What We Can’t Learn From Nature

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Abstract

When attempting to design bio-inspired materials and structures, it is important to remember that Nature employs some strategies for optimising the use of load-bearing materials which we, as engineers, cannot replicate. A material in a biological structure, such as a bone or plant stem, experiences stresses which are higher than would be allowed in an engineering structure, even if we were using exactly the same material. There are several reasons for this: biological materials are subject to continuous inspection and repair; they are constructed in more optimal ways, especially in respect to fibre orientations, and they are allowed to operate at higher failure rates. In the present paper I discuss four particular examples of Nature’s strategies and, in each case, I try to quantify their effect for the case of cortical bone. The overall conclusion is that, thanks to these four little tricks, Nature is able to operate bone at a stress which is about 17 times greater than the stress at which it could be used in an engineering component. Considering how a typical bone is loaded, this implies an increase in weight of about a factor of 10.

Introduction: Nature’s Little Tricks

There is no doubt that we can learn much from Nature when trying to develop new materials with superior physical and mechanical properties. Nature, through the long process of evolution, has developed many interesting strategies in order to create materials and structures for load-bearing purposes. However, the experience of those working in biomimetics is that it’s not possible to create a new engineering material simply by making a direct copy of a biological material. In most cases the complex microstructures of these materials prevent us from reproducing them exactly, and any attempts to make, for example, artificial bone using the natural ingredients of hydroxyapatite and collagen, lead to a material with greatly inferior mechanical properties. But there is no doubt that we can learn some useful strategies which we can apply to our own materials.

However, it is important to realise that not all of Nature’s strategies are suitable for incorporation into engineering solutions. In this paper I will discuss four aspects of biological materials which I will call Nature’s “tricks”. These tricks enable biological materials to be used at much higher stresses and for much longer periods of time, but they cannot, at least at the present time, be used by engineering designers, either because we don’t have the technology, or because the result would be unacceptable from the point of view of safety or
cost. The tricks I will describe appear in many different biological materials, in a wide range of animals and plants, however in this article I will focus on bone as the main example. The important consequence here is that, by using these tricks, Nature can operate materials at higher applied stresses, thus allowing the use of thinner, lighter structural members. I have tried to make a quantitative estimate of this effect in terms of the increase in operating stress, and the decrease in component weight, which each trick confers, for the case of cortical bone.

**Trick 1: High Failure Probabilities**

Living materials operate at much higher failure rates than engineering materials. Survival strategies for many organisms are based on sacrificing large numbers of individuals in order to ensure that genes are passed on to the next generation and that therefore the species as a whole survives. Structural units such as bones require a high cost in terms of energy to produce and maintain. They are also heavy and so require energy for movement. Therefore it makes sense to optimise performance by using a lighter, thinner bone and accept the resulting increase in failure rate. Evidence from primates in the wild (quoted by Currey [1]) suggests a failure rate of the order of 1-3% per bone over an individual’s lifetime. Engineering components are generally designed to much lower failure probabilities. The acceptable value depends on many factors, such as the importance of the component and the consequences of its failure, and in many cases the accurate estimation of a failure probability is difficult as it depends on many aspects of the material properties and loading which may not be precisely known. A typical value for an acceptable failure probability, for an individual load-bearing component whose failure would be critical to the whole structure, would be $10^{-6}$, i.e. a one-in-a-million chance of failing during the expected lifetime of the structure.

We can estimate the difference in stress level for these two different failure probabilities by drawing on some of my previous work [2; 3] in which I showed that, as regards high cycle fatigue, bone conforms to the well known two-parameter Weibull probability distribution, in which the exponent in the Weibull equation, $n$, is equal to 8:

$$P_f = 1 - e^{-\left(\frac{\sigma}{\sigma_n}\right)^n}$$

We can rearrange this equation to estimate the ratio of stresses $\sigma_1$ and $\sigma_2$ corresponding to failure probabilities $P_{f1}$ and $P_{f2}$ thus:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{\ln(1-P_{f1})}{\ln(1-P_{f2})}\right)^{1/n}$$

