

Chapter 1

Strong Materials

Basic Materials Principles

Why This Chapter is Important

Most people have a general understanding of what they mean when they say that an object is "strong" or "stiff" or "tough." They know that materials have different characteristics and that steel is intrinsically "different" from nylon. This book will discuss the nature of the class of "strong" materials called composites, but, to do this usefully, it will be necessary to use the precise language of the materials engineer. ***This chapter is a very short "crash course" in the essentials of materials science.*** The principles apply to any strong material, but will be particularly important when discussing the special nature of composites.

In this chapter, we will briefly discuss the elementary principles that explain how strong materials work, how they differ, and why we have strong materials at all. In later chapters, we will look at how forces exist in practical structures. ***No algebra will be necessary.***

Intuition About Strong Materials

We can't get through life if we don't have some intuitive ideas about the strength of materials. We don't cross a stream on a log if the log looks rotten, but we may cross the same stream on a smaller log if the log looks fresh and green. We know about how strong a shoelace is. Children eventually learn how not to break everything they touch. We buy rope for an application in a size that seems to be "about right" in our experience, knowing that steel cable is "stronger" than cotton rope and that nylon is somewhere in between. We know about how thick a wooden shelf should be. We put strapping tape on a package so that it seems safe, but ***we do not engineer these daily decisions.***

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As pilots and airplane builders, we probably have a better intuitive feel for materials than the general population, based partly on actual experience with a variety of aircraft materials. The FAA allows us to make simple repairs on certificated aircraft, generally following handbooks of standard practice (some very old) for the material and structure in question. Pilots are usually a conservative lot (not a bad thing for drivers of flying machines!) and they tend to stick to the familiar. A pilot trained in a *J-3 Cub* or a *Citabria*, may choose to build a tube and fabric aircraft (with its many, many pieces). If the pilot was trained in a *Cessna 152* or owns a *Bonanza*, she may elect to build an aluminum plane. Some just like wood. The author regularly visits with active builders at neighboring airports and is surprised at how many have never considered a composite project. If asked why not, the answer is usually something very general like “Well, I never was really comfortable with ‘plastic’, besides my plastic garbage can has a crack in it, so I don’t want to use that stuff in my airplane.”

The new combinations of high performance materials we call **composites** are generally outside the experience of most pilots and many designers. These materials are very different from wood, steel, and aluminum. Often, the designs and construction techniques are radically different from familiar practice. It is only to be expected that a pilot would be cautious.

Action and Reaction

When undergraduate engineers take a course in “Statics”, they learn that if an object is stationary, it must be because all the forces on that object balance, or **add to zero**. For example, we can hang a simple hardware store spring scale from a tree, put a one pound fish on it, and observe that the scale pointer moves one inch and stops. The weight of the fish is balanced by the reaction force of the deflected spring. A parked airplane may press on the pavement with a weight of 1,500 pounds applied through the three wheels. All the component weights, including the engine, wing structure, battery, fuel tanks, and whatever, are brought through the structure in a complex way, but they must add up to the 1,500 total pounds measured at the wheels. But the airplane does not move, so the pavement must press up at each of the three wheels exactly enough to balance the total load.

What actually happens is that the concrete under the tires deflects a tiny bit, exactly as the spring scale does, so that the necessary opposite force is generated. Concrete pavement has the useful property of being very stiff (defined below), so that we do not *see* this tiny deflection. If we put three precision spring scales under the wheels (as we would do for a center of gravity measurement) then the parked plane would find a new rest position, and we would read the required deflection on the three scales. *The point is that every solid material, even diamond, must deflect under load and must produce a reaction force against that load.*

Forces in a Solid

In any solid, the atoms are held in a rigid position by the electrical forces between them. Atomic forces are the basis for chemical reactions between atoms and we need not distinguish between “chemical” and “electrical” bonds. The useful strength of the bonds varies widely from one solid material to another. When a load is placed on a solid, the solid must deflect just enough to develop an equal counter force. The only movement in the system must be the bonds between the atoms. Therefore, the stiffness of a material is determined by the strength of these bonds.

A very simple way to think of the nature of a solid is as an array of tiny solid balls, each ball connected to its neighbors by springs. (A coil spring mattress would be a good analogy.)

