Calcif Tissue Int (2001) 68:205–210
DOI: 10.1007/s002230020040

Calcified Tissue International

Review

Bone Strength: What are We Trying to Measure?

J. D. Currey

Department of Biology, University of York, PO Box 373, York YO10 5YW, UK

Received: 20 November 2000 / Accepted: 8 January 2001 / Online publication: 11 April 2001

At a recent bone densitometric meeting, where I, as a 'rude mechanical,' had been brought in for light relief, I was struck by the cheerful way in which people using noninvasive techniques to try to measure the likelihood of bone fracturing used the word 'strength.' The implication seemed to be that there was a straightforward relationship between strength and likelihood of fracturing—if a bone is not strong enough, it fractures. Although a fracture is usually easy to recognize, the events leading up to the fracture may be different in different cases and, in particular, the properties required of a bone in order that it should not fracture, that it should be 'strong' enough, may be different and indeed sometimes contradictory under different circumstances. The aim of this review is to disregard the concepts that lie behind the word 'strength' so that these viewing bone in a clinical context may have a better understanding of what is involved. Of interest is bone fracture in general, not only with those of the hip and Colles' fracture, which are traditionally of interest in clinical investigations of osteoporosis. The concern here is with the properties of whole bones and of bone material, not with such factors as propensity to fall, neuromuscular coordination, thickness of soft tissues, etc.

Failure

Nearly always the way in which bones fail, that is cease to carry out their appropriate function, is because they break. However, they may break because they are too flexible, not resistant enough to static loading, or not tough enough or fatigue-resistant enough.

The stiffness, static strength, toughness, and fatigue resistance of the bone *material* interact with bone's *architecture*, that is, its large-scale structure, and if insufficient can cause failure. In cancellous bone the question of whether one is dealing with a material or a structure is difficult, and cancellous bone should be considered to be in the middle of the spectrum. Nevertheless, even though it is the whole bone that fails, it is convenient to start with material properties.

Stress and Strain

Stress can be considered the intensity of force, and is measured by force divided by the area over which it acts. A force of one newton acting over an area of one square meter is called a 'pascal.' In bone, interesting physiological values tend to be in the region of millions of pascals [megapascals (MPa)]. Strain is the proportional change in length that the material undergoes, for whatever reason. If a specimen is stretched by 1% it is said to be undergoing a strain of 1% or, as it is often called, 10,000 microstrain. Sometimes the abbreviation for microstrain ($\mu\epsilon$) is thought of as some basic unit of strain, as a newton (N) is a unit of force. However, because strain is a ratio it has no units. (There are other kinds of stress and strain, such as shear stress, shear strain, and bulk strain, but it is not necessary to consider them here.) Given these concepts we can consider the important properties of bone material (Fig. 1).

Bone Material Properties

Stiffness

This is usually measured as Young's modulus of elasticity, often denoted as '*E*,' but there are other measures. It is stress divided by strain in that part of the curve that is linear. If a specimen is loaded with a tensile stress of 100 MPa (10^8 Pa) and undergoes a strain of 0.005, it is said to have a Young's modulus of 10^8 Pa/0.005 $= 2 \times 10^{10}$ Pa $=$ 20 GPa. Such a Young's modulus would be characteristic of stiff bone. (There is a small terminological problem here. 'Stiffness' should really refer to a property of the whole structure, and stiffness of the material as 'modulus of elasticity.' Mechanicals frequently use 'stiffness' in both con-

