The Compressive Properties of Single Osteons [1]

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ABSTRACT The compressive strength of single human osteons has been investigated in specially prepared samples using a microtesting machine equipped with a microwave micrometer. The main conclusions which can be drawn from our results are: (1) In agreement with Gebhardt's theories the ultimate compressive strength is greatest for osteons having transversally oriented fiber bundles, lowest for osteons having longitudinally oriented fiber bundles, and intermediate for osteons whose fiber bundles change direction in successive lamellae through an angle of about 90°. (2) The modulus of elasticity is greatest in osteons with transversally oriented fiber bundles. (3) With all three types of osteon the stress-strain curves for fully calcified osteons are markedly different from those for osteons with low calcium content, the modulus of elasticity being much lower in osteons of the latter type. (4) Age seems to have no measurable influence on the compressive properties of osteons. (5) The comparison of compressive properties in single osteons and in macroscopic bone samples seems to support the view that the osteon is actually the mechanical unit of compact bone. (6) Fracture in osteon samples starts with microscopic fissures induced by shearing. (7) In every case these fissures form an angle of roughly 30°–35° with the axis of the osteon and do not appear to vary with the microscopic osteon structures. (8) Electron microscopy reveals distortion of bone crystals and breaking of collagen fibrils at the edges of the fissures.

Nearly 60 years ago the German investigator W. Gebhardt ('06) developed a theory designed to explain the relationship between structure and mechanical properties of osteons. As no suitable technique for performing investigations on isolated osteons was then available, Gebhardt founded his theory on macroscopic metallic models in which bone collagen and crystallites were represented by steel wires.

During the last few years we have carried out a series of investigations on the tensile properties of single osteons (Ascenzi and Bonucci, '64, '65, '67; Ascenzi, Bonucci and Checcucci, '66). As it was practically impossible to isolate a whole osteon, the studies in tensile strength were done using portions of longitudinally sectioned units. For this purpose the dissection technique described by Ascenzi and Fabry ('59) was applied. The apparatus used for measuring the variations in length of the osteons subjected to tensile stress was a microwave extensimeter based on cavity and pulse techniques. This apparatus was developed at the Physics Institute of the University of Pisa by Gozzini and co-workers (see Battaglia, Bruin and Gozzini, '58).

Recently further attempts have been made by us to test the compressive properties of cylindrical samples corresponding approximately to the middle portion of single osteons. The aim of this report is to present the results of these investigations.

MATERIAL AND METHOD

Preparation and selection of samples. The osteon, when fully formed, is an irregularly cylindrical and branching structure a few millimeters in length and usually oriented in the long axis of the bone. A cross section, no thicker than 500 μ, from the diaphysis usually contains the straight non-branching portions of many osteons. If these portions could be cut out from a bone section, they would be suitable samples for testing.

Working on this principle, cross sections of femoral shafts measuring about 500 μ in thickness were prepared by grinding on glass plates. Particular attention was paid to avoid heating the material. A thickness of 500 μ is a critical limit, because beyond it the bone section is no longer sufficiently transparent for examination under the polarizing microscope, although bone transparency may be increased to some extent by soaking the section in bromoform.

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The samples were obtained from cross sectioned osteons using a specially designed device consisting of a very thin and accurately sharpened steel needle eccentrically inserted on a dentist's drill. When the drill was turning, the tip of the needle described a circle having a diameter of about 180–200 μ, i.e., the average diameter of an osteon. If the rotating axis of the needle coincided with the axis of an osteon and this osteon was perpendicularly oriented with respect to the surfaces of a bone section, the tip of the needle itself cut just inside its limits an osteon sample having the shape of a cylinder with walls of uniform thickness (fig. 1).

To ensure that the rotating needle was perpendicular to the bone section the hand-piece of the drill was inserted in the body of a microscope from which the tube had been previously removed and the section was fixed firmly on the stage (fig. 2). With the coarse adjustment of the microscope it was easy to regulate the movement of the needle into the bone section. The cutting of the osteon was controlled by watching the operation with a stereoscopic microscope.

By applying the technique described here samples were prepared with the shape seen in figure 3. Particular attention was paid to ensure that the Haversian canal was in the long axis of the sample and that its diameter was as constant as possible.

The length and the cross-sectional area of the dissected osteons were accurately measured and calculated with an eyepiece

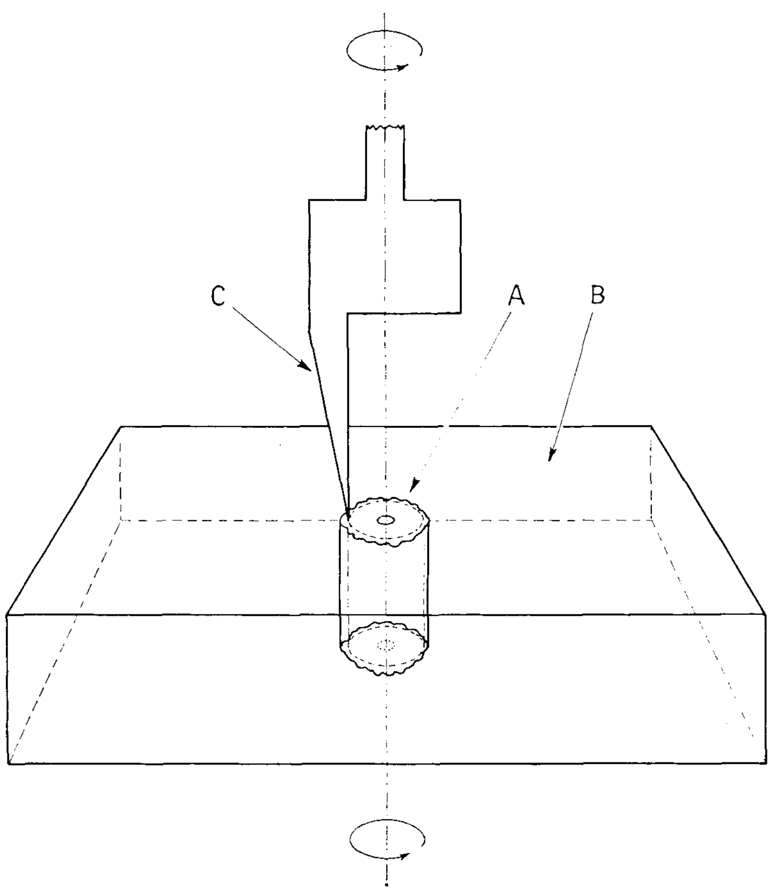

Fig. 1 Diagram illustrating the technical details involved in cutting an osteon just inside its limits (A) from a bone section (B) by a steel needle (C) inserted eccentrically in a dentist's drill.