Comparing Nature’s $P_f$ value of 0.01 with an engineering value of $10^{-6}$ gives a ratio of stresses equal to 3.2. Fig.1 shows values of this ratio for various different values of the engineering $P_f$. This analysis is simplified by assuming a constant applied stress; to get a better estimate one should also model the stress using a distribution function, and find where the two functions intersect. This would allow one to model the stress history of the bone, including occasional accidents such as falling out of trees, as well as high-cycle fatigue failures after lots of running. However it is known that the maximum strains which bones are subjected to are pretty constant from one species to another, so the above simple analysis is sufficient to give us a feeling for the advantage which Nature gains by allowing failure rates which for us would be quite unacceptable.
Trick 2: Pain

Pain is not pleasant, but it’s very useful, because it tells us that some damage has occurred and acts as a strong encouragement to cease using a particular body part until it has healed. The equivalent of pain in engineering terms is an inspection procedure to detect damage – for example a fatigue crack – before complete failure of the structure. The difference between biological structures and engineering structures is that Nature is inspecting continuously, whilst we can only inspect a car or an aircraft periodically.

In order to estimate the magnitude of this effect for bone, I used data on fatigue crack growth summarised in a recent paper by Kruzic et al [4]. Pain occurs in a bone as a result of a fatigue crack approximately 1mm long. If one were to continue using that bone (which for most of us would be impossibly painful) then failure would occur when the crack reached a length of about 4mm. Cracks above 1mm long in bone behave as classic long cracks in fatigue so we can use the Paris equation:

\[
\frac{da}{dN} = C\Delta K^m
\]

For bone the exponent m has a value of about 4.5. Integrating this equation we can find the time needed to grow the crack from the length at onset of pain (1mm) to the failure length (4mm). This depends strongly on the activity level of the person concerned. I used standard activity levels taken from Whalen et al [5] who defined six different activity levels as follows: Sedentary; Sedentary with Exercise; Normal; Active; Active with Exercise, and; Athletic. Each activity level was described in terms of the time spent per day in performing various load-bearing actions (slow walking, fast walking, running etc) and for each of these actions the applied force (relative to single-leg stance) was given. A number of studies using strain gauges attached directly to bones have shown that the strains during strenuous activities (e.g. fast running) are similar for many species in the range 2000-3000 με. From this information we can calculate the stress intensity range for a given crack and thus apply equation 3. Figure 2a shows the results: for someone with a normal activity level it turns out that failure would occur in only 2 days. If we assume that, like many engineering structures, the bone can only be inspected annually, then we need to reduce this failure time to more than one year. Figure 2b shows the results of calculations to estimate the factor by which stress would have to be reduced in order to prevent failure occurring before the next inspection period. For a normal or active person the reduction factor required is about 3.5.

Trick 3: Continuous Repair

Another trick which Nature uses – somewhat related to the previous one – is the ability to repair small amounts of damage continuously. There is a large body of research (see [6] for a summary) to show that microcracks of the order of 0.1mm long in bone can be detected by cells located inside the bone (osteocytes), which initiate a complex repair process involving removal and replacement of the damaged region. With current technology we cannot detect such small cracks in engineering components using non-destruction inspection equipment, nor are we able to monitor the material continuously. In my laboratory we have done some work to try to understand the mechanisms involved in the damage/repair process, which has a complex dynamic. We still don’t completely understand the mechanisms – for example we don’t know how osteocytes can detect cracks, though there are a number of theories on the matter – however we are able to model the various processes phenomenologically with
reasonable accuracy, because there is quite a lot of experimental data available. Central to our approach is the finding that cracking and stress-fracture at *in-vivo* stress levels is a high-cycle fatigue phenomenon (unlike failure at higher stresses which is dominated by creep) and that it can be described by a Weibull equation (see above). To include the effect of repair in this model we described the repair time as a second Weibull distribution, allowing us to predict the probability of failure *in vivo* as a function of time and activity level [7; 8]. This work has been useful in predicting the effect of exercise regimes as used by the military, for example, on the incidence of stress fractures.