Correspondence to: J. D. Currey

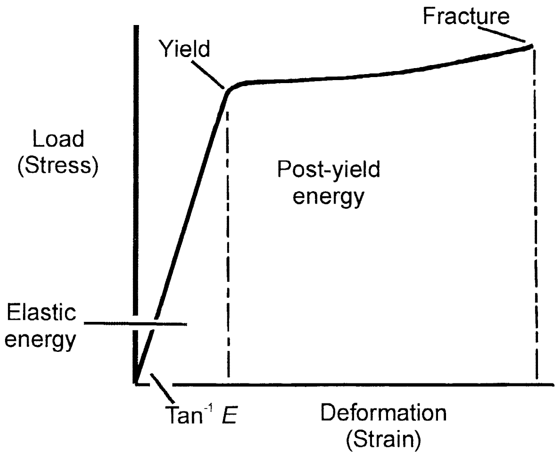


Fig. 1. Typical load-deformation curve for a bone specimen loaded in tension. The load divided by the cross-sectional area is the stress; the deformation divided by the original length is the strain. The initial part of the curve is more or less straight, and the Young's modulus of elasticity (*E*) is stress/strain in this region. The angle that this line makes with the strain axis is Young's modulus. Stiff materials have a steeper slope than more compliant ones. The area under the curve is the energy absorbed by the specimen. After the yield point the bone becomes increasingly damaged but may absorb a considerable amount of energy before it breaks.

texts, knowing that context will make the meaning clear. However, here, at the suggestion of a referee, I shall use 'flexibility' when referring to the whole-bone property, and 'modulus of elasticity' for the material property. 'Stiffness,' where it appears, will refer to *material* properties.)

Static Strength

This is the stress at which a material will fail if it is loaded slowly (the time to failure being greater than, say, 1/10 second). It refers to the greatest stress, wherever it occurs. (Stress is usually not uniform throughout a specimen. For instance, in a bending specimen the stresses vary throughout the specimen, some parts even feeling no stress.) The static strength of bone is about 150 MPa in tension and about 250 MPa in compression. The strength of bone is anisotropic, that is, it is different when measured in different directions and if it is loaded in an unusual direction may therefore be weaker than expected [1]. In life, things are usually arranged, however, so that they are loaded more or less in the strongest (and stiffest) direction.

Toughness

This is a tricky concept, best thought of as the amount of energy a material can absorb before failure; this is usually important in a fall. A large amount of energy is put into the specimen, and the question is. Can the specimen absorb it? It is a different criterion from static strength. The opposite of being tough is being brittle. Glass is quite strong, but brittle; wood is not very strong, but is tough. Tough materials are also much less weakened by flaws (such as iatrogenic screw holes) than brittle materials. Tough materials characteristically show a great deal of post-yield deformation (Fig. 1) which, though not accompanied by a great increase in stress, allows the specimen to absorb much more energy.

Fatigue

A stress that would not break a specimen if it is applied only once may break it if it is applied many times. The loading damages the material in some way, so that eventually a fatal crack develops. Fatigue-resistant materials are insensitive to being loaded very often to stresses that are not much less than stresses that would break them.

Which Properties are Important?

All these properties have been described as *normalized* so that the specimen size and shape are not relevant. In the clinical situation, of course, there is no concern for the material properties, but whether the whole bone breaks or not and there is no concern for the *stress* that the bone is bearing in some part, but rather the *load* that it can carry. The material properties and the whole bone properties are inextricably related by the architecture of the bone. One bone will carry the same compressive load as another bone, even though its bone material is half as strong, if it has twice the cross-sectional area. If bones do differ in quality of their material it is not, of course, sufficient merely to know their architectural properties; their material properties must also be known.

Two questions arise: Which of these properties are important in particular loading situations, and to what extent is bone that is good in one mode good in another?

Flexibility Versus Static Strength

Flexibility itself is rarely of interest to the clinician. However, if the material in long bones is very compliant (compliance is the opposite of stiffness) the bones may fail by 'Euler buckling.' This is the buckling that occurs when one pushes on the end of a long cane; it will deform sideways in a bow, and if pushing persists, the cane will break. The important thing about this is that although the cane failed because its strength was eventually exceeded, this failure was made inevitable by the buckling, and this was a function of the flexibility of the cane, not its strength. Such failure is sometimes seen in young people, who have lightly mineralized bones, when they fall on an outstretched arm [2].