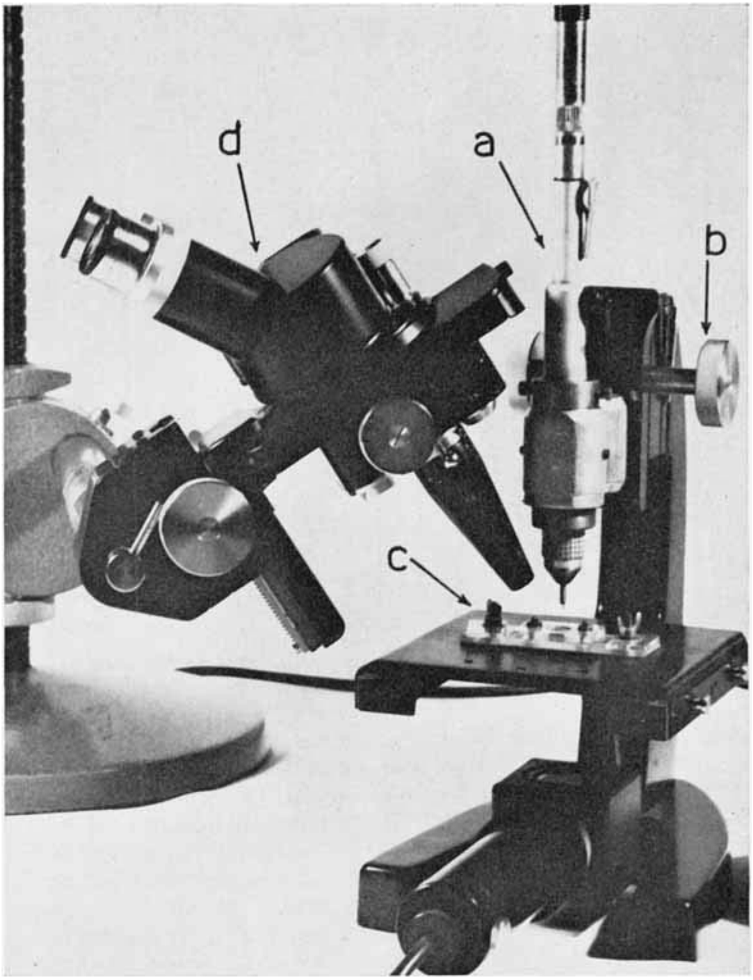

Fig. 2 Photograph showing the apparatus used for cutting osteons. The hand-piece of a dentist's drill (a) substitutes the tube of a microscope and its movement is regulated by coarse adjustment (b). A steel needle is inserted in it. The bone section is fixed firmly on the stage (c). A stereoscopic microscope (d) is used for controlling the operation.

micrometer. As the samples had been tested in a wet state the measurements were done with the samples wet.

The length to cross-section ratio ranged between 2.5:1 and 3:1.

The tested osteons differ in the degree of calcification and in the orientation of collagen bundles. The degree of calcification was determined by microradiographic technique in order to select units either at the initial stage of calcification or when fully calcified. Among the different arrangements produced by differences in fiber bundle direction in successive lamellae those characteristic of three types of osteons were chosen. In the first (called here type one) the fibers have a marked transversal spiral course in successive lamellae. Under the polarizing microscope the osteons belonging to this type appear homogeneously bright in cross section (fig. 4a). In the second type (called type two) the fibers in one lamella have a marked longitudinal spiral course, while in the next the fibers have an almost transversal spiral course so that the fibers in two suc-

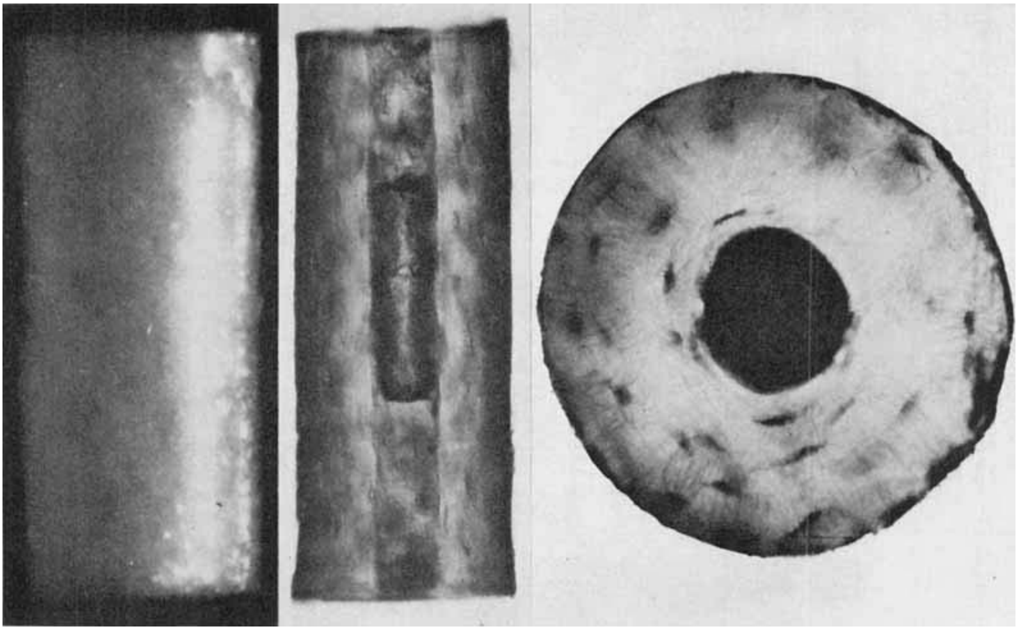

Fig. 3 From left to right: isolated osteon sample; isolated osteon sample as seen in transmitted light; an end surface of the sample.

cessive lamellae make an angle of nearly 90°. Under the polarizing microscope the osteons of this second type reveal an alternation of dark and bright lamellae in cross section (fig. 4b). In the third type (called type three) the fibers have a marked longitudinal spiral course with the pitch of the spiral changing so slightly that the angle of the fibers in one lamella was practically the same as that of the fibers of the next lamella. Under the polarizing microscope the osteons belonging to this type appear homogeneously dark in cross section, although frequently they are bordered by a bright lamella (fig. 4c). In every case this lamella was removed in cutting the osteon samples.