I reanalysed these results, calculating failure probabilities for the various activity levels of Whalen *et al*, both with and without repair. Given the finding reported above that a bone has a 1% failure rate over a lifetime for individuals in the wild, I calculated the time required to achieve this failure rate if there was no repair happening. As figure 3a shows, this depends strongly on activity level but is of the order of one month for normal or active people. I then calculated the reduction in stress that would be needed to increase this time to a full lifetime (25 years); the appropriate stress factors are shown in figure 3b. For the worst case of a very active individual – such as a professional athlete – the stress reduction factor turns out to be 3.5.

**Trick 4: Tailored Microstructures**

One aspect of biological materials which has received much attention is their ability to vary their microstructure from place to place. Key aspects of this variability are changes in composition (for example levels of mineralization) and changes in fibre orientation. There are some aspects of this trick which we can already reproduce in engineering materials. For example we can make laminated structures in which the fibre orientation changes from layer to layer, thus creating a sheet of material which has the desired stiffness and strength in prescribed loading directions; the whole lamination process also increases toughness. These two-dimensional fibre structures are also found very extensively in nature, for example in insect cuticle and sea shells. We are also beginning to be able to reproduce another aspect of natural materials – the ability to vary composition from place to place, forming functionally graded microstructures. An extensive discussion of these and other aspects of biological structures can be found in Vincent’s excellent book [9]. These two types of microstructural organisation form one of the most active areas for the development of bio-inspired materials at the moment.

However, it seems to me that there are some types of structural organisation which we are a long way from being able to imitate. I refer in particular to Nature’s ability to make fibre composite materials in which fibres are oriented in three dimensions (as opposed to the two dimensions common in engineering materials) and in which the fibre concentration and orientation also changes from place to place.

A good example of this is the joint made where the branch of a tree attaches to the trunk. Both trunk and branch are highly anisotropic structures; most of their fibres are aligned close to the axial direction, to resist tensile and compressive stresses due to self-weight and wind loading. The material in the branch has considerably lower stiffness than that in the trunk. Where the two meet, fibres from the branch continue into the trunk, curving around to adopt the near-vertical orientation of trunk fibres. Likewise fibres in the trunk adjust their orientations where they pass close to the branch junction. The net result is a gradual transition in fibre orientation as one moves through the joint. This is a relatively simple thing to
envisage in two dimensions, but introducing the third dimension (and remembering that the branch has a smaller diameter than the trunk) the fibre patterns get quite complex. With our current technology, we cannot achieve this kind of fibre arrangement in, say, a carbon fibre epoxy composite, at least not at any reasonable cost. For the tree, the use of this structure, combined with careful control of local geometry to reduce notch effects, is able to remove any potential weakness at the joint region. An interesting study was carried out by Muller et al [10] in which they compared the strain distribution in an actual branch-trunk joint with the strain distribution in a model which was geometrically identical but made from an isotropic material. The results are not easy to interpret, but they certainly showed that the natural joint achieved a lower stress concentration factor.

A similar situation arises where a tendon attaches to a bone; fibres from the tendon insert into the bone, and hydroxyapatite crystals in the bone nearby are oriented to align with local stresses due to the muscle forces acting through the tendon [11]. In addition the collagen of the tendon is gradually mineralised as it approaches the bone, to avoid any sudden change in stiffness that would cause stress concentration at the interface.

It is difficult to estimate the advantage, in terms of increased strength, which this particular trick confers, as clearly it will vary considerably from case to case, being dependant on the local geometry as well are material properties. A reasonable upper limit to the estimate would be the anisotropy factor of the material, defined as the ratio of the strength in the best direction to the strength in the worst direction. For cortical bone this factor is about 2.5 [12]; for some other materials, including wood, at can be as high as 5 or 10. This would be an estimate of the reduced strength that would have occurred if the joint had been made in a simple way, with the branch attached to the surface of the trunk, for example, so that tensile and compressive forces in the branch would act perpendicular to fibres in the trunk, thus loading them in their weakest direction. This however is very much an upper bound value; for the case of bone I think a more realistic estimate of the likely improvement that this trick confers is about half of the maximum value, so I suggest a stress factor of 1.5 in this case.

**All Four Tricks Combined**

What is the total advantage due to all four of these tricks working together? Of course any attempt to make this calculation should be treated with caution because in each case I have made only an approximate estimate. Two of the above tricks – pain and repair – will both be compensated for by the same reduction in stress, since they relate to effects of the same type but operating at different size scales. Looking at figs 2 and 3, we can see that the factor due to repair is always less than the factor due to pain, for any given activity level. So both tricks will be accounted for if we use the pain factor, which for individuals with typical activity levels is 3.5.

