# CONSIDERATIONS ON THE METHODS USING TO MEASURE THE MECHANICAL PROPERTIES OF THE HUMAN BONES

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**Abstract.** This paper presents some of the important methods to measure the properties of bone under loading, used successfully in testing laboratories. This list remains open for other methods. The knowledge of the dynamic behavior has an important influence to design the human bone prosthesis. The experimental studies can contribute to understand the biomechanical phenomenons, to increase the quality of prosthesis and to increase the lifetime of these. The obtained results can be used in the Finite Element Methods.

**Keywords**: bone strength, testing method, elastical and mechanical properties

## 1. INTRODUCTION

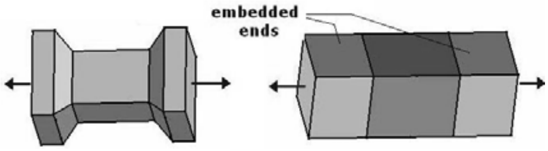
During normal activities, bone tissue is subjected to tensile, compression or shear stress. Geometry, structure and elastic and plastic characteristics of the bone are an obstacle to realize correctly a numerical and experimental analysis. Mechanical properties of the bone structures depend on the kind of bone, the age, anatomical location and the testing conditions. Although these conditions are usually recorded, some aspects of the testing conditions and the sample preservation are sometimes overlooked (bone hydration, temperature, etc).

## 2. BIOMECHANICAL BEHAVIOR OF HUMAN BONES

Forces and moments can be applied to a structure in various directions, producing: tension, compression, shear, torsion, and combined loading. Bone is an anisotropic material, exhibiting diverse mechanical properties.

### 2.1. Tensile

The tensile testing can be one of the most accurate methods to measure mechanical properties, but the bone specimens must be relatively large and carefully machined. Tensile test specimens for cortical and cancellous bones are presented in *fig. 1*, [2, 14]. These are made so that the maximum stress will occur in the central region of the specimen. The strains measurement can be realized by means an attached extensometer in the midsection of the bone specimen. Assuming that the force is applied without to introduce a coupled bending moment, the tensile testing will provide a very accurate date about the mechanical properties of the bone.




a. b.

Fig. 1. Tensile test specimens for: a) cortical bone, b) cancellous bone

During the tensile testing, the equal and contrary loads are applied outward from the surface of the structure, resulting stresses and strain inside of the structure. The maximum stress will occur on a perpendicular plane to the applied load. At the microscopical level, debonding at the cement lines and pulling out of the osteons mainly induct the failure mechanism for bone tissue loaded in tension. The failures produced by tensile loading are observed in bones with a large proportion of cancellous bone (metatarsal bone, calcaneus). The tensile testing is limited by need for relatively large specimens (the specimens from *fig. 1* have 15 - 20 mm in length). This limitation is often met in the case of the cancellous bone testing because the specimen must be so that the trabecular structure to be treated as a continuum. A specimen width of a least 4 to 8 mm is required, [8].

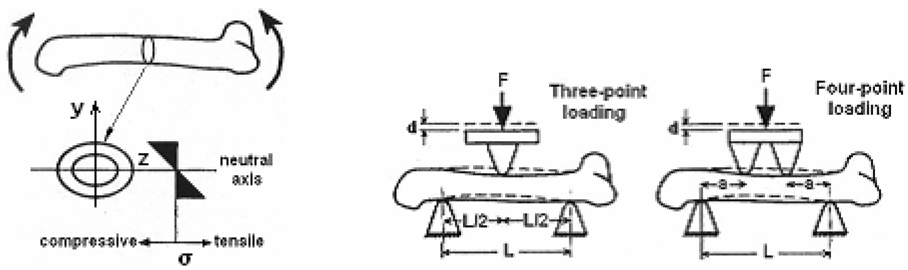
### 2.2. Bending

This kind of testing is useful to measure the mechanical properties of the smaller bones. For these small bones, it is very difficult to fix it on the testing machines. The stresses due to bending are calculated with the relation

$$\sigma = \frac{M_z \cdot y}{I_z} \tag{1}$$

where $M_z$ is the bending moment, $\sigma$ is the stress, $I_z$ is the cross-sectional moment of inertia around the axis of bending (*fig. 2a*).