The samples were subjected to a direct compressive strength parallel with their long axis. For this purpose the specimen was placed between two metallic cylinders. One cylinder (the lower one) was fixed. A thin nylon thread was attached to the other (the upper one or "push" cylinder) and loads of 5 gm each were added. The shortenings of the osteon were recorded with a specially devised microwave micrometer (see later). As soon as the shortening of an osteon produced by the addition of a load became constant, additional weights were added (see also Ascenzi and Bonucci, '67).

Particular attention was paid in order to avoid any torsion or bending of the sample. All the measurements were performed at a temperature of about 20° C.

Normal speed motion micro-pictures were taken of osteons at the moment of the fracture.

The material used in the present investigation was obtained from femoral shafts of two human subjects aged 30 and 80, apparently free from skeletal defects. The total number of prepared osteon samples was 105, of which 44 were discarded as unsuitable for measurement. The wet osteons were obtained by hydration of the material using saline solution.

Microwave micrometer. In measuring the variations in length of osteons subjected to compressive stress a microwave micrometer based on cavity and pulse technique was used. The principle on which it works is the same as that of the extensimeter described in previous papers what is angle here

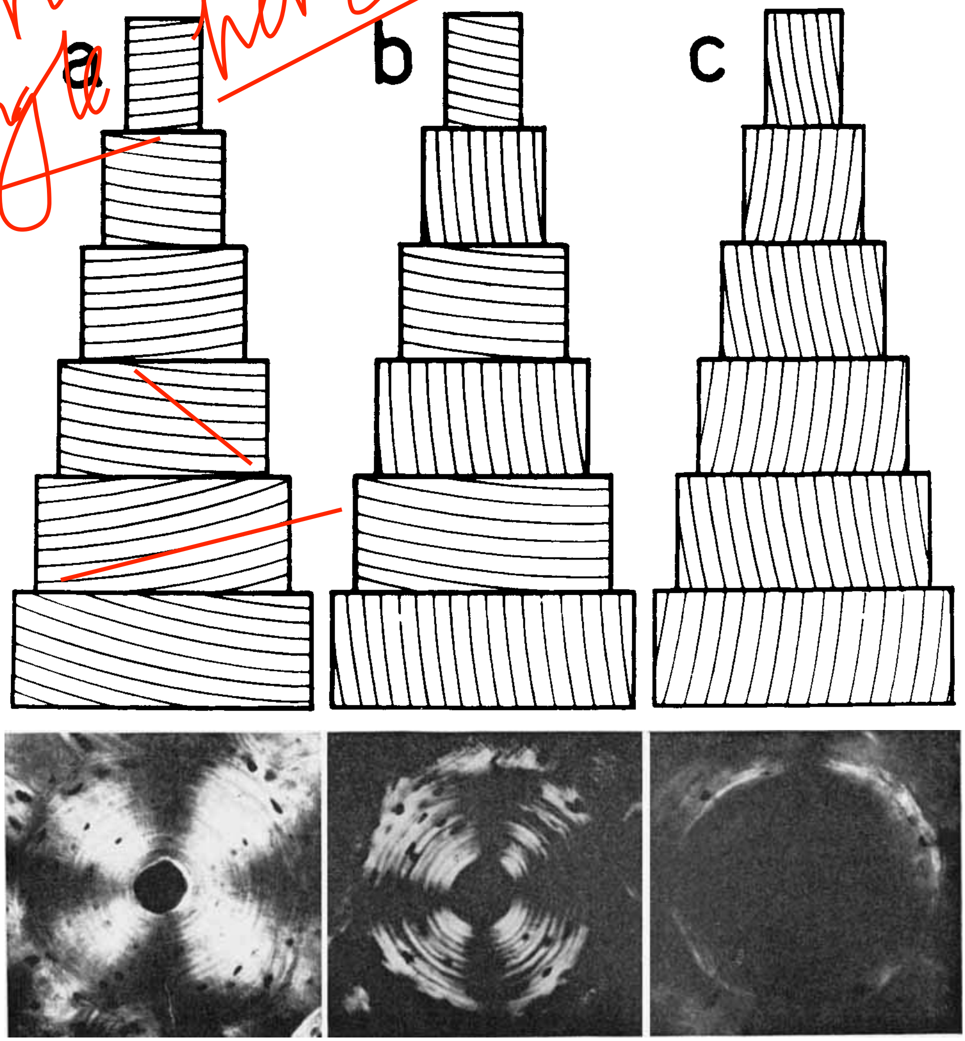

Fig. 4 The three types of osteon samples chosen as seen in cross section under the polarizing microscope with diagrams illustrating the orientation of fiber bundles in successive lamellae. (a) Osteon having marked transversal spiral course of fiber bundles in successive lamellae (type one). (b) Osteon with fiber bundles in one lamella making an angle of nearly 90° with the fiber bundles in the next one (type two). (c) Osteon having marked longitudinal spiral course of fiber bundles in successive lamellae (type three).

(Ascenzi, Bonucci and Checcucci, '66; Ascenzi and Bonucci, '67).

