Geometric principles in additive systems for construction of vaults: The block and the joint.

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Abstract
Vaults and shell constructions are among the most fascinating elements in architecture. Covering large spaces has always been a challenge in architecture and engineering and the vault with curved and double curved form has a special significance. Throughout the history of Christianity domes and vaults has been looked at as synonymous with representations of the vault of heaven, paradise or the universe. Pantheons dome was a temple of all Gods, Hagia Sofia’s dome was a representation of the golden heaven of Christ. The Renaissance in Italy was initiated with the dome of Santa Maria della Fiore. The Baroque style followed with the domes of Borromini; Bernini and Guarini. The Period of Enlightenment had iconic tunnel- and dome vault projects by Etienne l. Boulée. All these stone vaults were made by additive systems in bricks and mortar. In the 20.th century concrete was introduced and the reinforced concrete made new large spans possible. These was in-situ caste d and not additive systems. Utzon’s Sydney opera house from the mid-fifties combined the additive system, iron reinforcement and concrete into at new prefabricated vault system, which could handle the complex geometry of the shells.

Before starting a research project on prefabricated additive systems for vaulting, we wanted to find out more about the basic principles or methods for additive systems used for vaulting.

The research project focuses on the use of prefabricated additive systems for vaults:single and double curved shells. We wanted to examine vault systems which make use of repetitions of units. The objective was to describe the additive system and isolate the components.

The research project started to investigate the vaulting systems of some famous/well known vaults and domes from the history of architecture and engineering in order to “decompose” them and describe the geometric principles of the system.

We found that old vaulting systems made with added components consist of solid standard blocks and an adaptable joint layer. We could see that this fundamental principle of the systems barely had changed throughout history. This paper will describe this approach to vaulting systems.

This investigation looks at modular systems without focussing on the static aspect. Which geometric principles are used and how are they joined together, creating a complex vault geometry.

The study of these principles are at last compared to principles of joining elements in other materials.

Keywords: Vaults, additive systems, shells, complex geometry, basic geometric principles.
1. Introduction

Domes and vaults make a great difference in architecture: It changes some fundamental ways we experience form and space. The homogeneous continuity between walls at ceiling creates quite another experience of space which is unique. Making stones soar weightless 40 meters above the floor has fascinated humans since the Roman Antique.

The ancient Greeks constructed the temples in modular systems but didn’t use mortar for joints – they used bronze and precision. It took long time and was expensive – and they had not the same fascination for interior spaces as the later Romans. They didn’t develop the arch into a vault system.

The vault and the dome introduce the curved and double curved form in architecture as a structural/static solution to cover spaces with stone. Its history goes far back to the pre-classic Greek period where the treasury of Atreus, which were constructed by stacking carefully hewn stone blocks without any joint layer. The system is a corbelled or “false” dome. The geometry of the modular stacking system, the friction and the weight/gravity force gave the construction its stability.

The development of mortar opened for new possibilities, where the joint could be a “glue” between the elements instead of just a thin “void”. The mortar joint therefore made it possible to “glue” the blocks into larger sections or “continuous rows” of stones – and perhaps more important: to use prefabricated standard rectangular blocks. Just as the invention of mortar changed the significance of the joint, the of burning clay into bricks changed the modular block systems because they could now easily be mass produced.

The Romans developed the chalk based mortar technique into the much stronger pozzolano concrete, which made it possible to cast a vault into “one block”. You might say this radically changed the relation between the block and the joint: The mortar became the dominant element in the vault and the block the secondary element. They used the bricks as permanent scaffolding for the concrete casting and created a hybrid between the cast and the modular constructed vault.

During the Early Christian, Byzantine and Gothic period the pozzolano concrete know-how was lost but the master builders anyway managed to develop the chalk based mortar, brick and stonework to a mastering of double curved shells and fascinating rib structures covering impressing (church) spaces. The Romanesque and Gothic brick vault developed the skills and the know-how.

All the high-gothic cathedrals had a max. width of approx. 15 meter of free span. The width of the nave of Reims is 14.65 m, Saint-Étienne de Sens, 15.25 m and Notre Dame de Paris 12 m. The only comparable construction was the vault in The Cathedral of Saint Mary of Girona. They began in 1416 the construction of a vault over the nave with a 22 meters span – with a new concept for vaults, the so called Timbrel-vault.