Under compression, the interatomic springs between the layers move together, as when a person sits down on a mattress, and a net upward force is produced which is equal and opposite to the force applied. Similarly, under tension, the springs are stretched and a resisting force is generated in the opposite direction.

These tiny atomic deflections in the body of a solid have been confirmed by actual experiments. If a single-crystal specimen is stretched in a testing machine by a small percentage, the atomic spacing will be found to vary in exactly the same percentage.

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Stress and Strain

The words “stress” and “strain” have been grossly misused in ordinary conversation to mean many things other than the accurate meaning intended by materials scientists. For a materials scientist, **stress** only means the load applied to a given area divided by some measure of that area, or **load per unit area**. A 20-pound box placed on a surface with an area of 10 square inches will place a **stress** of 2 pounds per square inch on the surface. **No statement is made about how far the surface will deflect under that 2-pound stress.**

Example: Stress in a Practical Bolt

*We see from an aircraft supply catalog that an “AN” aircraft bolt family made from 8740 alloy steel is rated at 125,000 pounds per square inch. This is a **statement of allowed stress** in tension **before** safety factors are applied. The AN3 bolt from this family is 3/16 inch in diameter and so has an **area** of 0.0276 in², so it is rated to carry 3,451 pounds. The corresponding AN8 is a 1/2 inch diameter bolt so has an area of 0.196 in², so will take 24,500 pounds. The **loads** are different, but the **stress** is the **same**. The two examples look the same to the iron atoms inside the bolts because the atomic deflections necessary to carry the load are the same. The designer must provide a sufficiently large bolt to carry the required load at the allowed maximum **stress**.*

Strain

Strain is defined by materials scientists as the **deformation** per unit length **resulting** from a stress, so:

If we had a very long bolt, say 100 inches long, and loaded it so that it stretched (deformed) 1/2 inch to 100.5 inches, the **strain** would be .5/100, or 0.005, or 0.5%. Strain is always just a fraction or ratio, so has no unit dimensions. **Again: No statement is made about the magnitude of the force (or stress) that caused that strain.**

*Stress and strain are expressions of how the atoms of a structure are deformed by a load and are independent of the size and shape of the structure. Stress and strain are characteristics of the **material**, **not** the structure.*

Hooke's Law

It may seem obvious, after going through the above argument, that twice the deformation of a body should produce twice the reaction force, but it wasn't obvious for a very long time. People didn't understand that ordinary bodies had to deform to react to a load. Robert Hooke (1639-1713) was the English physicist who studied springs in clocks and first stated that the reaction force of a spring was proportional to the force on the spring. This simple statement is known now as **Hooke's law**.

In practical engineering materials, Hooke's law is valid for **elastic** solids. An elastic solid is one which returns to its original shape when a load is removed. Rubber, glass, steel, and diamond are elastic. (Grease, in contrast, is an **inelastic** solid.)

Ordinary elastic materials obey Hooke's Law up to the load where the specimen breaks or the material permanently deforms.

Actually, Hooke's Law is only an approximation valid for the small deformations we would allow in safe engineering design. Experiments with very strong silicon "whiskers" (more about whiskers later) show that the interatomic force diminishes for very large strains which we do not achieve in practice. (The specimen breaks first.)

Stiffness - "E"

Engineers who followed Hooke didn't seem entirely clear on the difference between elasticity as an intrinsic property of a material and as a property of the shape and dimensions of the particular object they were deforming.

Thomas Young (1773-1829) understood (in 1807) that it was important to characterize the intrinsic "stiffness" of a material independent of its application. He found that, for useful materials, the **strain resulting from an applied stress was a constant**. He defined that constant to be the **stiffness** and this characteristic is recorded in engineering handbooks under the symbol "**E**," or **Young's modulus**.

Strain is just a ratio, a plain number, so Young's modulus has the **same dimensions as a stress**, or force per unit area. Numerically, it is the stress which produces 100% strain, so E is typically a rather large num-

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ber, which does not represent a practical stress. (Rubber can stand 100% strain, but steel can't!)

Values of E for some typical materials are shown below.