Figure 5 is a diagram of the cavity used for measuring the shortening of the osteon specimens submitted to compressive stress. The lower end of a specimen is supported by the upper base of the fixed cylinder. The upper end is in contact with the push cylinder whose upper surface is the lower plane of a cylindrical cavity, which functions as a resonator for electromagnetic waves. The push cylinder, which is very light (3.5 gm), can move freely inside the vertically oriented cavity. When weights are added to the thread attached to the push cylinder, the osteon sample undergoes a shortening which makes the lower plane of the cylindrical cavity fall, thus increasing the height of the cavity. As the shortening of the sample ($-\Delta l$) is ex-

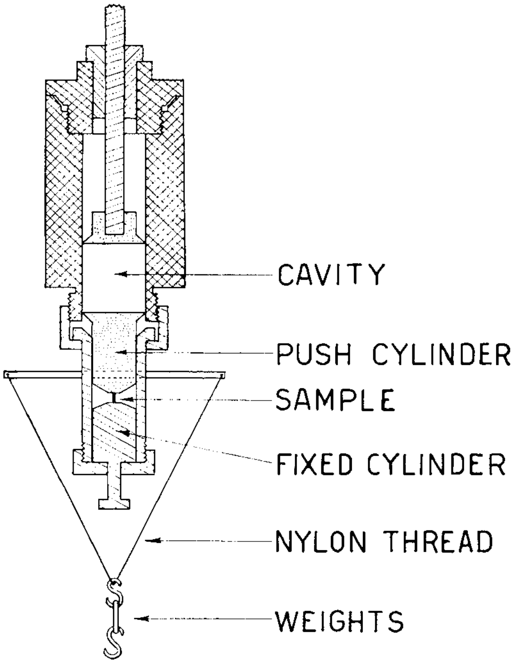

Fig. 5 Diagram of the cavity used as microwave micrometer and testing machine.

actly equal to the elongation in the height of the cavity (Δl), changes in the length of the sample are easily deduced from changes in the resonant frequency of the cavity. If Δl is very small compared with the height h of the cavity, the corresponding fractional change in the resonant frequency is

$$\frac{\Delta f_o}{f_o} = \frac{\Delta l}{h} \left(\frac{1}{1 + 1.488\,(h/D)^2} \right) \qquad (1)$$

h and D being, respectively, the height and diameter of the cavity, f_o the resonant frequency of the cavity, and "Te_{012} mode" the configuration of the electromagnetic field inside the cavity.

Under the present experimental conditions the values of D, h and f_o were D = 2.22, h = 1.78 cm, $f_o \approx$ 23,400 Mhz (Megahertz).

Measurements of changes in length for a single sample were accurate to within 1%.

Optical and electron microscopic examination of the tested osteons. To investigate the histological changes produced by compressive stress in isolated osteons, these were fixed after fracture in 4% formalin, buffered to pH 7.2 according to Millonig ('62), dehydrated in a graded series of acetone and embedded in Araldite. The specimens were sectioned with a Porter-Blum microtome fitted with glass knives. To avoid decalcification (Boothroyd, '64) ultrathin sections were in no case left in water for longer than three minutes.

Sections ½-1 μ thick were stained with Azure II-Methylene Blue and examined under the light microscope.

RESULTS

The diagrams in figure 6 give a unified conspectus of the stress-strain curves recorded for the types of osteon samples, based on the arrangement of their fiber bundles and their degree of calcification. All the diagrams refer to osteons from the femur of a 30-year-old man.

Figure 6 does not show all the individual curves—one for each osteon—pertaining to the types of tested osteon, only the interval between the curves occupying extreme positions for each of these types. In order to allow direct comparisons between the single sets of recorded curves, compressive strength is expressed in grams per square micron of section (ordinates) and the shortening is given as a percentage of the original length of the sample (abscissae). Moreover, in order to avoid the confusion which would arise from superimposing the charts, the origin of the co-ordinate system is transferred along the abscissae axis for each set of diagrams.

Diagram *a* was obtained from 13 stress-strain curves for fully calcified osteons of type one. The curves approximate a straight line up to the proportional limit, indicating a proportionality between stress and strain in accordance with Hooke's Law, but beyond this they are markedly curved. The modulus of elasticity is 94,905 ± 16,670 Kg/cm². The ultimate compressive strength is 0.0167 ± 0.00119 gm/μ^2, i.e., 16.70 ± 1.19 Kg/mm². The percentage shortening at the breaking point is 1.88 ± 0.29.

Diagram *b* was obtained from seven stress-strain curves from type one osteons with the lowest amount of calcium salts microradiographically demonstrable. In