Bending causes the tensile stresses on one side of the bone and compressive stresses on the other side. The bone is weaker in tension that in compression, [13]. So in the bending test, the failure occurs on the tensile side of the bone. The cross-sectional moment of inertia can be estimated for the cross-section of a long bone by using the relation for a perfectly elliptical cross-section, [10, 18]. Cross-sectional moment can be measured about any axis through a cross-section, but for a bending test, they should be measured about the axis of bending that contains the center of mass of the cross-section. This axis, called neutral axis undergoes no compressive or tensile stresses during bending. The tensile and compressive stresses increase linearly with the distance from the neutral axis (*fig. 2.a*), so that the highest stresses are on the outside surface of the bone. For a bone cross-section, the moment of inertia can be measured by means a digitizing system or by point counting techniques.




a. b.

Fig. 2. Bending test: a) stress magnitude, b) kind of bending tests used for bone specimens

Bone can be subjected in bending using either three-point or four-point loaded (*fig. 2.b*). The span of the specimen ($L$), that is loaded, must be sufficiently long to obtain an accurate test. If $L$ is too short, many of displacement will be due to shear stresses and no bending. In general, $L$ should be about 16 times higher than the thickness of the specimen. The advantage of three-point loading is its simplicity, but its disadvantage is the introduction of some high shear stresses near the midsection of a specimen. The four-point loading produces the pure bending between two points and the shear stresses will be zero. However, the four-point loading requires that the forces in every loading point to have the same value. This requirement is simple to achieve regularly shaped specimens, but it is difficult to achieve in whole bone tests. Stress ($\sigma$), strain ($\varepsilon$) and Young's modulus ($E$) can be computed with the relations, [7]

- for three-point loading

$$\sigma = \frac{F \cdot L \cdot y}{4 \cdot I_z}; \quad \varepsilon = \frac{12 \cdot y \cdot d}{L^2}; \quad E = \frac{F}{d} \cdot \frac{L^3}{48 \cdot I_z} \tag{2}$$

- for four-point loading

$$\sigma = \frac{F \cdot a \cdot y}{2 \cdot I_z}; \quad \varepsilon = \frac{6 \cdot y \cdot d}{a \cdot (3 \cdot L - 4 \cdot a)}; \quad E = \frac{F}{d} \cdot \frac{a^2}{12 \cdot I_z} \cdot (3 \cdot L - 4 \cdot a) \tag{2`}$$

Indirect calculation of strain is sometimes inaccurate. In addition, some deformations appear and are produced by the shear stresses (these stresses produce 10 ÷ 15% from the measured strain with the bending testing). These errors cause an overestimated strain and an underestimated Young's modulus. The strain can be measured using a strain gage bonded directly on the bending specimen.

### 2.3. Torsion

Torsion test can be used to measure the mechanical properties of o bone in shear. When a torsion moment is applied to a circular specimen, shear stress varies from zero in the center of the specimen to maximum value at surface. The general equation to measure the shear stress using a torsion test is

$$\tau = \frac{M_x \cdot r}{I_p} \tag{4}$$

where $M_X$ is torque, $r$ is radius, $I_P$ is polar moment of inertia. This relationship is not so exactly when the cross-section of the specimen is not circularly. In this case another relationship can be used and will consider the cross-section shape, [15].

For thin-walled cylinder, shear stress can be approximately using the relation

$$\tau = \frac{M_x}{2 \cdot A \cdot t} \tag{5}$$

where $A$ is the average of the inner and outer areas of the cylinder and, $t$ is the thickness of the cylinder wall, [18]. This relation is used to approximate the shear stress for all bones. Sometimes, the *equation 5* can lead to substantial errors. The polar moment of inertia can be measured using the relation, [18]

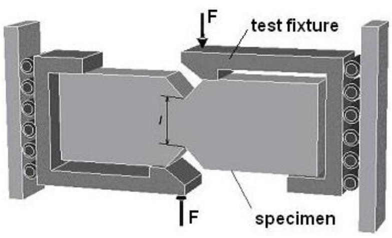
$$I_p = \frac{\pi}{2} \cdot r^4 \quad \text{or} \quad I_p = \frac{\pi}{2} \cdot \left(r_o^4 - r^4\right) \quad \text{(for circular tubes)} \tag{6}$$

where $r_o$ is the outer radius and $r_i$ is the inner radius.