The other two tricks – tailored microstructure and high failure rates - operate independently of the pain/repair trick and independently of each other, so the total effect can be estimated by multiplying three factors together, giving $3.5 \times 3.2 \times 1.5 = 16.7$.

This is a very big factor; it means that even if we could make a material which had exactly the same chemical composition and microstructure as bone, we could not actually use it to replace a bone in the human body. In order to do so we would have to increase the bone’s cross section so as to reduce the applied stress by a factor of 16.7. Given that a typical bone experiences a mixture of compression and bending loading, this means that the cross section
would need to be increased by about a factor of 10. This would have the knock-on effect of increasing total body weight, which would add some more to the applied stress, and would greatly increase the energy needed to move a limb. The human body would effectively become impossible.

**Discussion**

Nature employs many strategies to allow it to maximise the use of materials for structural purposes. There are big differences between Nature’s approach and our own engineering approach. For one thing, Nature has different purposes – this has been demonstrated especially in the above paper with regard to failure rates. Nature can make a tree as big as a house, but the design specifications for a tree and a house are totally different. On the materials side, it’s worth remembering that Nature constructs load-bearing elements from very poor quality materials – materials such as collagen, hydroxyapatite, chitin and calcite which have mechanical properties greatly inferior to modern engineering materials such as steel, carbon fibre, high-strength concrete and epoxy. We can learn a lot by examining the various strategies which Nature uses, but we have to remember that not all of these approaches can be translated directly into engineering design and material development. In some cases this is because we don’t have the technology at present to copy Nature; in other cases it’s because the result of adopting Nature’s approach would be unacceptable in terms of cost or risk.

**Conclusions**

1) By adopting a higher failure rate, Nature can make thinner, lighter structures. Thus the stresses experienced *in vivo* can be much higher than those that would be allowed for the same material in an engineering structure. For the case of bone this stress factor is about 3.2.

2) By using pain to alert the individual to sub-critical damage, complete failure can be avoided. In order to have the same amount of protection whilst using annual inspections (as in engineering) rather than continuous monitoring *in vivo*, stress has to be reduced. For bone the reduction factor is about 3.5.

3) Nature also gains an advantage by continuously detecting and repairing microscopic fatigue damage. The estimated stress reduction factor in this case is slightly less than that for pain, and the same stress reduction will solve both problems.

4) The use of three-dimensional fibre arrangements in structures such as junctions (e.g. branch/trunk or tendon/bone) avoids creating weaknesses by the non-optimal use of fibre composite material. For the case of bone the stress reduction factor is estimated to be 1.5.

5) Combining all the above factors gives an overall stress factor of about 17, with a consequent increase in bone weight by a factor of 10. Thus these four tricks, which currently cannot be copied in bio-inspired materials, give Nature a very considerable advantage.

**References**


Figure Captions

Figure 1: Estimates for bone, showing the stress factor, defined as the factor by which the applied stress would have to be reduced, in order to reduce the failure probability from 0.01 to the required failure probability shown. For engineering components a probability of $10^{-6}$ is commonly used, resulting in a stress factor of 3.2.

Figure 2: (a) The time to failure, defined as the time taken for a fatigue crack to grow from the size at which pain occurs (1mm) to final failure, as a function of activity level as defined by Whalen et al [5]. (b) The corresponding stress factor, assuming an engineering inspection rate of once per year.

Figure 3: (a) The time to failure, defined as the time by which 1% of bones would have failed, assuming no repair of microcracks, as a function of activity level. (b) The corresponding stress factor, assuming this failure time is increased to 25 years.
FIG. 1

Stress Factor

Required Probability of Failure

1.0E-06 1.0E-05 1.0E-04 1.0E-03 1.0E-02

0 1 2 3 4
FIG. 2

(a) Time to Failure (Days)

(b) Stress Factor

Activity Level

Athletic  Act+Ex  Active  Normal  Sed+Ex  Sedentary
FIG. 3

(a) Time to 1% Failure Probability

(b) Stress Factor