Brunelleschi’s dome in Firenze from 1420-36 was the first monumental dome built in Western Europe after Pantheon (120 AD) and Hagia Sophia (527 AD)

It was an octagonal ribbed dome with a double shell. The material was brick and mortar and it was a revolutionary construction in the beginning of the 14.cent. The size of the cupola was immense compared to other vaults at the time. For the first time since Pantheon a dome was built with a free span exceeding 40 meters and it was at double shell construction.

Furthermore the dome in Firenze was built without any scaffolding (falsework) to support the dome during the construction: a technique never tried before in this scale. Brunelleschi used bricks both
special designed and traditional – and used the first types in a herring-bone system so they interlocked. The “curve” or the tilting of the vault was made in the mortar layers/joints. The blocks were rectangular handcrafted but mass produced bricks. The vault in each section was only single curved because the dome was an octagon – but consisted of multiple layers of bricks in horizontal and herringbone curses to ensure strength and avoid cracks. It is a kind of a gigantic puzzle.

Several layers of stones were also used in the timbrel vault of the Cathedral of Saint Mary – where the architect was among the first to use this type of “laminated” stone vault. This was later developed by Raphael Gustavino between 1889-1950. The principle was the same: Standard rectangular blocks and flexible joints – but now flat tile blocks in several layers and changing directions and often using herringbone patterns. This type of “laminated” stone vault had great success in Spain and United States.
The stone and mortar building technique didn’t change until iron and cement was introduced. During the 18.th century iron becomes an important part of the building constructions. It started with the development of bridges, greenhouses and train station coverings using additive prefabricated cast iron construction and montage systems. Inspired by the greenhouses Henri Labrouste combined iron and terracotta-tiles in vault systems like the domes in Bibliothèque National and Bibliothèque Sainte-Geneviève. In the 20th century concrete vaults were reintroduced after the invention of the cement, so now the engineers could begin where Hadrian stopped with Pantheon, but now in-situ cast with iron reinforcement.

Cast concrete vault constructions represent a construction method (in relation to the modular block and joint system) where the flexible joint-layer is expanded to the size of the whole vault and the solid is reduced to the fill (of stones). The size of the fill is controlled but shapes of the stones are arbitrary. If iron rods are added (for strength), this system consists of 3 elements. Normally we don’t call this an additive system.

Additive vaulting systems or shell systems were not really in focus until Utzon introduced them in the Sydney Opera House. His solution for the shells made it possible to avoid huge in-situ cast constructions and instead use a prefab module system and cranes without the need of enormous scaffolding. (like Brunelleschi 600 years earlier).

The vault system at the Opera house is based on ribs made by double curved hollow blocks and a straight joint – but all the units are not unique. Each rib is made of number of additive system of unique elements – but the ribs are repeated and therefore the elements/blocks can be mass-produced.

Investigating the possibilities of the additive system in relation to architecture was an issue of great importance to Joern Utzon in all his work.
2. Geometric principles in additive systems of vaults.

The most simple and common additive system for making shells and vaults is the combination of a geometric rectangular block and a flexible joint layer which forms a curved or a wedge shaped geometry. Like brick with mortar creating an arch.

The other principle is the opposite: The block is carved or casted into a curve shaped geometry and the joint layer has a just “rectangular” geometry. The block is “flexible” and unique (depending of the geometry of the vault) while joint is standard.

These principles can of course be combined, but the principles follow typical these guidelines.
2.1. Solid rectangular blocks and “curved” joint-layer.

The two types of form and material can be combined in different ways – but generally, the logic behind the system is: if you choose to construct with simple geometric /rectangular solids you need a curved or double curved “joint-layer”.

The geometry of the joint layer (the glue) which fills the gap between the blocks is typical some kind wedge form. The wedge change the direction of the blocks and results in a curved construction, which is not really curved, but made of straight-lined blocks. The joint layer is the active shaping element in this system – the block is “fill”. Looking at the whole system the fill is a “flexible” grid surrounding the blocks.
2.2. Solid curved block systems and rectangular joint layer.
In this system the geometry of the block is curved – in one or two directions – and the joint layer is now reduced to a straight layer of “glue”. The curved geometry of the vault is a result from curved geometry of the blocks. The joint layer is passive in this version. The result of this type of modular curved system is much more precise and smooth – but far less flexible during the construction. It’s a montage system with many unique elements. The block is the active curve shaping element in this system. Looking at the whole system the fill is a fixed grid surrounding the curving blocks.
2.3. Hybrid vaults combining the systems.
In these systems we often find a mix of curved ribs and vault sections with rectangular blocks. A gothic vault with ribs in curved cut stones/bricks line up the precise geometry of the vault sections, while the fill often is made of rectangular bricks. This shows a rational way to combine and use the advantages of the two systems – even though the regular bricks need to be cut to fit into the “frames” of the ribs.