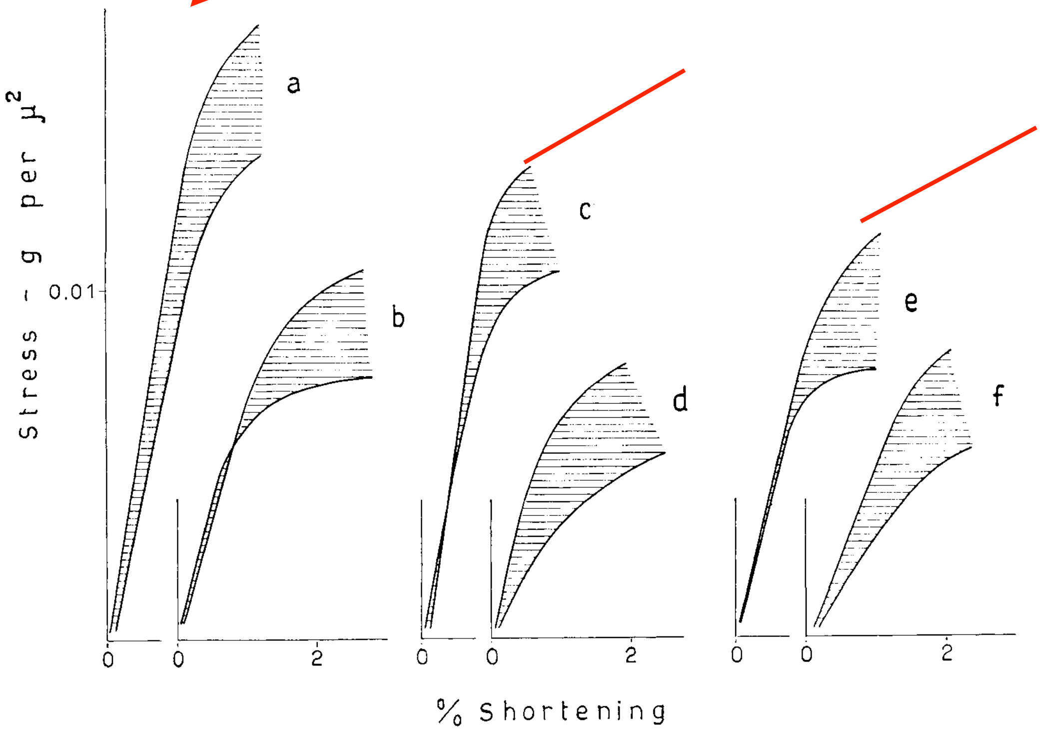

Fig. 6 Diagrams indicating the interval covered by the compressive stress-strain curves recorded for wet osteons taken from a man of 30. (a) Fully calcified osteons of type one and (b) osteons of type one at initial stage of calcification. (c) Fully calcified osteons of type two and (d) osteons of type two at the initial stage of calcification. (e) Fully calcified osteons of type three and (f) osteons of type three at the initial stage of calcification.

diagram *b* the curves again approximate a straight line up to the proportional limit, but this limit occurs earlier and the uppermost points show a more deviating curve than those in diagram *a*. The modulus of elasticity (73,662 ± 5,606 Kg/cm²) is significantly less than that of fully calcified osteons. The ultimate compressive strength (0.01002 ± 0.00105 gm/μ^2, i.e., 10.02 ± 1.05 Kg/mm²) is also much lower than that of fully calcified, type one osteons. The percentage shortening at the breaking point (2.82 ± 0.57) is greater.

Diagram *c* shows the interval covered by 12 compressive stress-strain curves recorded for fully calcified osteons of type two. The curves in diagram *c* are similar to those in diagram *a*, the proportional limit and the breaking point being reached at an earlier stage. The modulus of elasticity (75,404 ± 16,349 Kg/cm²) is significantly less than that of the curves in diagram *a*. The ultimate tensile strength (0.01366 ± 0.00095 gm/μ^2, i.e., 13.66 ± 0.95 Kg/mm²) is also lower but the percentage shortening at the breaking point (2.09 ± 0.51) is greater.

Diagram *d* was obtained from seven compressive stress-strain curves recorded from type two osteons having the lowest amount of calcium salts microradiographically demonstrable. Here the curves deviate from proportionality right from the beginning indicating that plasticity begins at an early stage. This seriously reduces the possibility of calculating the modulus of elasticity or of attributing any precise meaning to it. Its approximate value is 33,611 ± 17,063 Kg/cm². The ultimate compressive strength (0.00799 ± 0.00137 gm/μ^2, i.e., 7.99 ± 1.37 Kg/mm²) is significantly lower than that of the osteons in diagrams *a*, *b* and *c*, despite the fact that the osteons in diagram *b* are, like these, at the initial stage of calcification. The percentage shortening is 3.04 ± 0.59.

The osteons in diagram *e* and *f* both have fiber bundles with a marked longitudinal spiral course in successive lamellae (type three), but those in diagram *e* are fully calcified, whereas those in diagram *f* are at the initial stage of calcification. The curves in diagram *e*, which were obtained from seven osteons, are similar to those in diagram *a* and *c*, but the proportional limit comes at an earlier point and the breaking stress is lower. The modulus of elasticity (64,497 ± 18,489 Kg/cm²) is significantly lower than that of the osteons in diagram *a*, but not significantly different from that of osteons in diagram *c*. The ultimate tensile strength is 0.0112 ± 0.00103 gm/μ^2, i.e., 11.20 ± 1.03 Kg/mm². The percentage shortening at the breaking point is 2.46 ± 0.40.

The curves in diagram *f*, which were obtained from seven osteons, are similar to those in diagram *d*. As the curves deviate from proportionality at an early stage it is not possible to calculate the modulus of elasticity exactly or to attribute any precise meaning to it. Its approximate value is 49,063 ± 15,298 Kg/cm². The ultimate compressive strength is 0.00896 ± 0.00094 gm/μ^2, i.e., 8.96 ± 0.94 Kg/mm². The percentage shortening is 2.97 ± 0.36.

The measurements concerning the 80-year-old man were carried out on fully calcified osteons of type three. Diagram e_1 (fig. 7) recorded for eight osteons, was obtained from the man aged 80. Here the modulus of elasticity (72,109 ± 10,872 Kg/cm²) and the ultimate compressive strength (0.01089 ± 0.00122 gm/μ^2, i.e., 10.89 ± 1.22 Kg/mm²) appear slightly, but not significantly lower than in diagram *e*. The percentage shortening at the breaking point (2.57 ± 0.14) is not significantly greater than type three osteons of the 30-year-old man (diagram *e*).

All the osteons tested were examined under the optical and polarizing microscope to visualize the effects concerned with the deformation of the material. All samples were obviously shortened and of course they were also enlarged to varying degrees. At times this enlargement was uniform; at other times, it affected one

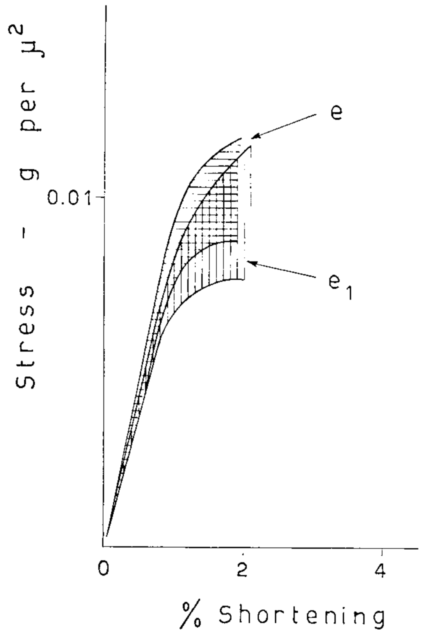

Fig. 7 (e_1) Interval covered by the tensile stress-strain curves recorded for wet and fully calcified osteons of type three. Man of 80. (e) This is the same diagram reported in figure 6.

portion of an osteon more than any other. Shortening and cross-sectional enlargement did not depend, statistically, on the type of osteon, but this was, perhaps, due to the serious deformation of the osteon at the moment of fracture. This deformation is shown clearly in figure 8. The fractures vary in number within the same osteon sample, as well as in different osteons. In appearance they ranged from wide fractures to very thin ones which looked like fissures. Fractures and fissures crossed, but their inclination to the long axis of the osteon was fairly constant, in most cases between 30°–35° (fig. 9); it was apparently independent of the structure and degree of calcification of osteons. Figure 10 shows a semithin section of the tested osteon 64 as examined under the optical and polarizing microscope. It is seen that bone fissures continue uninterruptedly through the lamellae.