Young's Modulus for Typical Materials

Material	Young's Modulus (E) (1,000s of psi)
Rubber	1
Cheap bottle "plastic"	200
Composite matrix resins (typical)	800
Nylon fiber	800
Bamboo lignin (the matrix)	1,000
Wood (approx., spruce)	2,000
Plaster of Paris	2,000
Concrete	2,500
Bamboo fiber	4,000
Bone	6,000
Magnesium metal	6,000
Portland cement	10,000
Ordinary glasses (beer)	10,000
Aluminum (2024T3)	10,600
Kevlar 49 fiber	19,000
Steel	30,000
Carbon (graphite) fiber	34,000
Aluminum oxide (sapphire)	60,000
Diamond	170,000

Note that Hooke's Law, and therefore Young's Modulus, applies equally for both tension and compression. Remember that the ideal model is simply that of pulling or pushing on the interatomic bond "springs". Some practical materials, like concrete and cast iron, contain internal flaws which open up with tension loads and propagate cracks, so these materials will fail sooner in tension than in compression. (But we hardly ever use concrete or cast iron in our aircraft designs.)

Strength

Numerically, **strength** is the measured **stress** required to **break a structure**. Strength may be measured for either the tension or compression case, but is usually quoted for tension. (Concrete, of course, is an exception because concrete is generally assumed to have zero tensile strength.)

Strength makes no statement about stiffness [Young's modulus (E)]. Porcelain is very stiff (high E), but it breaks at a very small strain, so we say that it has low strength. Nylon is flexible (low E), but is very strong (high breaking stress).

Some typical tensile strengths for common and aircraft materials are given below, in thousands of pounds per square inch. These figures came from different sources, for tests under different conditions, and can only be used as a rough guide, still there are probably some surprises here!

Material	Breaking Strength 1,000s psi stress
Iron & Steels:	
Cast iron	10-40
Hardware store mild	60
Automotive sheet (high)	200-300
Piano wire (brittle)	450
Other Metals:	
Aluminum, cast (pure)	10
Magnesium alloys	30-40
Aluminum (alloys)	20-80
Titanium alloys	100-200

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Non-metals:	
Wood, spruce, across grain	0.5
Wood, spruce, along grain	15
Glass, (beer, window)	5-25
Porcelain, good quality electrical	50
Fibers (Isolated - not in laminate):	
Hemp rope	12
Spider web	35
Silk	50
Cotton	50
Flax	100
Fiberglass (E-glass)	500
Kevlar 49	700

Thus, Strength is an expression of breaking stress, not the total load required to break a structure.

Strength and Structure:

Our simple model of a solid consisting of tiny atomic balls held together by electrical “springs” is generally satisfactory only for very small deflections. Practical materials of practical size actually fail for other reasons long before the interatomic bonds are broken. Practical materials are usually complex and have a structure which affects the measured strength.

A *composite* material is a combination of a strong material (usually as a fiber) imbedded in a weaker or less-stiff matrix. The combination produces a new material with properties which can greatly outperform the properties of either component alone.

Concrete and Wood As Structures

Concrete actually meets our definition of a *composite* material, so when we test a specimen of concrete, we test a complex structure consisting of a mixture of cement, sand, and granite pebbles, which work together to carry the load. In architecture, designers have been able to do great

things while always keeping the materials in compression. Roman arches, domes of great churches, and buttressed cathedrals are all examples of successful designs which use materials only in compression.

Wood is primarily a complex *structure* of cellulose. Under a microscope, wood is seen to consist of an array of tubular closed cells surrounding empty space. Depending on the state of seasoning, the spaces may contain some free water. The table of strengths above shows radically different figures for wood for strength tests along and across the grain. See from the table that cotton (which is essentially pure cellulose fibers) tests in tension very much stronger than practical wood and approaches the strength figure for mild steel. Wood, therefore, as a *structure* of cellulose, does not achieve the tensile strength of *pure* cellulose. As we shall see, wood is a surprisingly efficient material, due to its combination of low density, stiffness, and toughness. It is subject to detrimental effects such as rot and swelling, however.