Material strength and material stiffness are often closely related. The static bending strength of compact bone and its modulus of elasticity are roughly proportional to each other (Young's modulus being about 100 times greater than the bending strength [3]). The static compressive strength of cancellous bone and its Young's modulus are also proportional to each other [4] again, though coincidentally, the Young's modulus is about 100 times greater than the strength. The reasons for these ratios are complex and not properly understood, however, we should be thankful for these rules of thumb.

Toughness and Fatigue versus Strength and Modulus of Elasticity

In general, the toughness of bone material is *inversely* related to its bending strength and modulus of elasticity. Thus, children's bone material, because of its lower mineralization, is weaker in static loading than adults', but much better at resisting impact loading [5]. The reasons are again complex, but they concern the fact that a stiff material is less able to rearrange itself around an incipient dangerous crack and is therefore less able to show a long post-yield region in which stress does not increase much, whereas strain does.

It is unknown how fatigue resistance is related to other properties, except in a general way. There is some indication that toughness may be good for fatigue. It is certainly true that the most highly mineralized bones in the body, around the ear, are particularly prone to fatigue fracture, even though they are hardly loaded at all [6]. Another problem in understanding how important fatigue is clinically is that fatigue may damage the bone material, producing microdamage and reducing its stiffness and static and impact strength, but not appear as a classic fatigue (stress) fracture. The eventual fracture will be attributed solely to the final event that causes failure.

Damage probably increases with age. Is damage necessarily bad? There is some evidence that under certain circumstances microcracking/damage may actually strengthen bone, certainly in impact [7]. However, damage makes the bones less stiff and therefore hinders them in carrying out their primary role, which is to be stiff structures, not bending much or deforming when loads are placed on them.

Bone Architectural Properties

Architectural properties are mainly what noninvasive methods measure. One knows more or less how much bone material there is and where it is. An engineer would laugh if asked to predict the strength (of whatever kind) of a very complex structure like the proximal femur, given only the information available to the clinician. What is generally made use of is the fact that proximal femurs are similar in their general shape, and when bone is lost it is lost in a somewhat similar pattern, so that the likelihood of fracture is closely related to the amount of bone material there. Epidemiological studies then show how fracture incidence and the amount of bone present are related. This is clearly a roundabout, rough and ready way of determining the strength. If we are to obtain even the beginnings of an analytical understanding of bone strength, there are other things to be considered.

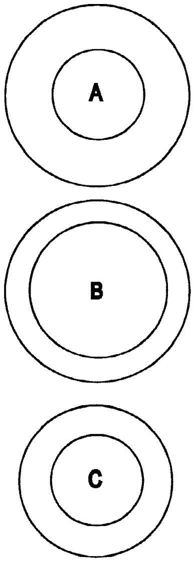
Compact Versus Cancellous Bone

One situation in which it is not enough to know simply the amount of material present is when both cancellous and compact bone are present in appreciable quantities. Imagine a thin cylinder of compact bone, and two fatter cylinders of cancellous bone, all of the same length and all having the same amount of bone material. Suppose the relative densities of the bones (amount of bone per cubic centimeter) are in the relative proportions of 1, 0.2, and 0.1 for the compact and the two cancellous cylinders. Roughly, their compressive strengths will be in the ratios of 1:0.04:0.01 because the strength (and modulus of elasticity) of cancellous bone is roughly proportional to the *square* of the density. If the cross-sectional area of the bone material in compact bone loaded in compression or tension is halved (by erosion of the outer surfaces), its strength will be halved. However, if the amount of material of the cancellous bone is halved (by erosion of all the surfaces), then its strength will be reduced to a quarter. If one is dealing with a structure that has significant amounts of both compact and cancellous bone it is important to know how the mass is distributed between the two types. For the same general reasons, if bone is then lost from the whole structure it is important to distinguish how much is lost from the compact bone and how much from the cancellous bone.