The findings obtained with the electron microscope have been grouped together in figures 11–13. Figure 11 shows many fissures running through bone tissue. It is

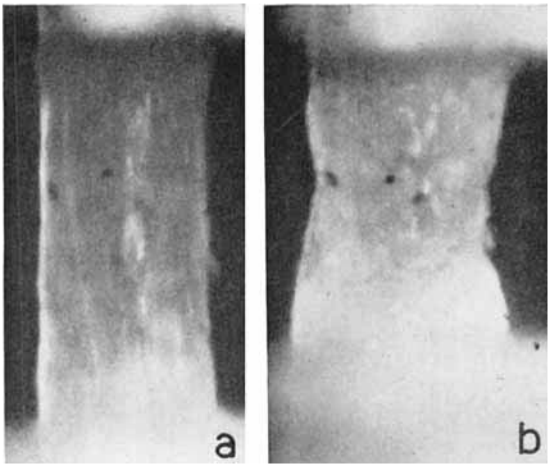

Fig. 8 Photomicrographic record, selected from a motion picture film, of the behaviour of an osteon (a) before and (b) after fracture.

obvious that the fissures are the result of loading, not of artefacts produced in preparing ultrathin sections, because they are full of embedding medium, i.e., araldite. Figure 12 shows two fissures at higher magnification. Misshapen and closely-packed crystals are seen at the edges. Figure 13 is of an ultrathin section whose organic matrix was decalcified and stained with PTA. Some collagen fibrils are broken off.

DISCUSSION

The first study on the compressive properties of fresh or soaked samples of macroscopic size from compact bone was carried out by Rauber (1876) who used fresh cubes prepared from the shaft of human femura, tibiae and humeri. He found that in males the average ultimate compressive strength of the samples loaded in the direction of the long axis of the bone was greatest (16.78 Kg/mm^2) in the tibia, intermediate (14.36 Kg/mm^2) in femoral samples and least (13.93 Kg/mm^2) in humeral samples. In females the ultimate compressive strength of the femur was lower (13.06 Kg/mm^2) than in males.

The cubes of fresh human shafts tested by Hülsen (1896), by loading them in the direction of the long axis of the bone, were generally stronger than Rauber's samples. Thus, the average values recorded for the tibia and humerus were, respectively, 20.93 Kg/mm^2 and 20.42 Kg/mm^2. Similar results (20.41 Kg/mm^2) were obtained using fresh humeral rings loaded parallel with the long axis of the bone. The ultimate compressive strength (16.50 Kg/mm^2) of fresh tibial cubes loaded perpendicular to the long axis of the bone was less than that of those loaded parallel with their long axis.

Recently Calabrisi and Smith ('51) tested fresh samples from human femurs and tibiae in a hydraulic testing machine calibrated to an accuracy of $\pm$ 1%. The samples loaded in the direction of their fiber were hollow cylinders taken from the middle third of the shaft, but machined to have walls of uniform thickness. The average ultimate compressive strength of these femurs was higher than Hülsen's samples: 21.19 Kg/mm^2 in males and 21.79 Kg/mm^2 in females. The tibiae investigated were less strong than Rauber's and Hülsen's samples, the average ultimate compressive strength being 15.53 Kg/mm^2 in males and 18.89 Kg/mm^2 in females.

Dempster and Liddicoat ('52) tested cubic samples of compact bone under compression in a materials testing machine. The average ultimate compressive strength for seven wet cubic specimens loaded in the direction of the long axis of the bone was 13.2 Kg/mm^2. In radial compression, bone had 89% of its longitudinal strength, i.e., 11.8 Kg/mm^2; in tangential compres-