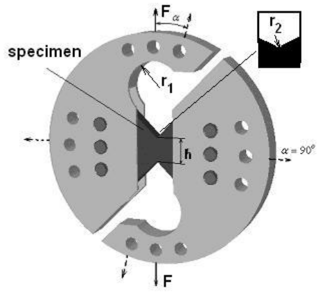
### 2.4. Pure shear tests

Torsion testing creates shear stresses in cross-section of a bone, but because of the composite nature of the bone, the tensile of structure can also appear, [12]. The determination of the shear properties in torsion test is very sensitive at the testing conditions. Because of these difficulties other testing methods were proposed to measure the shear stresses (rail shear test, tension-compression of notched specimens, etc), [17]. Each of these methods presents some limitations. To realize the rail tests, large specimens are required because of the buckling effect and the griping surface between specimen and the testing fixture device what can induce inhomogenities in the stress state. When the rail shear test is used to measure shear modulus, some precautions must considerer for its application to in-plane shear strength, [18]. In the case of the crossbeam, stress concentrations are presented at the cornets, so that the shear stress distributions are not uniform. The used standards for crossbeam are difficult to apply for bones. Some kinds of notch specimens have been developed to measure the interlaminar shear

stresses of the composite materials. It is difficult to obtain with these specimens. Stress concentrations in the notched specimens cause often the introduction of the errors in the measurements of the shear strength.
The best methods for shear testing are the method of Iosipescu [9, 19] (used often for the materials clouted) and Arcan, [1]. The Iosipescu test uses a notched specimen in offset four-point loading, while the Arcan test require a *butterfly* shaped specimens and a special shape of the testing fixture. The Iosipescu's specimens are four times longer than they are wide, with 90º notched in the center that have 20% of the specimen width. The specimen thickness should be at least 2.5 mm. In the case of the specimens used to Arcan testing, the critical dimensions are related to the width of the test region denoted *h* (*figure 3.b*).




a.




b.

Fig. 3. Methods for shear testing: a. Iosipescu method, b. Arcan method

The radius $r_2$ is equal to $h$, and fillet radius $r_1$ is equal to 1,14·h. It is important that the notches have fillets because stress concentrations can be created and will cause premature failure of the test specimen. For the both kinds of specimens, the shear stress can be computed with the relation

$$\tau = F/(h \cdot t) \tag{7}$$

where $t$ is the specimen thickness.

The shear strain are approximately equal to the total displacement between the contact points of the test fixture, assuming the test fixture is much stiffer than the bone specimen. The pure shear presents some advantage over the torsion test because they tend to be more accurate, and for the Arcan test smaller specimens can be used. These specimens are specially machined and took off from a long bone.

### 2.5. Fatigue tests

The fatigue testing requires test machines capable of applying cyclic loading (a servo-hydraulic testing machine or a purpose built fatigue machine). The results of the fatigue tests can be represented on stress – number of cycles curves what depict the peak-applied stress as a function of a number of cycles before failure (*fig. 4*). For instance, a bone specimen loaded between 0 and 100 MPa should last for 10 cycles before failure, while between 0 and 50 MPa will last longer than 100000 cycles. In general, the failure is defined as the number of cycles required to cause a specimen to lose 30% of its stiffness (slope of the stress-strain curve decreases by 30%). The fatigue properties of a bone are very sensitive to testing temperature; the loaded specimen at room temperature undergo twice as many loading cycles before failure compared to a bone tested at 37ºC, [5].

