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Unusual uses of holes—With input from biology

*Julian F.V. Vincent**

Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, United Kingdom

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ABSTRACT

This short review, some of it covering work not otherwise published in a peer-reviewed journal, is not meant to be exhaustive but rather to highlight some mechanical influences of holes that are apparently not much used in engineering. Apart from initiating fracture, holes can, if judiciously placed and of the right dimensions, improve the durability of a material or structure and generate information about its state of strain. By increasing the morphological complexity of the structure, they can also increase the potential for multifunctionality.

1. Introduction

Holes are a neglected resource in engineering with a bad reputation because we do not always know how to use them to advantage. If a hole in a plate under tension has an angular outline, or is too close to another hole, or is too large, a crack can start from it that can spread throughout the material (Atkins and Mai, 1985). In a perfectly uniform material, a round hole can triple the local stress intensity. Holes in three dimensions are better known as cellular materials (Gibson and Ashby, 1997). In both two-dimensional (2D) and three-dimensional (3D) structures, their main use is in lightening structures.

Biology demonstrates a much wider range of usage and design that can be incorporated into our technology. However, it seems that there has been relatively little work on the influence which holes, whether in plates or solids, can have on each other, and none on the ways in which holes of different sizes and shapes can interact. These experiments have been performed by biological organisms but we have neither investigated many examples nor, as a consequence, realised their significance.

Holes can

- save money, since you need no material to make them;
- make an object lighter;
- make an object more durable;
- control the way a material fails, and so make it safer;
- generate information about an object;
- be used to repair an object; and,
- by subdividing the structure, prepare it for multifunctionality.

However, there are places where holes are relatively safe. In a bending beam, the main resistance to the load is from

* Tel.: +44 1225 835 076, +44 7941 933 901.
E-mail address: j.f.v.vincent@bath.ac.uk.

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the material furthest from the neutral axis, which has the largest second moment of area. Therefore, there is less need of material in the middle, and some of it can safely be left out. In a beam, this is where the lightening holes are drilled, and in a strut or column we either put a hole down the middle or replace it with a foam or cellular structure. The Romans knew this and lightened their buildings by adding empty urns to the cement that they packed into the column or shell structure. This technique was used to lighten the upper part of the dome of the Pantheon in Rome, an unreinforced concrete structure whose span remained unchallenged for nearly 2000 years. Cellular structures are common in nature. Examples are the stems of non-woody plants, fruiting bodies of fungi, the spines of the hedgehog, the quills of the porcupine, most of the bones in the body, and antler bone. All of these have a dense cortex and a cellular medulla. This paper deals only with holes in a plane.

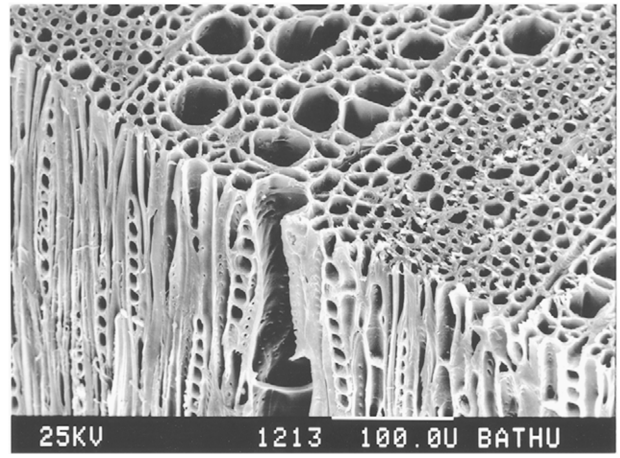

Fig. 1 – Cells in oakwood, showing the smaller-diameter parenchyma cells and the large tracheids. The scale bar is 100 μm. Courtesy of M.P. Ansell.

2. Effect of holes on failure

2.1. *Compression*

Holes can, by affecting the distribution of strain energy, control the way a material fractures and significantly increase the energy absorption. An initial, relatively uncontrolled, study suggested that the local compliance introduced by the removal of material, as when a hole is formed, acts as a focus for the dissipation of strain energy, protecting against more global failure (Khan and Vincent, 1996). The idea was triggered by the observation that a piece of apple tissue (a cellular structure) was made tougher (tested at room temperature in crack-opening mode) by freezing. We suggested that cells were being randomly burst by the growth of ice crystals, which penetrated the cell wall. The cell then effectively became an empty space in the overall structure which could either be acting as a crack stopper or, by introducing compliance, be increasing the yield strain and thus, by some mechanism, be increasing the dissipation of fracture energy.

There are some biological materials in which holes of significant size occur naturally and which, we found, affect or even control the way the material fails. The example we chose to examine was hardwood (from broad-leaved trees, mostly deciduous in temperate climates), which is immediately distinguishable from softwood (from needle-bearing trees, mostly evergreen) by the more complex morphology. Softwoods are composed of parallel arrays of tubes, whose walls are made of cellulose nanofibres in a matrix of lignin, about 0.1 mm diameter. In addition, hardwoods possess large vessels, about 0.5 mm diameter, which provide the main route for transport of water. In a section taken across the tubes, these vessels appear as large holes in a field of smaller ones (Fig. 1). They provide localised low-density or compliant areas around which the structure collapses preferentially when the wood is compressed across the grain (Hepworth et al., 2002). If the vessels are arranged in layers (*ring-porous* wood, found in some oaks and willow, providing water freely early in the growing season) then the wood will fail fairly easily since the holes represent a weak layer within the material. Willow and oak may be strong, but they are rather brittle. But if the vessels are arranged evenly throughout the wood (which is different from "random", which allows clumping, although both are called *diffuse-porous* and provide water transport at a similar rate throughout the growing season) then the damage is spread evenly and the full toughness of the wood can be realised. Examples are ash and hickory, which are used for handles of tools, wheel spokes, and the like. In such uses, the wood is likely to suffer frequent and often impact loads. Within the wood, each of the large holes allows greater local deformation (Fig. 2), thus causing a local concentration of strain and thus of stress. As each crack grows, it removes strain energy from the surrounding region, and so inhibits the further propagation of other starter cracks. So the distributed holes in wood absorb strain energy before it can be transferred to the tip of a growing major crack. However, if there are too many holes in the structure it will be weakened, since the cracks only have to join up the holes for the material to break. It is impossible to relate the relationship between toughness and the distribution and number of holes to the biology of trees since, as far as is known, their occurrence in the tree is not related to mechanical properties but to the provision of water from the roots to the leaves.

The significance of the larger holes in controlling this mechanism was confirmed experimentally by drilling holes of diameter 0.6 mm into a piece of softwood, which does not contain large vessels. Although a relatively large amount of material was removed by drilling the larger holes, the energy absorption did not degrade in proportion. Indeed, a slight increase in energy absorption was noted (Hepworth et al., 2002).

2.2. *Tension*

A similar mechanism seems to operate in a tensile membrane (Harvey, 2005), where, using tracing paper, we showed how the strain energy could be partitioned between intact areas of paper and those areas with holes, and that the applied strain energy was concentrated by the holes, relieving the intact areas. Experimentally it was determined that 0.75 mm diameter holes did not compromise the strength of the paper, nor did they initiate a crack. In order to investigate the effect of the density of holes on the distribution of strain energy, they were