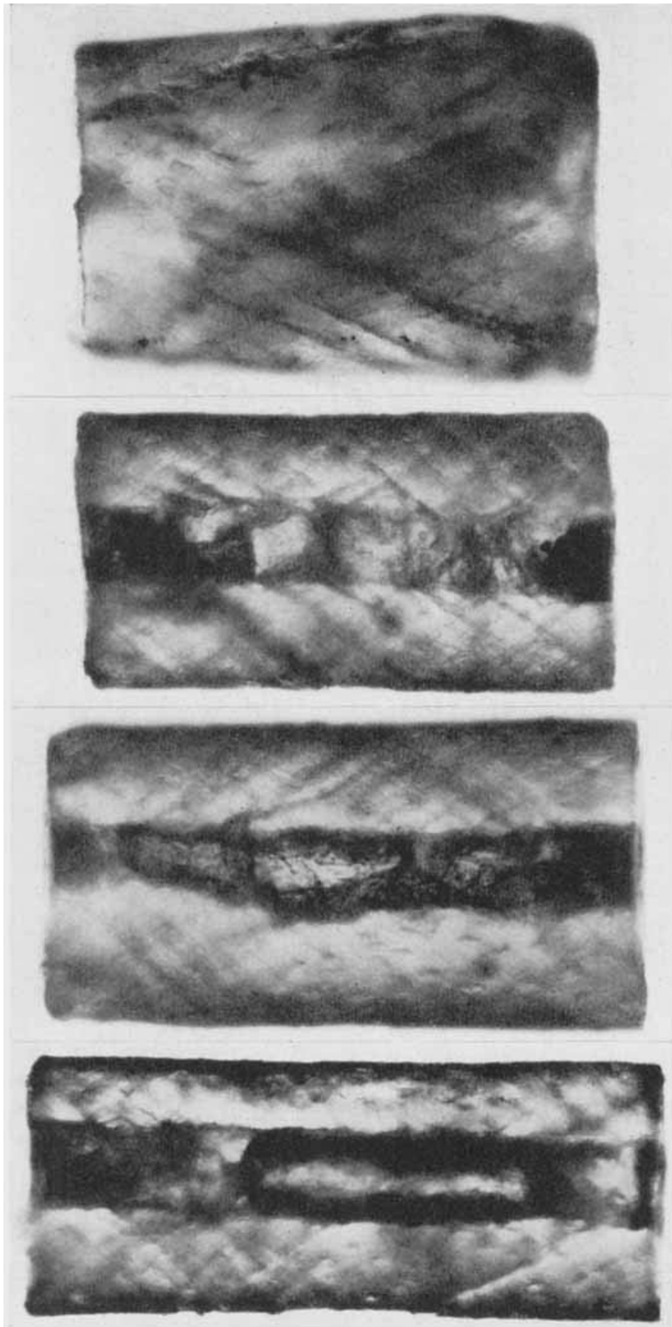

Fig. 9 A series of tested osteon samples (N° 24, 30, 64, 68) from a man of 30. In all specimens a network of fissures is clearly evident. × 100.

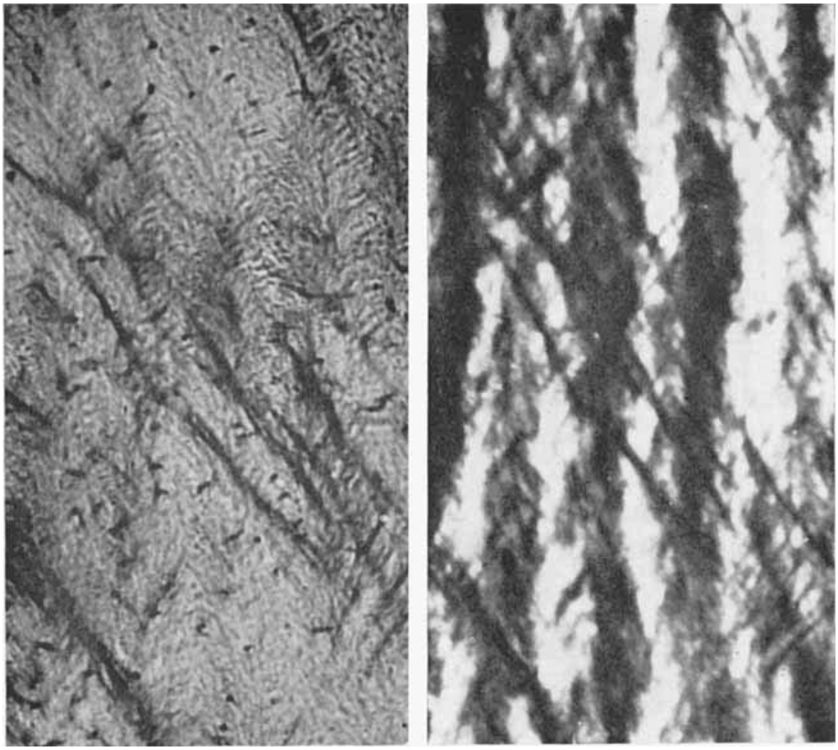

Fig. 10 Semithin section of the osteon N° 64 stained with Azure II-Methylene blue and showing some fissures (left). The same semithin section as seen under polarizing microscope. The fissures cross the bone lamellae (right). × 1,400.

sion, the equivalent value was 82%, i.e., 10.7 Kg/mm^2. Dempster and Liddicoat are the only investigators who have published a stress-strain curve for wet compact bone under compression. This curve has an elastic range, a proportional limit which occurs about half way to fracture, and a non-elastic range prior to failure. For the specimens loaded in the direction of the long axis of the bone, the modulus of elasticity varied significantly with the length to cross section ratios of the samples. For specimens of rectangular or circular section having a length/thickness ratio of about 7:1 the modulus of elasticity ranged between 143,426 and 144,833 Kg/cm^2. For cubic specimens the modulus of elasticity was 88,727 Kg/cm^2.

In comparing the compressive behaviour of bone samples of macroscopic size and that of single osteons, it appeared advisable to us to consider first fully calcified osteons, because they are the most representative units in compact bone. The ultimate compressive strength ranged from a minimum of 11.20 ± 1.03 Kg/mm^2 for osteons of type three to a maximum of 16.70 ± 1.19 Kg/mm^2 for osteons of type one. Rauber's results, which were for macroscopic bone samples, are, despite this, fairly similar to these. Dempster and Liddicoat's value for average ultimate compressive strength for specimens loaded parallel with the long axis of macroscopic bone samples (13.2 ± 2.2 Kg/mm^2) is within the range covered by the three types of single osteons tested by us. But the macroscopic bone specimens tested by Hülsen and by Calabrisi and Smith yielded values for ultimate compressive strength higher than those obtained by us for single osteons.

The stress-strain curves for the three types of fully calcified osteon investigated by us were strikingly similar to the curves Dempster and Liddicoat obtained for macroscopic bone samples, although their samples, of course, were non-homogeneous. Moreover their curves, like ours, contained only a very short deviating portion between the proportional limit and fracture, the rest of these curves being a straight line from the origin to the proportional limit.

It is interesting to note that the modulus of elasticity of osteons of type one is 94,905 ± 16,670 Kg/cm^2 and that of osteons of type two is 75,404 ± 16,349 Kg/cm^2, while the modulus of elasticity of the cubic whole bone samples investigated by Dempster and Liddicoat, containing, of course, both these types of osteon, was 88,727 Kg/cm^2—that is, intermediate between the other two figures. This kind of relationship does not, however, exist between our figures and those obtained by Dempster and Liddicoat for columnar samples. This may be due to the fact that the length/cross section ratio of our samples was more like that of their cubic samples than that of their columnar ones.

The ultimate compressive strength of osteons at the initial stage of calcification is significantly lower than that of fully calcified ones. The influence of calcification on the compressive properties of osteons is indicated by differences in stress-strain curves.

As between the curves for fully calcified osteons of types one, two and three, a progressive shortening of these curves is noticeable, indicating a progressive decrease in resistance to pressure. Together with this there is a progressive decrease in modulus of elasticity and a progressively greater deviating portion of the curve before fracture. Despite this, all these curves are longer, and deviate less, than the corresponding curves in each case for osteons of low calcium content.