There are situations in which cancellous bone material, though good at preventing a bone from *starting* to crack, is not good for resisting crack travel. This is seen, for instance, in the horse metacarpal and metatarsal. The trabeculae underneath the joint surface are arranged excellently for stiffness and strength because they are longitudinal plates aligned in the direction of loading, and as such, support the subchondral bone very well. The plates are attached to each other by little cross struts. However, once the cortex is damaged, the cancellous bone offers essentially no protection from further crack travel because the crack travels just between one pair of plates, and the little cross struts are snapped through easily, one after another [8].

Compression Versus Bending

In considering the compressive loading of the cylinder of compact bone, I implied that it did not matter much how the bone was lost since the resulting strength would be proportional to the remaining cross-sectional area. This is broadly true, unless the cylinder becomes so slender that it is liable to buckle. However, if the bone is in danger of fracturing in bending, it becomes very important to know where the bone



	Diameters	Relative Area	Relative Strength	1/Relative Flexibility
A	2,1	1	1	1
B	2, 1.5	0.58	0.73	0.73
C	1.66, 1	0.58	0.53	0.44

Fig. 2. Diagram showing the effects of architecture on bending strength and flexibility (flexibility is shown as its reciprocal, so that the lower the value in the table the more flexible the bone). **(A)** is a cross-section of a hollow cylindrical bone; its cross-sectional area, strength, and flexibility are taken arbitrarily as unity. **(B)** The wall thickness is reduced to half its former value, the bone being eroded from the inside In **(C)** the wall is eroded from the outside, the resulting cross-sectional area being the same as in **(B).** Note that (in the particular set-up shown here) the bone eroded from the inside **(B)** loses strength and 1/flexibility *less* than it loses area, whereas the bone losing the same amount of area, but eroded from the outside **(C)** loses strength and 1/flexibility *more* than it loses area.

is lost because, in bending, the strength is proportional to the 'second moment of area' divided by the depth of the section of interest. The point here is that in bending, bone material pulls its weight much more if it is far from the plane of bending than if it is close to it. This importance of far-away bone is even more marked if it is flexibility that is likely to lead to failure, as in buckling. (Fig. 2).

Smith and Walker [9], and much work since [10], have shown that the femoral expansion that occurs during aging, although accompanied by thinning of the cortex, compensates, at least in theory, for the loss of cross-sectional area. What is true for bending is also true, with a few of the equations changed slightly, for torsion. In torsion, resistance to fracture is better if the bone material is situated well away from the central axis. These examples show that bone loss will affect the likelihood of fractures resulting from compression and from bending differently.

Static Versus Fatigue Loading

Falls induce high loading rates, and usually energy considerations are paramount. Nevertheless, static loading may be important at times. For instance, osteopenic vertebrae may fracture when subjected to high, slowly applied loads such as may occur in bedmaking. Almost nothing is known about architectural properties that may differentially affect static and fatigue loading. There is a study by McCubbrey et al. [11] suggesting that the status of the parts of the vertebrae that are significant in producing variations in fatigue resistance are different from those producing variations in static loading resistance, even though the loads were positioned similarly. However, the effects were subtle, and it is probably true that, if the material properties are the same fatigue resistance, or susceptibility, and static load resistance or susceptibility are produced by the same kinds of architecture. Of much more importance is the distinction between static and impact loading.

Impact Versus Static Loading

In talking about material properties I have mentioned that the kind of bone that may be good at resisting static loading may not be so good at resisting impact loading; this may also be true of whole bones. Suppose we are interested in loading a bone so that it absorbs the maximum possible amount of energy, yet no part of it is damaged (the stress is always less than the point marked 'Yield' in Fig. 1). The trick is to get as much as possible of the bone volume loaded as strongly as possible (Fig. 3).

