The present concern for the welfare of threatened species and other natural resources, evident among many nations of the world, coupled with the rapid degradation of our environment, with its potential toxic and climatic consequences, highlights the folly of ignoring revealed Divine wisdom.

God will not, of course, allow this process to reach an irreparable stage, but will intervene (Rev. 11:18). The solution to current environmental problems will only be realised when the Kingdom is established and creation is released to reveal its true potential. Then the deserts will blossom (Isa. 35:1), handfuls of corn will be harvested from previously barren wastes (Ps. 72:16), and men will dwell safely in their own farmsteads, each sitting under his own vine and his own fig tree (Mic. 4:4).

Composite materials—an example of Divine design

Peter Ormiston

IN ITS WIDEST sense a composite material is one which employs two or more materials, usually quite different in nature, to obtain special properties. These properties may be absent from the constituent materials, or may be unusable because of the form or shape in which those materials are available. For example, glass fibres are very strong and stiff, but can only be produced with these properties in the form of thin fibres. However, they can be used to reinforce a plastic such as polyester. The result is a bulk material that can be used for structural applications such as bridge-building or car construction. In such a material the plastic that surrounds and supports the fibres is referred to as the *matrix*.

However, the composite materials which man has devised pale into insignificance when compared with those which occur all around us in creation. These natural materials make up the living tissue of plants and animals, although perhaps we have not thought of these as being composites.

Even man-made composite materials are not new. Well over 3,000 years ago the Israelites were forced to reinforce mud (the matrix) with straw (the fibres) for Egyptian construction projects: "Ye shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves" (Ex. 5:7). The straw made the mud bricks stronger and more durable, by a process of crack deflection. As cracks are formed and propagate (travel and grow) through the mud they are diverted and often stopped by the many straw fibres. It is very unlikely that the Egyptians thought of this idea without any help; they would have observed the fibrous structures that occur in a multitude of plants. The combination of fibres and matrices can provide strength and stiffness, as in wood (and the straw-reinforced bricks), or strength and flexibility, as in tender twigs and plant fronds. The latter construction is copied, at least in part, in man-made textiles.

This copying or mimicking of structures and control processes from 'nature' has become thoroughly organised in recent times. A descriptive name, *biomimetics*, has been coined for the practice.[1] The word 'nature' is placed in single quotes because, sadly, it is often used not simply to describe the created world around us, but also to obscure the fact that such things are God-made rather than man-made. Man happily acknowledges that his own designs are the products of an intelligent mind, but abandons his logic when it is clear that the even more elegant designs which he copies result from a far greater intelligence, that of the Creator Himself.

It is the purpose of this article to consider briefly one area of the Creator's wonderful handiwork. Natural composite materials provide many examples of the intricate interplay of complex designs, which could not possibly have resulted from chance processes.

Properties of fibre composites

Composite materials, both natural and man-made, require certain properties in order to function effectively. In this article, most attention

1. See "Imitating nature's designs", *The Testimony*, Sept. 1998, p. 346.

Maximum relative strengths and stiffnesses for a number of materials
(taking steel as 10; for simplicity, technical units have been omitted)

Material	Relative strength	Relative stiffness (tension)	Relative stiffness (bending)
Steel	10	10	10
Aluminium	7	10	17
Timber	7	9	22
Keratin	11	-	-
Spider silk	47	-	-
Kevlar	70	-	-
Bone	2.5	4	12

will be paid to mechanical properties, which are needed for the material to meet its structural functions, although other properties will be mentioned briefly. The mechanical properties are:

1 **strength**, measured by taking the breaking load for similar-sized pieces;
2 **stiffness**, which is resistance to bending;
3 **toughness or impact strength**, which is a measure of how much energy a material can absorb before it breaks.

In order to compare materials such as wood (with a low density) and steel (with a high density) it is usual to refer to the *relative strength* and *stiffness*, calculated relative to the density of each material. Some of these relative values are presented in the table above, where it will be seen that natural materials such as wood compare very favourably with those produced synthetically, such as metals. In particular, keratin[2] is a little stronger than high strength steel, and spider silk is much stronger. In the created world, stiffness in bending is often more important than stiffness in tension (pulling). Thus bone compares well with iron and steel, and timber is superior to it. The work of the Divine Designer is very evident in bone and timber, but He is also the provider of the metals: "For the LORD thy God bringeth thee into a good land . . . whose stones are iron, and out of whose hills thou mayest dig brass" (Deut. 8:7-9).