Systems with standard blocks curved in one direction and straight in the other directions are often used for single curved vaults. Barrel vaults. Using these blocks for double curved vaults will of course result in a smooth vault surface in one direction and a faceted vault in the other, because the wedge shaped joint is used in this direction to create the curve.\textsuperscript{IV}

Fig. 6. Hybrid vault. Ribbed gothic vault system with curved blocks forming the ribs and rectangular standard blocks used for the “fill”. Ill. |Florida Center for Instructional Technology.
Fig. 7. Hybrid vault system. Ribs in laminated wood with standard “blocks” between. Stepped vault in one direction. Standard blocks and unique arches. Screws and space as joint. Ill. Arch. Tiez-Baccon.

2.4. Conclusion on block and joint geometry.
Looking at the geometry of the block and the joint, we can conclude they are opposites: If the block is straight, the joint has to be a “curve/wedge” and vice versa. The geometric principles for both elements are the same. The block is prefabricated and the joint is cast “in situ”.
Typical geometry of the block is: straight lined rectangular geometric form, wedge shaped form, a combination straight lined and curved form and double curved form.
The geometry of the “flexible” joint: straight lined geometric form, wedge shaped geometric form and a combination straight lined and curved form.

2.5. Simple or complex geometry of the block versus simple or complex geometry of the joint?
If a vault is going to have a complex double curved geometry - a “free organic form” - we have to consider which system to choose:
Complex geometry of the blocks (and simple geometry of joints) will result in high quality of form, smooth curves and high finish of surfaces – but also lead to a unique geometry of elements and slow and costly production of the system.
Simple geometry of blocks (and complex geometry of joints) typical result in lower quality of form and surfaces – but also lead to easy and inexpensive production of elements.
Hybrid vaults represent a possibility to use the “best from two worlds”, but also the danger of creating a mediocre result full of compromises. This type of vault typical uses special designed rib-blocks with some degree of complex geometry to shape the ribs and simple blocks for the fill.
Hybrid vaults in brick and mortar have not really been popular since the gothic period, but could have potential for further investigations.
3.1. Outside the world of traditional vaults.
Looking outside the brick and mortar systems, wooden solutions, such as laminated furniture or boat building techniques, demonstrate how much is changed if the parameters are changed. Laminated wood use of thin layers of wood which allows the solid layer to be flexible. The joint layers are a thin continuous film of glue and join the elements together in continuous layers horizontally instead of vertically in rows as seen in brick constructions. The result is thin and strong.
The Timbrel or Catalan vault could be seen as a mix of these to principles, where the modular system with standard blocks with flexible joints, but “laminated” in layers in different directions.
The quality of the joint is important and a place for possible improvement. Finger joints is a well-known method to connect elements of wood. This could inspire to improve the joining of bricks.
At vault system is a big scale puzzle. Looking into horizontal interlocking systems like for example “puzzle pieces”, could be a place to search for inspiration to work with the elements.

Figure 8: Additive puzzle: From top to middle are the elements different in the vertical columns, but identical in the horizontal rows. Curved “blocks” and straight “joints”. Ill. www.sampaikini.com

3. Conclusion
Experiments and research on new types of additive vault systems needs an awareness of the systems we work with. Development of new additive vault systems will depend on of how we interpret the mass produced block and flexible joint and how we manage to twist the restrictions of the systems.
The system where the block is a standard rectangular geometry and all the flexibility to create complex geometric form lies in the mortar joint is by far the most simple – but also with the lowest level of curved finish and ability to making sharp curves. It is shaped in situ.
When the block is shaped into curves in one or two directions the complexity and the finish of system will increase and often end up with a system where most of the blocks are unique. These systems are
more or less montage systems where the complex geometry is prefabricated. Production takes time and is costly - even if it is done digital and automatic.

Further research should focus on geometric additive principles where the traditional principles are “turned upside down” – but also remember to put focus of the geometry of both systems at the same time.

References


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