Vaulting over the building!

In sustainable design, historical and traditional methods of construction are often reinvented with the added benefit of technological advances in the use of materials or processes. Recently, for example, we have seen the resurgence of materials such as rammed earth, hydraulic lime mortars and clay plasters. Here, Paul Mallion explains why Mediterranean style brick timbrel vaulting could enjoy a re-emergence following the successful use on the Pines Calyx building in Dover.

Steelwork or reinforced concrete is often the automatic choice of material in the design of wide span structures. Both are well tested and easy to prove conformity using established codes of practice. Whilst the materials themselves are relatively inexpensive, there are, however, hidden environmental costs to consider – huge embodied energy, pollutant by-products and transportation, as well as the heavy plant and machinery required to place them.

Right: Crossways, Staplehurst where the architect, Richard Hawkes, has designed himself a new house based on an arch enclosing a cluster of cubical shapes. The method of constructing the arch was uncertain, until Andrew Bassant, of Ecolibrium Solutions, recommended timbrel vaulting. Richard Hawkes became enthused by the idea and found a local pottery, Babylon, to fabricate them using local clay usually used for Kent peg tiles.

The timber gridshell is a viable alternative to steel or concrete and has been used to stunning effect at the Weald and Downland Museum in West Sussex and The Savill Building at Windsor Great Park. There is another option for wide span construction however, which is worthy of consideration and this is the Timbrel vault.

History of timbrel vaulting [1]

A Mediterranean system by origin, perhaps a continuation of Roman, Moorish and Byzantine designs, it was developed and perfected in the Catalonia region of Spain where records can be traced back to the 15th century. In the 1880's the design was exported to the USA by Rafael Guastavino, and it was in use until the 1940's when it was finally exceeded by steel and concrete due to rising labour costs.

Rafael Guastavino Y Moreno (1842-1908) originally trained as an architect, but found greater success designing and constructing vaults, domes and stairs in the local tradition. He emigrated to the USA in 1881 with his son Rafael Guastavino Y Esposito (1892-1950), who continued the family business. The buildings he left behind were inspirational to architects such as Gaudi.

Traditional vaults or domes, as used by the Romans, utilised shaped stones or voussoires. These needed to be supported by centring until the final keystone is placed. They rely on the weight of the masonry and gravity to hold them in place, and must be countered by strong buttresses to resist the outward thrust at the spring point.

Timbrel vaults on the other hand are very thin and do not require any support during construction. They rely on their geometry for their support, they could be described as thin film masonry. The name timbrel comes from the Spanish word for tambourine, as a correctly constructed vault will ring when tapped. Guastavino used the term 'cohesive construction'.

Such was the success of the system that when the Guastavino Fire Proof Construction Co. finally closed in the 1960's, it had completed over 1000 buildings, including many landmarks in New York, Manhattan and across the USA, including Grand Central Terminal and St John the Divine Cathedral in New York City.

Method/principle

The principle of the timbrel vault is to create a series of laminations of terracotta tiles, each layer arranged at an angle to break the pattern of tiles below – straight, diagonal etc. Tiles laid flat (a plano in Spanish), in the plane of the vault, rather than perpendicular as in an arch. The first layer is perhaps the most remarkable and requires a huge leap of faith for the uninitiated. As no support or centring is used, the first layer of tiles are simply stuck together edge to edge with an adhesive. Typically the tile edge dimension is 25mm, and face sizes of 300 x 150mm, or any other ratio of 2:1.

Plaster of Paris is used as the adhesive for the first layer as it can set within seconds, leaving the newly adhered tile suspended, which is quite uncanny at first. Subsequent layers are laid in cement or hydraulic lime mortar. Usually three layers are used. The first layer can be laid in either stretcher bond or herringbone pattern.

It has been reported that during the construction of St John the Divine Cathedral in New York City in 1909, a span of 132 feet (40m), the workers progressed at a rate of 18" each day, standing on the previous day's work with nothing in front of them but a 150' drop, completing the work without incident in 15 weeks[2].

Once the work has cured, it can be punctured or perforated without harm, as discovered during the erection of the Boston Public Library, when a two ton stone was accidentally dropped through a vault with no ill effect. The hole was patched up, and the vault is still in use today[3].

Above: the Oyster Bar in Grand Central Station, New York, which is actually below sea level!

Benefits

Compared with traditional vaulting, the tile vault is extremely light. The lateral thrust of a dome or vault is much less than its masonry counterpart due to the monolithic nature. Very flat arches, vaults and domes can be created. It is non-combustible; indeed Guastavino called his company the Guastavino Fireproof Construction Co. The tiles protect mortar from fire and heat. Tests were carried out in 1897 where a trial vault survived a fire and load test of 1385°C and 45 tonnes respectively, and resulting in total deflection of only 9.4mm.

Scaffolding was not required in the past, but today edge protection is essential. It is usual to construct a working platform below the workface. The system has several benefits:

- temporary formwork essential in normal masonry can be dispensed with
- no reinforcement required
- repairable when damaged
- simple construction principles can be quickly learnt by bricklayers or plasterers
- it can be used to create domes, arches, vaults, and also flat floors, undulating roofs, walls and partitions (Gaudi) and parabolic, helical and spiral stairs.

Can it be a modern sustainable solution?

In its heyday the timbrel vault was quicker, cheaper and lighter than the competition, but as the cost of labour increased in America, steel and concrete alternatives began to win over. There have been occasional revivals in various countries, to overcome shortages in steel (including Cuba), so is the scene now set for another revival?