Bone

The skeletal systems of plants and animals are built up by the development of fibres outside the cell walls. These have somehow to be manipulated into precise directions within the supporting tissues to provide the mechanical and optical properties required. In some materials (for example, beetle cuticle) the fibres have to be aligned at a particular angle to an axis (termed direction). "Without accurate control of fibre architecture many animals and plants would collapse".[3] A number of macromolecules are used, such as the polysaccharides, cellulose and chitin, and the proteins collagen and keratin.

Assembly involves the production of fibrils, fibres, and structures called 'plywoods', because of the man-made material they resemble. Some of these are structurally very advanced, having been developed to form an architecture, which often involves helices, spirals and / or helicoids.

Bone consists of collagen fibres reinforcing polysaccharides, calcified with hydroxyapatite, a form of calcium phosphate.[4] Approximately equal amounts of each constituent are employed. The fibres have to be precisely aligned to resist the forces in bone, which may be direct, or twisting. In addition, there is a need for just enough calcification to provide toughness. All this has to be capable of growth, while maintaining strength, toughness and stiffness. This necessitates the almost constant addition of new material and the modification or replacement of old material; not only without loss of structural stability to the

2. Keratin is a term applied to any of a group of fibrous proteins occurring in hair, feathers, hooves and horns.
3. A. C. Neville, *Biology of Fibrous Composites—Development Beyond the Cell Membrane* (Cambridge University Press, 1993).
4. J. F. V. Vincent, "Materials technology from nature", *Metals and Materials,* Jan. 1990, pp. 7-11.

animal or human in question, but also without loss of all the other functions that must be performed.

No system made by man comes close to this degree of integrated complexity. “As thou knowest not what is the way of the spirit, nor how the bones do grow in the womb of her that is with child: even so thou knowest not the works of God Who maketh all” (Eccl. 11:5). Man is seeking to adapt his own inventions to achieve such ends, but, in so far as he succeeds, he is only uncovering what God has left to be discovered and then copying the techniques that the Divine Creator has used already.

Horns and antlers

Many animals are equipped with horns (see Figure 1), which are often used in combat. This places even greater demands on the material than is the case with the bones, which form the rest of the skeleton. Horns have a bony core, an extension of one of the skull bones. The horn is covered with a ‘skin’, containing a substantial proportion of keratin, which enhances the toughness or impact strength of the horn. The horn surface is the part which receives the full impact of attack, and hence must be tough. The inner bone core provides the stiffness and strength of the horn. Horns are unbranched (unlike antlers) and, unless damaged, are retained intact by the animal for life. The horny material is not confined to horns in the usual sense, but is also found in hair, bristles, nails and hooves, quills and feathers. The study of quills, and in particular feathers, which provide other very necessary benefits to their owners, is also a remarkable confirmation of the work of the Divine Designer, but is outside the scope of this article.

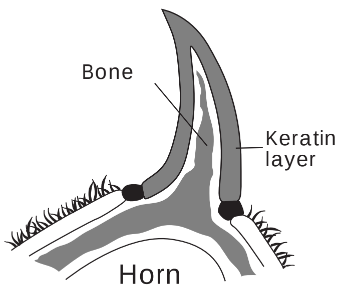

Figure 1: The structure of a horn

The skull bones also provide a starting point for antlers (see Figure 2). Early in their formation antlers are covered with a velvety skin. However, this does not develop into a hard, tough layer, but dies and is rubbed off by the animal. Antlers are shed each year, hence the protection provided for lifelong horns is not necessary. The precise shape of antlers is fitted to their purpose. Hence, broad, flat antlers have been provided for reindeer, to assist in clearing snow when the creatures are searching for food. Size too is important, and each year the new antlers are closely matched to the needs of the animal bearing them, not too large and not too small. This ensures that not too many are broken, and that excessively large antlers do not encumber the stag.[5]