Theoretical Strength

For a very long time, engineers have wondered why is steel “stronger” than copper, why it is that diamond is so hard and rubber so soft, or why don’t all solid materials have the same strength - or none? So far in this discussion, we have used the model of the tiny atomic balls attached to each other with springs. It would be nice if that model could be checked for validity.

Materials scientists have tried to measure the strength of the bond between layers of atoms by actual experiment, essentially pulling on a brittle specimen, and measuring the force and elongation at fracture. Knowing the spacing between atoms, the force to break the “springs” could be calculated.

Based on the simple “spring” model, scientists have tried to calculate the stress that would just separate two adjacent layers of atoms, which would presumably be the stress at failure for a given material. It is interesting to note that the *theoretical* breaking *strain* for a very wide range of materials is about 10-20%, which, of course, very few practical materials actually achieve. The breaking strength, then, should be about one tenth to one fifth of the Young’s modulus, and we don’t achieve a test figure this high in real life.

Griffith's Model Material: Glass Fibers

So things aren't nearly as strong as they "ought" to be! Why not?

Shortly after World War I, at the Royal Aircraft Establishment at Farnborough, A. A. Griffith, a materials scientist, tried to answer this basic question. The most obvious experimental material might have been steel, but steel is actually a complex structure of different interlocking crystals and uncertain crystal boundary states. Ductile steel usually fails by having crystals *slide* past each other, rather than by breaking the fundamental atomic bonds. Griffith wanted to study a model material which had a simple *brittle* failure.

He chose common glass.

Using the simple "atom ball and spring" model, and the measured Young's Modulus, Griffith predicted that the strength of common glass should be close to 2 million psi at room temperature. Actual glass rods of about one millimeter thickness broke at 25,000 psi - quite a bit short!

He then heated the test rods and drew them down to smaller fibers, then continued the tests. At two thousandths of an inch, he tested near 50,000 psi. At one thousandth, over 100,000 psi. At half a thousandth, nearly 250,000 psi. At around a ten-thousandth, he got 500,000 psi. Extrapolating to a fiber of zero thickness gives an ultimate strength of 1,600,000 psi, close enough to the prediction, considering the rough model!

We conclude that the "atom ball and spring" model isn't too bad when we are just stressing a tiny area of not too many atoms at a time. In the real world, where we must use lots of atoms at a time, other factors make the specimen fail.

Why Things Break

Suppose we could make a perfect "large" crystal of a test solid, in which the "atom ball and spring" model applied exactly. The surface of this ideal specimen would be perfectly smooth with all the atoms lined up perfectly in layers. If we test this beautiful piece, Griffith's work suggests that we should see the true strength of the interatomic bond, even in a "large" specimen. For this idealization, we have all of the atomic

bonds across the entire piece bearing their fair and equal share of the load, until they all fail at once.

Suppose we test this ideal crystal and strain it until we find just the stress that causes failure, i.e., just separates the atomic layers.

Now, let's repeat the test, but assume that our perfect specimen has a tiny scratch or flaw on the side, one atomic layer wide and several atoms deep. The atom layers on either side of the scratch are no longer attached to their neighbors. As the test stress is applied, the first **attached** bond must receive the added stress that **would** have gone to several neighboring **unattached** bonds. The bond fails. Now the next bond in line has even more stress. It fails, too. A **tear** then propagates across the entire specimen, started by the surface flaw. This is **brittle failure**, caused by a **stress concentration**, and happens to be the chief failure mode of glass for large practical specimens.

This is illustrated by the trick where a macho man tears a telephone book in half. The trick is to push the pages in from the side to make an arch of bent pages. Tear from the bottom and the "strong" man needs to break only one page at a time at the stress concentration!

We can extend our ideal thought experiment to another less obvious real life case: Suppose our perfect crystal does not have a scratch extending into the body of the crystal, but, instead, has a **step**. A **step is any sharp discontinuity of thickness**, where the specimen abruptly goes from one uniform thickness to another.

