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STUDY ON PURE SHEAR TESTS AND FATIGUE PROPERTIES OF HUMAN CORTICAL BONE

Constantin BÎTCA*, Paul Doru BÂRSANESCU, Mihai MIHALCUT
Gh. Asachi Technical University of Iasi, Strength of Materials Department
* bitcos@yahoo.ie

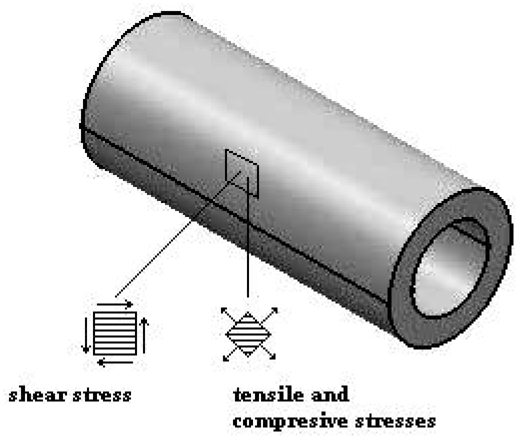
Abstract: This paper presents the influence of the pure shear tests on the rightness of the data obtained by other types of tests. Shear properties have been often measured under torsion. Pure shear strength is about 35% less than that determined in the case of torsion. Also, fatigue tests have been done under the pure shear. Perhaps fatigue failure is the principal cause of the tibia and femur fracture resulted under impact. Shearing applied transversal to the bone long axis can cause the fracture along a 45º plane. This coincides with the maximum tensile stress. Fracture pattern is similarly to spiral fractures caused by torsion.

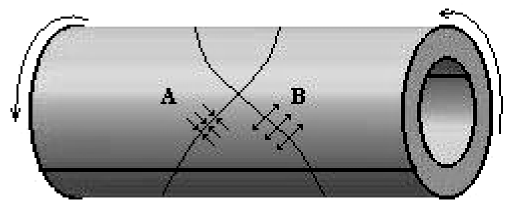
INTRODUCTION

Shear tests protocol depends vitally by the bone structure and the orientation of the loads in relation with the elastical symmetry axis of the material. Elastical and mechanical properties of human bones depend on the trabecular orientation.

During normal activities, bone tissue is subjected to tensile, compression or shear stress. Usually shear stress magnitude is relatively small, but it can develop substantial in long bones subjected to torsion. Sever torsion can result in long bone fracture. Fracture surfaces produced by torsional loads are helical [9], creating a spiral fracture. Torsional loading creates both transverse and longitudinal shear stresses in the bone as well as tensile and compressive stress at 45º from the shear direction (*fig. 1.a*). Bone will fail along the plane in which it is weakest.

Often this fracture plane coincides with the maximum tensile stresses, which in the case of torsional loading, falls along a helical plane at 45º from long axis (the maximum compressive shear appears along a perpendicular helical plane, *fig. 1.b*), suggesting that torsion causes bone to fail in tension rather than shear.





a. b.

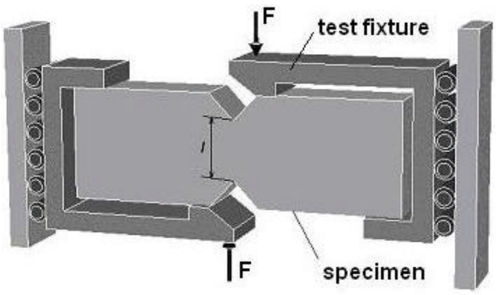
Fig. 1. Torsional loading produces: a. shear stress along and transverse to the long axis of the bone, b. compressive stress (A) and tensile stress (B)

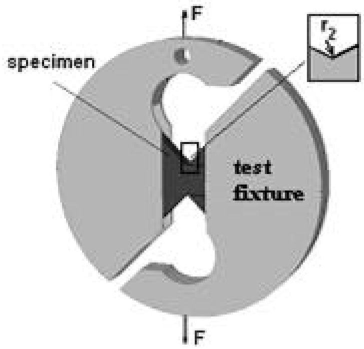
When the bone is subjected to cyclical loads, microdamage develops within the bone tissue and with time can accumulate. The combination of the bone weakening effects and bone resorption is started by microdamage can lead to stress fracture, [3]. Microdamage may be caused by the tensile, compressive or shear stresses. Because the cortical bone is weaker in shear [7], particularly in the longitudinal plane, the shear fatigue of the bone may be a key factor in the stress fracture pathologenesis. Yet there are no data available to test this possibility because the fatigue properties of the cortical bone in shear fatigue have not been measured.