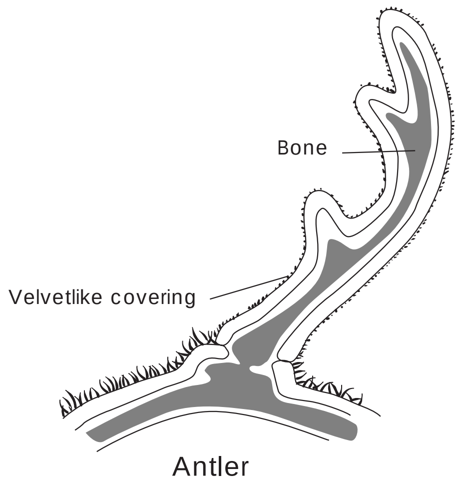

Figure 2: The structure of an antler

Optimisation is evident in the size, shape and materials in bones and antlers. Hence the leg bone which supports a cow is about fifty per cent mineral, to provide essential stiffness rather than toughness. In antlers, stiffness is sacrificed for toughness since the antler is not responsible for supporting the weight of the animal, but high impact strength is essential if the antlers are to last the season. A thirty-per-cent mineral content reduces the stiffness to about a half of that obtained with fifty-per-cent mineral content. Toughness is increased tenfold, but only if the antler is wet. This, of course, is no accident, for the animal knows that it must soak the antlers to render them ‘fit for purpose’. Optimisation implies an intelligent designer. We may continue to marvel at the works of God: “Behold now behemoth, which I made with thee . . . his strength is in his loins . . . his bones are like bars of iron” (Job 40:15-18).

5. A. C. Kitchener, *The Functional Design of Horns* (PhD thesis, University of Reading, 1985).

Trees and timber

Trees are a wonderful example of the Creator's versatile provisions for man. They supply food, shelter and natural construction materials as well as being a source of great beauty. Recent times have also revealed their essential role in maintaining balance in the ecosystem. The destruction of the rain forests has brought problems, which may not be solvable without Divine intervention.

Throughout his history man has utilised wood as a construction material in a wealth of different ways. In so doing, he makes use of its strength, stiffness and toughness as well as its natural beauty, which can be increased by judicious cutting and polishing. Wood has highly directional properties; it is stronger and stiffer parallel to the grain. Sometimes this is a disadvantage for structural use, which has led to the development of materials such as plywood, which consists of layers placed at different angles, and chipboard, in which a mixture of wood and glue is used to achieve more uniform properties. However, for other uses, this directionality (called anisotropy) is an advantage. This is particularly so when the tree is growing. Indeed, without its unique combination of properties a tree would never reach maturity. Plywood is not man's invention. As indicated earlier in this article, similar structures exist in animal tissue, so similar in fact that the term 'plywoods' is used to describe them.[6]

A tree has to perform a number of functions during its growth and development.[7] For the purposes of this article we are interested in timber as a load-bearing material, having to withstand considerable wind forces that subject it to bending and impact loads (during gusts), as well as supporting a weight of branches and leaves, not to mention animals. All this has to be achieved while the tree raises nutrients considerable heights and adds to its own dimensions without losing its mechanical properties in the process. In addition to nutrients from the ground, a tree has to inhale carbon dioxide from the air and to combine it with water to form carbohydrates, using the energy of sunlight to achieve this. The vast array of leaves provides the large surface area necessary to gather enough energy and material.[8]

Leaves too derive their moderate, but necessary, strength from a fibrous structure. They need greater flexibility (less stiffness) than the branches and hence resemble textiles. No doubt this property prompted Adam and Eve to use them. They were to discover, however, that Divinely approved symbolic qualities were even more important than structural qualities for such a purpose: "and they sewed fig leaves together, and made themselves aprons . . . Unto Adam also and to his wife did the LORD God make coats of skins, and clothed them" (Gen. 3:7,21).

To achieve all this the Creator has designed a remarkable fibre-reinforced material. Wood may be considered as an amorphous matrix (lignin) heavily reinforced with fibrous tracheids (closed, tubelike cells) a few millimetres long with a diameter of a few hundredths of a millimetre. The structure of the tracheids is shown in Figure 3. The strength of the tracheids is provided principally by crystals of cellulose, which

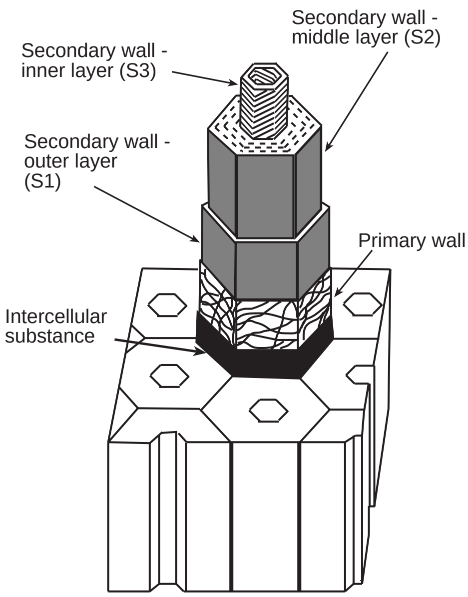

Figure 3: The structure of timber showing tracheids

form the so-called S2 layer. This is surrounded by polysaccharides (sugars), which are themselves partially crystalline adjacent to the crystalline cellulose, but become progressively less so as the distance from the core increases. This is no mere accident; man-made fibre composites

6. Neville, *op. cit.*
7. E. J. Gibson, "Wood: a natural fibre reinforced composite", *Metals and Materials*, Jun. 1992, pp. 333-6.
8. For more on photosynthesis see "'After his kind'" in this Special Issue, p. 171.