Timbrel vaults and domes meet many of the criteria for sustainable construction:

- low embodied energy – tiles are usually quite lightweight terracotta, low baked rather than fully vitrified
- relatively small quantities of mortar are needed.
- low wastage – a single size of module is used, usually 150 x 300mm, any off cuts can be used in intermediate courses
- local materials – local clays and potteries can be used, set up costs are minimal for such simple tiles
- adaptable – holes can be cut into vaults to suit future needs, repairs can be made easily
- demolition phase – no toxic chemicals in waste, can be broken up for hardcore
- easily learnt by existing wet trades.

Challenges for the 21st Century

Assessing the structural integrity of a timbrel vault or dome was originally done by rule of thumb, but the Guastavinos organised empirical testing between 1887 and 1889 to establish data on compression, tension and shear. They also commissioned a 'Table of Theoretical Stresses' by Professor Lanza of the Massachusetts Institute of Technology (MIT).

There have been a number of buildings demolished in New York due to concerns over the integrity of the domes, primarily due to lack of knowledge or method of assessment using modern simulation techniques.

MIT is today still at the forefront of timbrel engineering, lead by Professor John Ochsendorf, employing highly sophisticated computer simulation software to predict stresses. This software apparently evolved from that used to simulate moving liquids in animations. MIT have links with Cambridge University in the UK, where advice can now be obtained.

With the structural issues resolved, we are left with thermal performance to tackle. In this respect, the vault is easier to tackle than the dome, being only one plane of curvature for an insulant to be cut to. Edge detailing and support of eaves, gutters etc require careful consideration. Finally, the roof membrane and method of fixing against wind uplift need addressing.

Paul Mallion

Case study - Pines Calyx

Pines Calyx (www.pinescalyx.co.uk) is a sustainable conference centre and community building in Dover, Kent (see also Volume 16, No 4, Spring 07). Here we provide more information on the roof domes. There are two domes spanning 12m each, with a maximum rise of 1320mm. Being a very shallow dome, significant outward thrust is created, which is countered by a reinforced concrete ring beam. If concrete was used for the domes, it is estimated that 35m^3 of concrete would have been used.

Tiles were handmade by local potters Robus Architectural Ceramics (specialising in mathematical tiles and architectural terracotta) from a stock of Gault clay obtained as waste from Bretts quarries, during gravel extraction. Gaultis a traditional Kent clay but no longer available commercially, with a pale creamy white to pink colour.

The tiles were too dense and heavy for the first course, to be stuck edge to edge with plaster of paris, therefore an additive known as Flolite was included to reduce weight, but due to expense was used for the first course only. Tiles cost £2.00 each – the equivalent of £25.00/m^2. Plaster of paris was obtained via British Gypsum, mixed in small batches with warm water to accelerate setting.

Profile gauges were set up to ensure the correct curvature was followed; these were movable plywood structures rotating around a central scaffold pole. The Spanish masons used a far more elegant solution, a simple cable triangulated top and bottom to the pole, and adjusted to check the radius of each course.

We searched for Spanish masons familiar with the system through the Spanish embassy and consulate, to no avail. UK health and safety employment law and insurance issues also had to be addressed. There seemed to be so many obstacles that the project seemed doomed at one stage. The turning point was the decision to construct a mini sample dome, 3m in diameter (1⁄4 scale of the full domes). Using sample Robus tiles, Michael Ramage from MIT visited the site and constructed the dome in a few days in May 2005, with assistance from main contractor Ecolibrium Solutions Ltd. The whole team was inspired by the simplicity and, we suddenly realised that scaling this up to full size was viable.

The main contractor agreed to employ a skilled and experienced mason, Sarah Pennel, from Somerset, who was known to MIT for her research into masonry arches and domes.

The search for masons continued, whilst compression and flexure tests were carried out on the proposed tile at Sandbergs in London. MIT and UK engineers Cameron Taylor worked on the structural design of the dome and ring beam respectively.

John Ochsendorf finally came up trumps with 3 willing masons from a Spanish technical college, Escuela Taller in Zafra, in the Estremadura region of Spain. The main contractor organised health and safety, insurance and dealt with employment and taxation issues. A weighty contract was required with Zafra Town Council. The masons consisted of Maxi Entry, Fernando Mavin, 'expert professors', and student Manuel Villar. MIT graduates and students also worked on the project (inset right).

The work was a brilliant collaboration between British builders, Spanish masons, US engineers and students, brought together by an enlightened client, and during my inspections as project manager all were united and fortified by a good cup of strong tea!

Once the first dome was completed the second dome was built entirely by the UK team from Ecolibrium Solutions and Sarah Pennel.

Finally, we collaborated on the design for a staircase using two parabolic arches. Tiles were glazed on their exposed faces. The geometry was very complex, but MIT worked this out with their 3D software. The result is in my view the pièce de résistance, built by Sarah Pennel.

Paul Mallion

Refs:

1. **The Transfer of Thin Masonry Vaulting from Spain to America. *George R Collins – Columbia University 1968.***
2. **New York Herald 19 Sept 1909.**
3. **Reported in Engineering News, 9 Nov 1889.**

Pages 52 and 53: various views of the vaulting at Pines Calyx. There are two domes spanning 12m each, with a maximum rise of 1320mm. Being a very shallow dome, significant outward thrust is created, which is countered by a reinforced concrete ring beam. If concrete was used for the domes, it is estimated that 35m^3 of concrete would have been used.