In many studies, the shear strength was determined from torsional tests applied to specimens of cortical bone. Often, torsion causes tensile failure in bone rather than shear. An alternative to the torsion test is pure shear testing following the protocols recommended for composite material testing. Additionally, the pure shear testing can be used to measure the response of cortical bone to cyclic fatigue loading in shear. This is a property of the bone that has not been sufficiently studied.

PURE SHEAR TESTS

Pure shear tests have been realized using the Iosipescu [11] and Arcan et al. [1] pure shear protocols. Shear stress and principal shear angle have been calculated in the critical test region (*fig. 2*).





a. ***b.***

Fig. 2. Pure shear testing devices: a. Iosipescu test method, b. Arcan test method

Shear tests have been realized on longitudinal specimens in which shearing occurs transverse to the long axis (transverse shear), or on transverse specimens where shear was parallel to the long axis (longitudinal shear). The Iosipescu method was used for transverse shear tests, but the sizes required have been dictated that the Arcan configuration be used for longitudinal shear test because of the degree of radial curvature of the bone.

For transverse shear tests, 6 – 7 mm sections from the femoral mid-diaphysis were cut into four quadrants, [18]. Specimens were obtained from the subjects with the age between 71 and 83 years. Rectangular pieces (40×10×3 mm) have been cut by means of a milling machine from each region, with its long axis parallel with the femoral long axis. Then two V-shaped notches of 90º and 3 mm depth were cut using a milling machine with a custom-made end mill cutter with a 0.5 mm tip radius (*fig. 3*). These notches are important in this case because change the distribution of tangential stress in the work section, from the classical aspect (parabolic law) to a constant distribution law, conducting to a stress state approached to the pure shear. It is important that the notches have fillets because stress concentrations can be created and will cause premature failure of the test specimen. Specimens have been tested at room temperature (22 ± 2ºC). These were loaded until fracture in shear at a rate of 1mm/sec, using a servohydraulic test system. Load is applied by means of a special catch device, in which the specimen is fixed.

For longitudinal shear tests, 3 – 4 specimens were cut from each quadrant of the femoral cortex. These specimens have been obtained from the same mid-diaphysis sections as were used for the transverse shear tests. Specimens were machined to 10×10×3 mm, with 90º notches and 2.5 mm in depth using the end mill cutter described above (*fig. 3*). The test region of the specimen was milled to a 1.5 mm thickness. Each specimen was mounted into a grip and loaded as specified by Arcan et al. [1]. Testing was done at room temperature. Ultimate load was measured for each specimen.

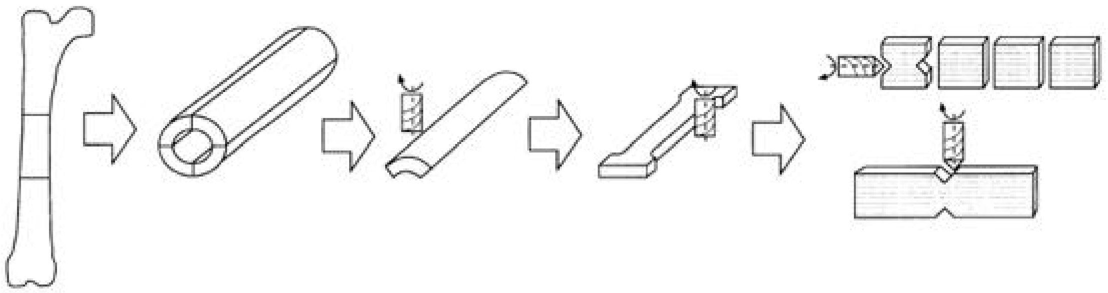


Fig. 3. Specimen preparation protocol for pure shear tests

For both test types (Arcan and Iosipescu), the shear stress was calculated with the equation

$$t = \frac{F}{h \cdot t} \quad (1)$$

where *F* is the applied force, *h* is the height of the critical section, and *t* is the specimen thickness.