If we load a specimen which has a step, the thicker section (larger area) must have less stress than the thinner section (less area), because the **load** is the same. Now see that the stress at the outer edge of the thick section **must turn at the step and add to the stress** already carried by the very first atomic layer **at** the step. Like with the scratch, this first atomic bond will fail at the **stress concentration** and the brittle tear propagates in the same way as with a crack. **The specimen fails where it is assumed to be "stronger!"**

Fracture Mechanisms

Materials break by one of two mechanisms, and which happens first depends on the material:

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- 1) **Brittle cracking**, by propagation of a tear crack, as we have just discussed, and
- 2) **Plastic flow**, where atomic layers slide past each other and reconnect when the strain displacement ends.

We say that a material is **brittle** if it fails first by cracking. (Bulk glass and porcelain are brittle.)

We say that a material is **ductile** if it fails first by plastic flow. Gold is extremely ductile. Copper is very ductile, but less so than gold. Ductility is generally associated with metals, and is very useful because we use that property when we draw copper wire, stamp steel automobile fenders, or hydroform a curved airplane engine nacelle from aluminum.

For the particular case of glass, which is going to be very important to our discussion, the chief limitation to the useful strength of bulk glass (beer bottles, windows) is tearing failure from surface flaws that are impossible to avoid. By going to thin glass FIBERS to reinforce a composite, we avoid the consequences of brittle failure and force the failure to occur by plastic flow at a much higher stress.

Note that permanent deformation by plastic flow is still a service failure of a part, even if the deformed part has not actually separated into pieces. **(If it is bent too far to serve its designed function, the part has failed.)**

We have such an easy familiarity with ductile steel in our lives, that we have a somewhat permissive attitude toward incidents of catastrophic failure in steel structures. To a degree, a failed ductile part, such as a propellor blade or landing gear strut, might be bent back to its original position and still serve safely, though this is almost never a safe procedure in aircraft service.

Whiskers - a Curiosity

It is possible to grow tiny pure crystals of many materials in the form of long smooth filaments, “whiskers”, thousands of times longer than their thickness. When tested, these tiny crystals usually turn out to be extremely strong. The surfaces of these grown crystals are generally quite smooth and free of cracks, and the interior is free of defects. Whisker crystals have been used as reinforcement in experimental compos-

ite materials to produce quite spectacular (but quite expensive) materials. The growth process does produce steps where the crystal build-up is not uniform. Whisker failure is found to occur at the stress concentration caused by these steps.

Toughness - or Resistance to Brittle Fracture

Considering our discussion this far, it seems a wonder that we can ever find a strong material. After all, we'll never be able to get perfect materials and we'll never avoid surface flaws, so why doesn't everything we own tear like Cellophane from the inevitable flaws? The answer is that practical "strong" materials are those that possess the quality of ***toughness***, or ***resistance to failure from propagation of cracks***. As aircraft mechanics, we drill "stop holes" at the end of obvious cracks in aluminum to limit that propagation. But there are plenty of other smaller flaws that are not obvious. To get toughness, we must stop cracks.

Work of Fracture

It is easy to ride a bicycle on a hard, dry pavement. It is very difficult to ride in deep mud. The difference is that considerably more energy must be expended to deform and fracture the mud than is required to just flex the tires a little and turn the bearings. This difference appears to the bicycle rider as resistance to her progress and to the materials scientist as increased ***work of fracture***.

Nature always takes the action that leads to a lower energy state, the "easy way out". When considering the flow of energy, "if it ***can*** happen, it ***will*** happen". This rule includes the propagation of cracks. If the energy of the system is reduced by propagating a crack, then a crack is what we'll have.

Griffith observed that there are two conditions for crack propagation:

- 1) The energy of the system is reduced by a crack, and
- 2) There must be a mechanism for the release of the energy.

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If these conditions are not met, there will be no crack propagation under load and we may say that the material is *tough*.

Strain Energy and Surface Energy

Let us apply Griffith's crack energy concept to a steel clock spring like those Mr. Hooke studied. Basically, a flat steel clock spring is a beam. When we wind it up, we are bending the beam the same way we do when we stand on the end of a diving board and make the board bend down.

As we apply force to a clock spring, or any other beam which follows Hooke's Law, the force required increases directly as the strain increases. Force times distance is defined as *work* and we get this work back if we let the spring unwind to drive the clock. But the *definition* of energy is the capacity for doing work: we store energy in a clock spring by deforming the little atomic springs in the volume of the material.