The fatigue failure in bones can appear in two ways: creep [11] and crack accumulation [4]. It shown that the creep is the major cause of the fatigue failure if the bone is loaded to tensile or at high stress (> 60 MPa), while the crack accumulation cause the failure if the specimen is loaded in compression at low stress (< 60 MPa), [3]. Other authors have shown that the microcracking accumulations appear in the bone loaded in fatigue at low stresses (< 50 MPa), [6]. A *catch-22* is designed to resist over 37 million cycles at low values of the fatigue stresses (24 MPa), [16].

The fatigue strength is an important property of the bone, especially when it is evaluated the bone what is subjected to the effects of an osteoporosis therapy. Unfortunately, the fatigue tests require more time consuming and special laboratories than other biomechanical tests discussed above. It is often prudent to use a simpler biomechanical test, followed later by fatigue testing.

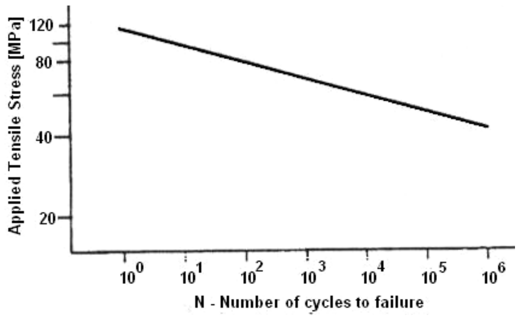



Fig. 4. Stress – number of cycles curve for a human bone, [18]

### 2.6. Ultrasonic test

The rate at which sound travels through a solid material depends on its elastic properties and density.

$$v = E / \sqrt{\rho} \Rightarrow E = \rho \cdot v^2 \quad (8)$$

where $v$ is the velocity, *E* is the Young's modulus, and *p* is the density.

Sound velocity can be measured by transmitting a wave through a specimen and measuring on an oscilloscope the time required for the wave to transverse the specimen. The width of the specimen divided by the time delay is the velocity, [2, 20]. Piezoelectric transducers are used to generate and detect waves for sound or ultrasound velocity measurement (ultrasound is acoustic waves above the audible frequency). Shear wave can be generated in a solid (*fig. 5*), and the elastic modulus in shear can be determined from the velocity of these waves

$$G = \rho \cdot v_s^2 \quad (9)$$

where *G* is the elastic shear modulus and $v_s$ is the propagation velocity of shear waves.

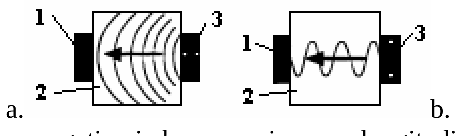



Fig. 5. Ultrasound wave propagation in bone specimen: a. longitudinal wave, b. shear wave;
1. receiving transducer, 2. specimen, 3. driving transducer, [18]

Longitudinal acoustic waves can propagate through material at two distinct velocities: bulk and bar, [21]. For bar wave propagation *equation 8* is valid. However, bulk waves travel through bone about 17% faster than bar waves, [22]. For bulk wave propagation *equation 10* is used

$$v = \sqrt{c / \rho} \quad (10)$$

where *c* is an elastic coefficient that is a combination of Young's modulus and Poisson's ratio.

For a cortical bone specimen with 5 mm in diameter, bulk wave propagation will occur if the ultrasonic frequency is greater than 2 MHz. If the frequency is less than 500 kHz, bar wave propagation will occur, [22]. In cancellous bone, bar wave propagation occurs if frequency is less than 100 kHz, [2]. Ultrasonic test methods have advantages and disadvantages compared to the mechanical tests. The main advantages are that they do not require an expensive mechanical testing machine and they are not destructive to the specimen. For this reason ultrasonic methods can achieve much greater precision than mechanical tests. Ultrasonic tests are versatile. They can be used accurately with small (3-5 mm) specimens. Specimens over 10 mm in length generally cannot be used, however, because the ultrasonic waves will attenuate too much traveling through the larger specimen.

## 3. CONCLUSIONS

In this paper, several types of testing used in biomechanical field are presented. This presentation is incomplete, because of the various shapes and the size of the bone. Elastical and mechanical properties of bones depend on the trabecular orientation, bone type, age, etc. The bone is subjected to diverse modes of loading during the physiological activities and the jogging. Many failures are produced by combined stresses. The actual testing methods must be developed.

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