The amount of energy that can be absorbed in the elastic region is half the maximum load times the deformation. This energy is absorbed throughout the volume of the bone, and although it will be the stress in a particular part of the bone that will cause the bone to break, what is important is how much energy the whole bone has absorbed up to that point. Suppose we have a radius of uniform structure along its length that can bear a static longitudinal load of 100 load units, and absorb energy of 100 energy units. We can think of the bone being divided into 10 segments, each of which absorbs 10 energy units and each of the cross-sections of the bone is stressed to the same extent (each segment must bear the same load, of course, because the load must reach from one end of the bone to the other). Suppose one tenth of the length of the bone undergoes erosion so that its cross-sectional area is halved. What will be the effect on the load, and on the energy that can be absorbed? The load is obvious. Where the cross-sectional area is halved, a given load will produce twice the stress. This segment will be the weakest link, and the total load that can be borne will be halved even though the rest of the bone is fine. So, the static load the bone can bear will be reduced to 50 load units.

Now consider the energy that can be absorbed by this bone with an eroded segment. At the load of 50 load units the small segment will be bearing half the original load, and will be deformed to the same extent as before, absorbing 5 instead of 10 energy units. Each of the other nine segments will be bearing the same load as the eroded segment (50 load units) but, because they have the original cross-sectional area, they will be feeling half the stress, and there-

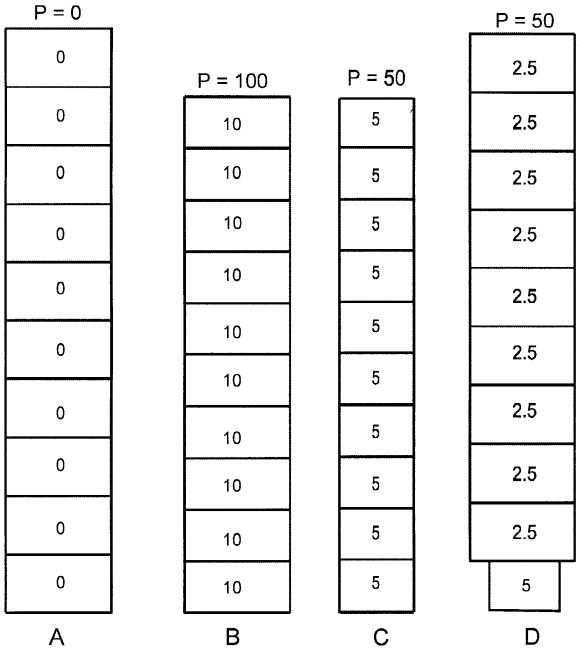


Fig. 3. Diagram showing energy distribution in a bone made of 10 segments, loaded longitudinally. The number in each box is the amount of energy absorbed by that segment when the bone is loaded by the load P. The lengths of the boxes indicate the approximate relative deformation, although these are greatly exaggerated. **(A)** The bone is unloaded. Total energy absorbed: 0. **(B)** The bone is loaded so that it is stressed uniformly to its maximum. Total energy absorbed: 100. **(C)** The bone is reduced in cross-sectional area to one-half its original value over its whole length. The maximum strain remains the same as in **(B),** but it can now bear a load of only 50. Total energy absorbed is 50. **(D)** The bone is reduced to one-half its cross-sectional area in only one segment. Because this is the weakest link, the bone can bear a load of only 50, and the remaining fatter segments are less stressed and less deformed than in **(B)** or **(C)** and so absorb less energy. Total energy absorbed: 27.5.

fore will only deform half as much at this load. Therefore, since energy is proportional to load × deformation, each one will absorb one quarter of the energy, that is, 2.5 energy units. So, the bone as a whole will absorb 1 × 1/2 × 10 + 9 × 1/4 × 10, which is 27.5 energy units. If the bone had all been eroded to the same extent it would have borne 10 × 1/2 × 10, which is 50 units. In other words, understressed bone actually *reduces* the amount of energy that can be absorbed, though it has no effect on the load that can be borne, which is solely determined by the weakest link.

If we consider the preferential loss of bone during aging from the ends of the radius, it is clear that this bone is particularly troubled. Not only is it losing mainly cancellous bone from the distal extremity, which has a disproportionate effect compared with loss of a similar amount of compact bone, but also the energy distribution in a fall is becoming unfavorable because the main part of the shaft is absorbing less energy than before. In predicting propensity to fracture, it is necessary to consider, as far as is possible, the architecture of the whole of the loaded system, or at least of the loaded bone [12].