(for example, carbon fibre reinforced plastics) are very strong and stiff, but if there is a sharp transition from the strong fibres to the softer, but still brittle, plastic matrix, they lack impact strength (toughness). The interposition of a transition layer between the fibres and the matrix (copying the Divine design) improves the toughness of the material, but rarely as effectively as in timber.

Readers will have observed concrete reinforced by steel wires or bars. Reinforcement is used not simply to increase overall strength but to compress the concrete, which has a very low strength in tension (pulling), and hence to make it behave a little more like a metal when stretched. Concrete, like stone, is very strong in compression, so there is little problem with forces which tend to 'squash' the material. The opposite is true of timber. Wood is relatively weak in compression, so that, if it were unstressed in still conditions, it would be likely to fail when compressive bending took place in windy conditions. However, the Creator has so designed trees that, as new material is added by growth, the surface layers experience tension and the inner layers are compressed (the opposite of reinforced concrete). This ensures that the part of the tree which experiences the greatest bending forces, the surface, starts in tension, lessening the size of any compressive forces which may result from severe gusts of wind.

In an ideal fibre composite, the fibres and matrix fracture at the same time (technically, at the same strain) when the material is loaded to breaking point. This provides the most efficient reinforcement, a situation which usually prevails in wood but is difficult to achieve in man-made composites.[9] The specific strength and stiffness of timber are compared with such materials as steel and aluminium in the table above. The stiffness values are comparable with the metals, and the strength values are considerably greater than the metals. It is true that composites reinforced with carbon fibres, such as Kevlar (a man-made high-strength fibre), provide even higher specific strengths, but it is worthy of note that these materials are more like timber, since they are produced from polymers.[10] In any case, man-made composites do not (yet) have to provide growth and feeding mechanisms, like timber.

A weak point in all fibre composites is likely to be joints.[11] These are usually necessary in man-made composites, and occur as knots in trees at branching points. Three types of joint in man-made composites are shown in Figure 4. The first two are relatively easy to produce, but the third is, practically, much more difficult. The similarity of type C to the knots in wood is evident. The Creator has built in the most efficient joint type and the mechanism for it to grow in-situ.

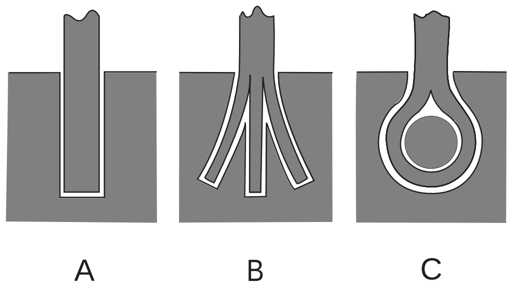

Figure 4: Three joint configurations used for fibre composite materials

Conclusion

When we consider the work of the Divine 'Constructional Engineer', we are reminded of words spoken of His only begotten Son: "He hath done all things well: he maketh both the deaf to hear, and the dumb to speak" (Mk. 7:37). Since Jesus did all that the Father showed him, the same may be said of God: "My Father worketh hitherto, and I work . . . The Son can do nothing of himself, but what he seeth the Father do" (Jno. 5:17,19). The evidence for creation and design all around us is so strong that those who study these things are constrained to include them in titles for books[12] and conferences.[13] How sad that so many ignore the evidence and choose to attribute these things to evolution! Let us not, like them, be faithless, but believing.

---

9. M. R. Piggott, *Load-Bearing Fibre Composites* (1st edition, Pergamon Press, 1980).
10. Polymers are long-chain chemical compounds, which include most of the materials making up living tissue, manufactured plastics (including fibres), rubbers and other substances.
11. Piggott, *op. cit.*
12. M. French, *Invention and Evolution—Design in Nature and Engineering* (2nd edition, Cambridge University Press, 1994).
13. "Biomimetics—ideas from nature are smart": an Institute of Materials workshop at the University of Reading, 23 Sept. 1996, *Biomimetics, op. cit.*