Comparing the curves of type one osteons when fully calcified and at the initial stage of calcification (fig. 6*a* and *b*) revealed the following differences. The former are elastic almost to the fracture point but the latter, which are weaker, have a fairly long deviating portion before fracture, showing that elasticity ends earlier in both relative and absolute terms. Together with this the modulus of elasticity decreases in osteons at the initial stage of calcification.

Comparison of the curves for type one, type two, and type three osteons at the initial stage of calcification (fig. 6*b*, *d* and *f*) shows the same characteristics, but more markedly. Deviation from elasticity for the latter two curves (fig. 6*d* and *f*) begins almost at once and fracture occurs earlier than with low-calcification osteons of type one (fig. 6*b*). The modulus of elasticity of the curves for type two and type three osteons is lower than for type one.

These results are a confirmation of the investigation of Ascenzi and Bonucci ('67), suggesting that the modulus of elasticity in bone tissue increases with the degree of calcification (see also Currey, '62).

The main problem in understanding the compressive properties of single osteons is how differences in ultimate compressive strength and in stress-strain curves depend on structural differences within osteons. From studies on metallic models Gebhardt concluded that osteons like those of type three are less able to support compressive loads than osteons of type one. He founded this conclusion on the assumption that when fiber bundles and crystallites are loaded in a direction almost parallel with their long axis as in osteons having longitudinally oriented fibers (type three), they are likely to bend and fracture easily. With osteons of type two, the fiber bundles and crystallites which run almost transversally to form a system of rings prevent the bending of their longitudinally oriented fiber bundles and crystallites. So osteons of type two should be stronger than those of type three. According to Gebhardt, it is obvious from the structure of osteons of, or like, type one that these should have the greatest compressive strength of all.

Our results on the compressive properties of single osteons are strengthened by those of our investigations (Ascenzi, Bonucci and Checcucci, '66; Ascenzi and Bonucci, '67) on their tensile properties. The latter indicated that in osteons having a marked longitudinal arrangement of fiber bundles in successive lamellae (type three) the ultimate tensile strength and modulus of elasticity are greater than in osteons with fiber bundles running alternately in such a way that their direction in successive lamellae changes through an angle of about 90° (type two). In other words, the former type of osteon resists tensile strength better than the latter.

Using Rauber's data, Koch ('17) stated that the ratio between ultimate tensile strength and ultimate compressive strength for fresh human bone is 0.73. As regards our isolated osteons, this was 0.70 for fully calcified osteons of type two and 1.04 for fully calcified osteons of type three. These data provide confirmation that the former osteon type is better able to support compressive strength than the latter.

As regards the compressive properties of osteons with advancing age, the stress-strain curves for osteons (all of type three) from an 80-year-old man were not significantly different from the curves (again for osteons of type three) in the case of the 30-year-old man. These findings are in agreement with those of Ascenzi and Bonucci ('67) on the tensile properties of single osteons. Evans and Lebow ('51) also reported no relationship between the age of the individual and tensile strength of bone.

As the last topic to be discussed, there are the microscopic changes undergone by the tested osteons. These mainly consisted of innumerable crossing fissures which are obliquely oriented and form an angle of about 30–35° with the osteon axis. Recently Rutishauser and Tschantz ('65) and Tschantz and Rutishauser ('67) observed a similar finding at the macro- and microscopic level in the ulna of dogs after the shaft of the radius had been removed. Here the fissures formed an angle of roughly 30° with the axis of the bone. The authors call the fissures "basophile lines" because of their staining properties and suggest they may be produced by compressive overloading of the ulna, as a consequence of the removal of the radius. The fissures did not show any apparent dependence on bone structure. Rutishauser and Tschantz report that some minerals undergo the same changes when tested in compressive testing machine. As far as we are aware, the finding of obliquely oriented fissures running at 30–35° with the osteon axis can be considered a result of shearing induced by loading when stress produced plastic deformation of the sample. This is also the opinion of Dempster and Liddicoat who were able to obtain similar fissures in cubes of compact bone which had been compressed longitudinally up to fracture.

In the loaded osteons tested by us the fissures do not seem to vary with the type of microscopic osteon structure. In all examined samples they crossed the lamellae at many points and induced breaking of collagen fibrils.

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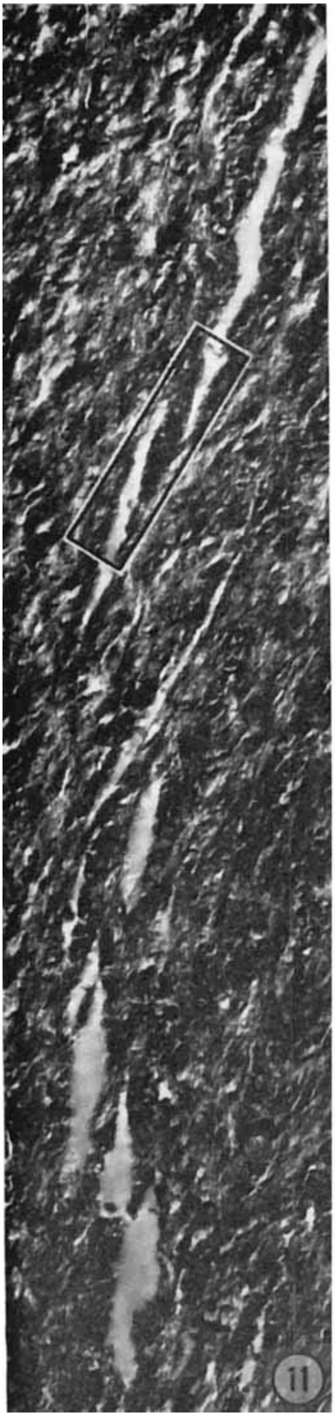
PLATE 1

EXPLANATION OF FIGURES

11 Osteon fissures as seen under the electron microscope. Unstained section. × 6,000.

12 Enlargement of framed area in figure 11. × 35,000.

13 Osteon fissure decalcified and stained with PTA. Arrows point to broken fibrils. × 90,000.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