In this discussion of impact loading, I have assumed that the bone should not be loaded beyond the yield point shown in Figure 1. If any part of the bone is loaded beyond this point, then the properties of the bone *material* will become of overriding importance, because the ability to stop a crack starting, and then traveling, which is mainly determined by the long post-yield region shown in Figure 1, is a strictly local property, showing itself in the bone's behavior close to the region where the crack is traveling. Zioupos [13] has an interesting discussion, reasonably accessible to nonmechanical people, of the events occurring in fracture that are affected by bone's toughness.

Conclusion

When the prediction of bone failure was mainly epidemiological, based on relatively straightforward measures of the amount of bone present and fracture incidence, the information in this brief review was probably not of great importance to the clinician. However, as methods of noninvasive characterization of bone become more sophisticated, and hopes of more accurate prediction rise, they will become increasingly important. The clinician is concerned with the individual patient, not a class of patients sharing some characteristics, and might reasonably hope that more sophisticated diagnostic methods will lead to a better understanding of the needs of the individual patient. If this is to come about it will be necessary to have a much clearer view as to what causes the various kinds of fractures in the first place. Is it fatigue, or impact (or both)? Is it the loading in bending, or is it longitudinal (or both)? Does the differential mode of loss of material from cancellous bone in men and women have any differential effect on strength? In the consideration of individual patients, the ability to obtain a decent measure of bone quality will be increasingly needed. Does the measure of the amount of bone mineral in this volume of bone refer to uniform material, or are there small regions of crack-inducing hypermineralization present? Is the collagen in the bone of this patient more or less degraded than in those of people of a similar age? There is no doubt that sophistication will bring a new set of headaches.

Acknowledgments. I thank Claus Glueer for inviting me to speak at the bone densitometric meeting at Warnemünde, which provided the stimulus for this paper. I thank a referee for helpful suggestions.

References

1. Reilly DT, Burstein AH (1975) The elastic and ultimate properties of compact bone tissue. J Biomech 8:393–405
2. Borden IV S (1974) Traumatic bowing of the forearm in children. J Bone Joint Surg 56A:611–616
3. Currey JD (1999) What determines the bending strength of compact bone? J Exp Biol 202:2495–2503

4. Hodgskinson R, Currey JD (1993) Separate effects of osteoporosis and density on the strength and stiffness of human cancellous bone. Clin Biomech 8:262–268
5. Currey JD, Butler G (1975) The mechanical properties of bone tissue in children. J Bone Joint Surg 57A:810–814
6. Sørensen MS, Bretlau P, Jørgensen MB (1992) Fatigue microdamage in perilabyrinthine bone. Acta Otolaryngol (Stockholm) (suppl) 496:20–27
7. Reilly GC, Currey JD (2000) The effects of damage and microcracking on the impact strength of bone. J Biomech 33:337–343
8. Riggs CM, Whitehouse GH, Boyde A (1999) Pathology of the distal condyles of the third metacarpal and third metatarsal bones of the horse. Equine Vet J 31:140–148
9. Smith RW, Walker RR (1964) Femoral expansion in aging women: implications for osteoporosis and fractures. Science 145:156–157
10. Stein MS, Thomas CDL, Feik SA, Wark JD, Clements JG (1998) Bone size and mechanics at the femoral diaphysis across age and sex. J Biomech 31:1101–1110
11. McCubbrey DA, Cody DD, Peterson EL, Kuhn JL, Flynn MJ, Goldstein SA (1995) Static and fatigue failure properties of thoracic and lumbar vertebral bodies and their relationship to regional density. J Biomech 28:891–899
12. Horsman A, Currey JD (1983) Estimation of mechanical properties of the distal radius from bone mineral content and cortical width. Clin Orthop Rel Res 176:298–304
13. Zioupos P (1998) Recent developments in the study of solid biomaterials and bone: ‘fracture’ and ‘pre-fracture’ toughness. Mat Sci Engng C 6:33–40