match the mechanical properties of the original bone as precisely as possible, in order to preserve standard physiological stress fields around the implant. These stress fields are required as to guarantee effective functioning of the biological cells resorbing bone and forming new bone. The present work aims at contributing to the latter aspect. Precise determination of the stress fields around an implant require profound knowledge of the material properties of both the bone material and the bone replacement material, under multiaxial stress states occurring in the living body. Since related experimental data are remarkably scarce in the open literature, we started a campaign of triaxial test series on bone and bone biomaterials. In this contribution, we concentrate on two quite distinct biomaterials, the first being based on polyurethane, the other on titanium. First results are sketched hereafter, and will be presented in more detail at the conference.

2. Materials and Methods

Cylindrical samples with 5 mm diameter and 10 mm height were machined from two types of bone replacement biomaterials: (a) polyurethane foam manufactured by Sawbones Pacific Research Laboratories, Vashon WA [6] with a density of 0.48 g/cm^3, (b) porous titanium produced on the basis of metal powder and space holder components at Fraunhofer Institute Bremen, with an apparent mass density of 1.64 g/cm^3. Hence, the mass density of the "pure" titanium matrix with some micron-sized pores in between, amounting to 3.80 g/cm^3, yields a macroporosity of 57 %.

Fig. 1: Experimental setup for uniaxial and triaxial tests at TU Wien: (a) 150 kN uniaxial testing machine, (b) pressure control, (c) 150 bar triaxial cell, (d) fixing of specimen: (1) specimen, (2) plasticine, (3) upper die, (4) lower die.

The samples are subjected to axial compressive loads by means of an 150 kN uniaxial electromechanical machine (LFM 150, Wille Geotechnik, Germany with displacement control (Figure 1 (a)), at a displacement rate of 0.01mm/s up to a strain of 30 %. Under uniaxial loading, an approximately uniform strain field inside the polyurethane samples was confirmed by 3D Electronic Speckle Pattern Interferometry (ESPI). Triaxial loading is realized through a high pressure triaxial testing cell (LT 63500-2/50-T, Wille Geotechnik, Germany, Figure 1 (c)), filled with oil up to a maximum pressure of 150 bar. In order to stabilize the sample during the filling process, it was attached to the lower die by means of plasticine (Figure 1(d)). An outlet valve on the top of the cell eliminated air bubbles within the testing chamber. This valve was locked once the chamber was properly filled with oil at the start of each triaxial test. The oil was pressurized using an electromechanical pressure control (DV 350-150/10, Wille Geotechnik, Germany, Figure 1(c)). A compressive force was applied simultaneously by the electromechanical uniaxial testing machine. The specimens were loaded to failure or to a maximum strain of 30 %, in a state of axisymmetric triaxial compressive stress, either with an approximately constant ratio of axial stress to radial pressure or with a constant radial pressure of 50 bar, provided by the pressure control.

3. Results and Discussion

Typical stress-strain relationships under uniaxial load reveal a linear elastic load range followed by hardening plasticity, for both the polyurethane samples and the titanium samples (Figures 2 and 3). Both regimes can be approximated by straight lines, the intersection of which defines a yield point, giving access to yield stress and strain given in Table 1. Young's modulus is derived from unloading the samples at a stress level amounting to roughly 30 % of the yield stress.

The remarkably high ductility of the biomaterials does not necessarily match the mechanical characteristics of natural bone, often showing a more brittle behavior in compression [5]. This underlines that, in addition to the anisotropy of natural bone [3], which is not mimicked by the tested biomaterials, also the inelastic constitutive behavior of man-made biomaterials needs still to be improved as to match more precisely the one of natural bone.

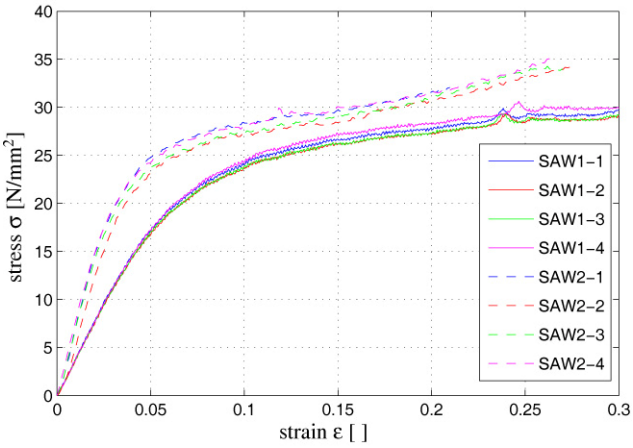

Fig. 2: Stress-strain diagram for polyurethane samples, tested uniaxially (SAW1) and triaxially under 50 MPa radial pressure (SAW2).

The first preliminary results in triaxial stress states (Figure 2) show that the yield stress of the polyurethane increases by only 15 %, due to lateral oil pressure. This shows our triaxial cell to be markedly suitable for highly porous (trabecular) bone [1, 4] or highly porous bone replacement materials, with only a few MPa strength. For more compact bone, we consider the employment of an ultra-high pressure cell, exceeding the capacity of the present one by one order of magnitude at least.

Tab. 1: Results of uniaxial mechanical tests.

material	polyurethane	titanium
Young's modulus E [MPa]	614	7032
Yield stress σ_{el} [N/mm^2]	26.2	81.6
Yield strain ε_{el} [%]	4.5	1.3

4. Acknowledgements

Support by the Network of Excellence "Knowledge-based multicomponent materials for durable and safe performance" (KMM-NoE) is gratefully acknowledged.

5. References

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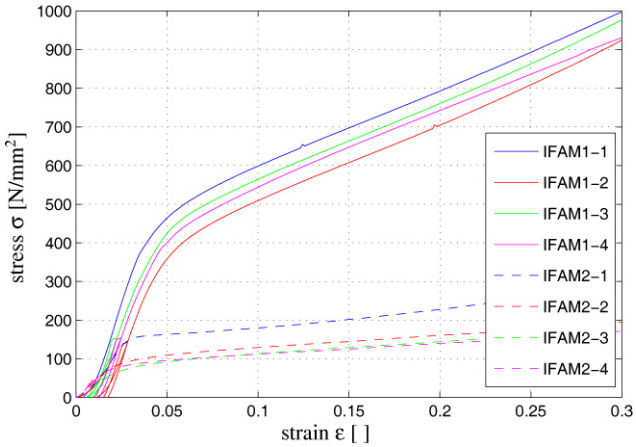

Fig. 3: Stress-strain diagram for uniaxially tested, porous (IFAM2) and "pure" (IFAM1) titanium samples.