Innovations in the design of long-span building structures

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Before iron became available as an economical structural material, the choice was between timber and bamboo, which had both tensile and compressive strength, but were easily destroyed by fire, and the masonry materials (stone, concrete, hard-burned brick and mud-brick or pisé de terre), which were fire resistant, but lacked tensile strength. These materials could be used over a significant horizontal span only in the form of an arch which was purely in compression.

The arch concept was known to the Ancient Egyptians, but they used it only for mudbricks. A catenary-shaped storage shed survives in the mortuary temple for Ramses II; its construction was abandoned when the Pharaoh died, so that this temporary arched structure, which would have been demolished in the ordinary way, survives.

However, this is not an isolated example. One sees to this day many mudbrick houses along the Nile outside the big cities. The larger ones have flat roofs made with wooden beams, the smaller ones are domed and entirely of mudbrick. The low strength of the material limits mudbrick domes to small spans. It seems likely that the same construction was used in Antiquity because many of the tombs in the Valley of the Kings cut into the solid rock, which model the lifestyle of the people buried there, have flat roofs for the larger rooms, but domed roofs for the smaller rooms.

So why didn’t the Egyptians use arches for their stone structures to avoid the use of a veritable forest of columns in the interior? Temples were originally of timber, which was considered a building material superior to mudbrick. One can see that from the decoration of the stone columns in both Ancient Egypt and Ancient Greece, and even more clearly from some early stone structures, whose ceiling soffit is carved to look like round logs of timber; the processional corridor of Pharaoh Sozer’s Step Pyramid at Sakkara is an example of a very early Egyptian stone structure (about 2800 BC), whose stone ceiling is carved to imitate round timber logs. So the early stone construction was based on the existing timber technology, and not on the more appropriate technology used for mudbrick.

It was left to the Romans to take this logical step. From the stone arch and barrel vault they developed the cross vault and the dome, and achieved an enormous increase in span. The Pantheon in Rome, built in the 2nd century AD retained the record for span for 16 centuries, until long-spanning iron structures were developed.

The Roman invention of the masonry arch was the basis of most of the great architectural structures prior to the Industrial Revolution. The Byzantines developed the shallow dome, which greatly reduced the hoop tension that develops in the lower portions of a hemispherical dome. This was adopted and greatly enhanced by the designers of Islamic domes, who added the muqamas (or stalactite structure) to the repertoire.

The cross vault and its imaginative variations are quite properly credited to the Gothic masterbuilders, but the concept was Roman. The Romans preferred domes to cross vaults, but they built enough for the idea to have come down to the medieval masons. For
example, the cross vault of the Basilica of Maxentius, which was prominently located in the Roman Forum, did not collapse until 1349 (due to an earthquake).

Brunelleschi was probably the first to use timber and iron reinforcement in domes to absorb the hoop tension and produce a lighter structure, and many Renaissance domes surpassed those of Ancient Rome in elegance, but not in span.

The Roman structural influence extended eventually as far as India, but probably not to China, where the masonry arch was also discovered, presumably independently. The Chinese built a number of stone arch bridges, whose maximum span was only slightly less than that of the longest Roman masonry arch bridges; but the Chinese never attempted to build arched masonry buildings. Significant buildings in China, Japan and Korea were generally of timber. In Japan some important wooden temples were rebuilt at regular intervals, according to tradition as copies of the original design. In China they were also replaced, according to tradition, by copies when they were destroyed or damaged by fire. Thus the designs may be old, but the material rarely is.

Iron eventually solved the problem of the structural deficiencies of timber and masonry, because it was incombustible and had tensile strength. The Chinese developed the manufacture of cast iron in the 6th century BC, but never used it as a major building material. The Europeans discovered cast iron only 1800 years later, and the material remained too scarce and expensive to be used as a principal building material until the early 19th century. The progress to the mass production of wrought iron and steel was then rapid, and their availability dramatically increased the potential for long-span construction. The largest domes were used for sporting events, and in the later part of the twentieth century their span had become so big that
the people in the rear seats could not see properly what was happening at the centre, so that television monitors had to be installed. The maximum useful span had evidently been reached.

However, steel did not just extend the useful span of traditional construction. There was one thing it could do that had been difficult with traditional building materials: it could resist direct tension. This was particularly useful for bridges, and the longest bridges in the world today are suspension bridges. However, the suspension structure does not work well for buildings. There is no need for a building span the length of the Golden Gate Bridge, and the shorter spans can generally be handled better by less flexible structures, which are easier to make watertight and cost less.

The use of cable stays for buildings is, I think, an innovation made after the Second World War. They are...
Brunelleschi avoided the great thickness of material needed in Roman domes to resist the hoop tension by placing a number of timber and iron chains in the structure, in fact the realisation of a dream of the designers of an earlier era for a sky hook, the replacement of a column under the roof by a cable above it. This has great potential for elegant long-span lightweight structures.

Australia did not produce many significant long-span structures prior to the Sydney Olympics of the year 2000. The major Australian cities all have a mild climate. Thus we did not need to provide long-span indoor facilities for sporting events or political meetings held at sub-zero temperatures or in great heat. However, the Olympics posed a new problem, because the international sporting community expected covered stadia holding a large number of people. Many of the buildings especially erected for the Olympics have noteworthy structures, nearly all cable-stayed, and I commend them to your attention if you are not familiar with them.¹

NOTES

¹ Monumental Australian Architecture, selected and introduced by Chris Johnson, NSW Government Architect. BT Latitude, Sydney 2002 (PO Box 837, Blacktown NSW 2148).