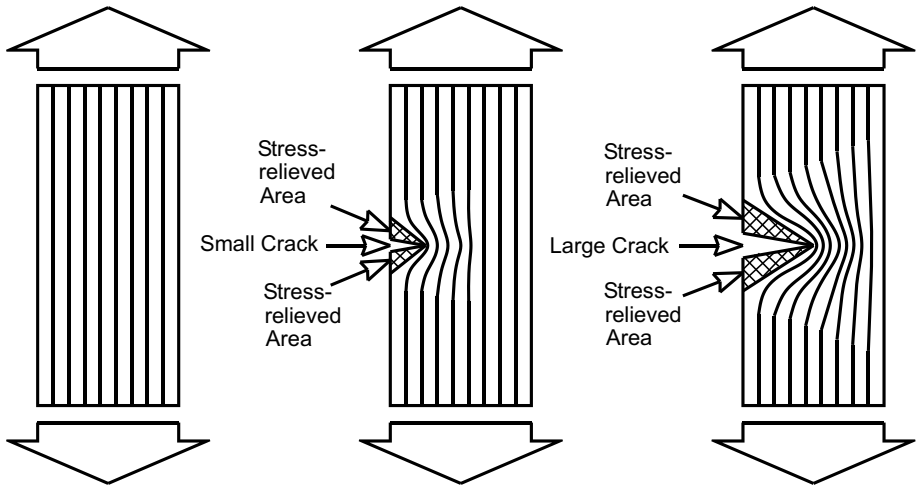
So why doesn't nature take the easy way out and propagate a crack from the first handy tiny flaw so that we can't have clock springs or airplanes?

The answer is that there is a competing energy state for the clock spring: *surface energy*. ***The crack will propagate if it takes less energy to make new surface area at the crack than is available in strain energy at the crack.***

The atoms *inside* a solid are happily attached in every direction to their neighbors. A surface is different; ***there are no neighbors on one side***. To form new surface, all of the broken atomic attachments of the atoms on each side of the new surface must be formed again with neighboring atoms or atoms dragged from the interior. This ***requires repositioning of surface atoms and takes energy***, which is associated with the new surface.

Suppose we have three tensile test specimens, all under stress, as shown on the facing page. The left hand specimen has no crack and the stress lines are evenly distributed. The middle specimen has a small crack and the right hand specimen has a large crack, so the stress lines are distributed as shown.

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In each case, the stress lines are concentrated in the vicinity of the crack. See that the material on each side of the crack is **no longer strained** (the crack has opened, relieving the strain), so there is no corresponding stress. The **strain energy formerly stored in the relieved volume of material is available to propagate the crack**. If the work required to make new surface is less than the strain energy released by the crack, Nature has her easy way out and the crack will grow to failure. This required work is the **work of fracture**, the same as illustrated by our example of riding a bicycle in the mud. If the work of fracture is too great, there will be no propagation.

Whether a crack propagates or not depends on the original size of the crack, as well as the qualities of the specimen. If the crack is very short, there is only a small volume of material which is relieved of strain, so there is only a small additional energy to contribute to the tear.

Consider the large crack on the right, in our sketch. Now the crack is twice as long, but the volume of material relieved of strain is **greater** than twice as much, approximately proportional to the **square** of the crack length. Eventually, this “square law” will catch up with us, when the strain energy will be enough to meet the work of fracture rule, and the tear will propagate. In the simple case, there will be a critical crack length, which is called the **critical Griffith length**. Below this limit, the crack is stable; above it, the specimen tears.

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Actual numbers for the critical Griffith length depend on the particular material and the application. We see, though, that ***for toughness in a material (large work of fracture) there is some mechanism where lots of energy is absorbed far from the fracture surface.*** Our bicycle-in-the-mud analogy illustrates this; the rider pedals hard to fracture the mud, but the actual fracturing takes place many inches from the pedals, due to the mechanism of the bicycle! Wood and steel are particularly good examples of tough materials because their failure mechanisms involve movement of cell walls or crystal boundaries over a large volume, far from where the load is applied. Give Nature too much work to do and she won't do it!

Strength and toughness are inherently mutually exclusive. Much of composite design is an attempt to find solutions to this compromise problem.