SHEAR FATIGUE TESTS

For these tests, 5 longitudinal shear specimens were used from each femur (for a total of 25), [18]. These specimens were loaded until fracture to determine the ultimate longitudinal shear stress. Then 4 specimens were tested under cyclic load with peak load levels that created shear stress that were 60%, 70%, 80% and 90% of the ultimate longitudinal shear stress. Tests were performed using a device according to the specification described by Arcan et al. [1]. To prevent bending and torsion of the specimen, universal joints were used.

Load was applied to the specimens with a frequency of 2 Hz, using a servohydraulic - testing machine. Specimens were kept wet by dripping of a physiological saline (at 37ºC) during the test. Fatigue failure is defined as the complete fracture of the specimen.

Equation 1 underestimats the average shear stress in the critical section by < 4%. Shear stress is virtually uniform across the 4 mm critical section for the both specimen types.

The shear strength under longitudinal shear was 51.6±1.9 MPa, which was significantly less than shear strength under transverse shear, 65.3±2.5 MPa, [18]. For transverse shearing, the fracture plane was always 45º from the direction of loading, whereas longitudinal shear always produces a fracture along the shear plane (*fig. 4*). The fracture plane caused by the transversal shearing coincides with the maximum tensile stress, hence the transverse shearing causes failure due to tension not shear.

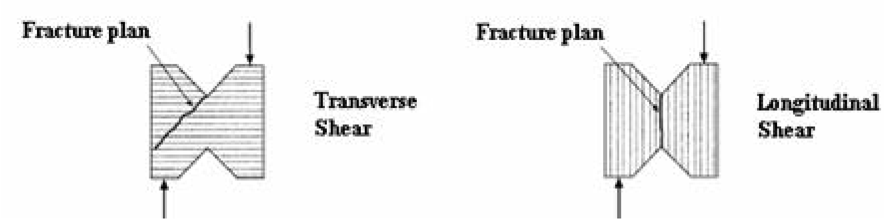


Fig. 4. Shear planes for transverse and longitudinal shear of a cortical bone

16 specimens were used for fatigue testing. *Figure 5* shows the shear stress – cycles curves (t – N).

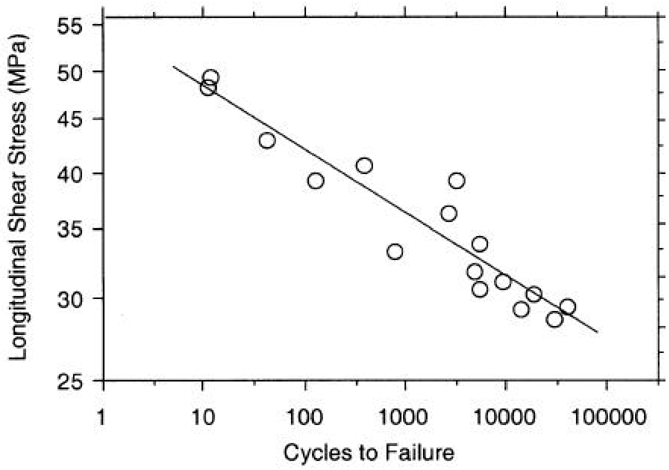


Fig. 5. s – N curve for fatigue of cortical bone in shear, [18]

Shear stress $t_{failure}$ and shear strain $g_{failure}$ can be calculated with the equations, [18]

$$t_{failure} = 55 \cdot N^{-0.06}, \text{ [MPa]} \quad (2)$$

$$g_{failure} = 8900 \cdot N^{-0.06} \quad (3)$$

where *N* is the number of cycles until failure.

Value of maximum shear strain was calculated by the ratio between the maximum shear stress and shear of the femur in the longitudinal – circumferential plane (6.23 GPa [2]).

DISCUSSION

In the *table 1*, a comparison between the tensile, compressive, and shear strengths for the human femoral bone obtained by some researchers is shown. It can observed that the cortical bone presents a weaker strength in both tensile and shear and the longitudinal shear stress is more lower than shear strength determined using torsion tests.

Shear strength of cortical bone is included between 68 – 70 MPa in the case of torsion tests, [6, 15]. These values are about 35% higher than the longitudinal shear strength reported in [18], but similar to transverse shear strength.

Tab. 1. Tensile, compressive and shear strengths of human femoral midshaft, [18]

Test type	Longitudinal [MPa]	Transversal [MPa]
Tensile strength, [15]	133.0	51.0
Compressive strength, [15]	193.0	133.0
Shear strength (torsion), [15]		68.0
Shear strength, [16]	50.4	
Shear strength, [18]	51.6	65.3

Transversal shear testing creates a failure plane at 45º from the longitudinal axis, coincidental with the plane of maximum tension. This fracture pattern is analogues to the spiral fracture resulting from torsion. The similarity of these results demonstrates that the transverse pure shear test provides results similar to the more widely accepted torsion test. Because the bngitudinal shear strength is substantially less than transverse shear strength, it is difficult to understand why the transverse shear specimens do not fail in the longitudinal direction, along the grain of the bone. It observes that the specimen can split down the long axis instead of failing at a 45º angle. Failure occurs along of each weakest plane (longitudinal shear or tensile). It is possible that the constraints placed upon the specimen and tested by Iosipescu test do not permit the longitudinal shear failure.

Nevertheless, there are clinical examples of longitudinal shear fractures. The most common the “boot top” fracture resulting from a skiing accident. This fracture results from the combination of torsion and three-point bending at the boot top. Both torsion and bending cause transverse shear loading to the tibia, resulting longitudinal shear stress. The fracture often includes a spiral fracture plane combined with longitudinal fracture planes, [8].

Comparative studies realized by some researchers on shear fatigue of cortical bone are presented in the *table 2*.

Tab. 2. Comparison between the fatigue properties of the various bone types, [18]

Reference	Bone type	Test type	Temperature	Frequency [Hz]
King and Evans, [12]	Embalmed human	Reversed flexural	Room temperature	30
Swanson et al., [17]	Human	Rotating bending	Room temperature	70
Gray and Korbacher, [10]	Bovine	Uniaxial compression	Room temperature	30
Carter et al., [4]	Bovine	Rotating bending	37ºC	125
Lafferty and Raju, [13]	Bovine	Rotating bending	21ºC	30
Carter et al., [5]	Human	Uniaxial reversed	37ºC	0.5 – 1.0
Turner et al., [18]	Human	Pure shear	37ºC*	2

* 37ºC saline was dripped on the specimens during the test

Cortical bone exhibits better fatigue proprieties under rotating bending or reversed flexural loading [4, 12, 13, 17] than under tensile [5], compression [10] or uniaxial tensile – compressive loading [5]. This comparison may be misleading, however, because bending and flexural tests were conducted at high frequencies (30 – 125 Hz) and uniaxial tests at lower frequencies (0.5 – 2 Hz). Also, the testing temperature has significant effects on fatigue life of bone. A decrease from 45ºC to 21ºC tripled fatigue life of cortical bone. This is important because most studies were realized at room temperature (20 – 22ºC), rather than body temperature (37ºC), [12, 13, 17].

CONCLUSIONS

Longitudinal shear strength determined by pure shear tests is about 35% less than for torsion tests. Shear stresses may play an important role in the pathologenesis of stress fracture in the human bone.

Elastical and mechanical properties of human bone depend on the trabecular orientation. Cortical bone is weaker in shear and is subjected to fatigue under cyclic shear loads.

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