

Chapter 4:

STONE: FROM TECHNIQUE TO TECHNOLOGY The Impact Of Technological Advances On Architectural Design

Of all of the materials that we will be referring to in the course, the study of stone construction requires the deepest search back into the history of architectural design . By its ancient nature, revelations concerning its structural characteristics are founded upon the type of experimentation that were based on techniques developed by the Greeks and Romans for their civic architecture. Even the majestic cathedrals constructed during the Gothic period relied on experimentation and often failure. Such structures lacked accuracy and reliability. It was not until the 1600's and 1700's that the mathematical and scientific fields which were to have a profound effect on the architectural design of stone buildings had advanced to such a point to be of value. It was knowledge in the fields of '*mensuration*' and '*stereometry*' which resulted in significant technological advances in stone construction. *Mensuration* is the branch of mathematics concerned with the accurate measurement of areas, lengths and volumes. *Stereometry* is defined as solid geometry or the art of measuring solids. The application of stereometry to stone or other types of construction requiring accurate cutting is referred to as *stereotomy*, or the use of geometric projections in determining the shape and dimensions of stone or wooden elements in arches, vaults, trusses, stairs and domes. Stereometry relies on the use of horizontal and vertical projections in determining in two dimensions the *precise* configuration of the complex parts of a building. Such accuracy was not possible in early times, even up to the Gothic or Renaissance periods.

DEFINITIONS:

Mensuration: Measuring; branch of mathematics concerned with measurement of areas, lengths and volumes

Stereometry: Art of measuring solids; solid geometry

Stereotomy: The use of geometric projections in determining the shape and dimensions of stone or wooden elements in arches, vaults, trusses, stairs and domes. To use horizontal and vertical projections in determining in two dimensions the precise configuration of complex parts buildings.

Technology: Scientific study of practical or industrial arts; practical arts collectively; terminology of a particular art of subject.

Science: Systematic and formulated knowledge; pursuit of this, principles regulating such pursuit.

THE ORIGINS OF THE ORDERS:

Much speculation and theorizing regarding the historical development of stone construction transpired during the Enlightenment as archeological discoveries in Pompeii and Herculaneum unearthed ancient Greek and Roman stone buildings. Although stone construction had continued to be used throughout the ages, it was not until the Enlightenment that the field of architectural theory started to search for an understanding of its style, form and meaning. Joseph Rykwert in his book "On Adam's House in Paradise" talks at great length about the notion of '*the primitive hut*', which scholars during the 1700's felt represented the origins of architectural form, from ancient buildings of timber, as translated into the stone structures of the Greeks. It was felt by scholars such as Auguste Choisy, Marc Antoine Laugier and Quatremere de Quincy that the first buildings in history were wooden buildings, and the classical language of architecture that resulted from the design of these structures reflected the early techniques in wood joinery.

1. On Adam's House in Paradise (Rykwert):
Every art and every science is born of necessity, and receives from the desire for improvement its slow and obscure growth. It is the business of philosophy to perfect them.
The Primitive Hut: A belief espoused by Sir William Chambers, Quatremere de Quincy, Marc Antoine Laugier Sir James Hall and Eugene Emmanuel Viollet le Duc that the first buildings which were created were wooden dwellings, and that the architectural solution and construction methods for wood were applied to stone construction (which came second) therefore the form of stone construction.
Quatremere de Quincy: Before the hut could be imitated in stone it had to be reasoned and developed.
Sir James Hall: The principle of imitation is essential to architecture. Stone, however, has no ornamental forms proper to its nature, nor has the act of building any immediate apparent forms to imitate.
The Rustic Hut: Laugier and Blondel.
2. The Rustic Hut: Chambers version.
3. Auguste Choisy: Stone and reconstructed timber origin of the Doric Order after Choisy.
The Rustic Hut: Milizia version.

PRINCIPLES OF STONE CONSTRUCTION:

4. Structure: The Essence of Architecture (Forrest Wilson) Needs to be an understanding of the difference in properties of stone and timber nevertheless. Stone good in compression, not good at all in tension. Lintel construction poor use of stone as it puts underside of beam in tension, causing cracking -therefore only very short spans possible.
5. Arch construction because of the line of action of weight (force) of the stone above coming down (gravity) makes the stone to act only in compression--therefore taking advantage of the positive properties of stone -getting longer spans.
6. The Gothic Vault (Acland): Though the pointed gothic arch better fits the ideal line of pressure, if too acutely pointed the crown tends to rise while the sides fall inwards.

- In a semicircular arch where the stones can slide the crown will fall while the sides are pressed out above the spring point or at the spring point.
 Rotational movement of stories during failure more normal
7. Barrel vault is an extrusion of a round arch. They exert continuous thrust out along their sides (at the spring point especially). Could be reinforced with heavy walls at the side or with tie bars across. Transverse arch rings used to reinforce barrel vault.
 8. Development of the dome (rotation of a semicircular arch).
 The first domes were developed from beehive corbelled domes by slightly canting the courses. Later domes with steeply pitched radiating joints required centering. Corbelling. Centering is the wooden formwork which supports and gives shaped to the dome (or arch) during construction
 Each ring of masonry in a dome is a structurally stable compression ring.
 The double curvature of the dome with interlocking compression rings makes it a very rigid form. Heavy loads at the crown will generate bursting forces just above the haunching.
 The bursting forces can be countered by loading down the shell with heavy buttresses or by introducing a tension ring or chain.
 9. In domes on pendentives the mason could rely on the stiffness of doubly curved surfaces. In gothic cross vaults the folds at the groins act as stiffening ribs bracing the entire fabric.
 Sacristy of San Lorenzo: Michaelangelo
 Example of a semicircular dome on a pendentive.
 10. The Gothic Vault (Acland)
 Thin cylindrical barrel vaults fail when the crown falls, pushing out the sides. Thin stiffening plates can reduce this flexure.
 A pyramidal roof is rigid but requires support below the sides. The cross ridged roof can rest on four isolated supports, channeling loads down the folded groins.
 Folding along the crown can replace the longitudinal stiffener. Folded ridges set transversely can brace the sides.
 In the pointed Gothic cross vault the panels of vaulting were curved to wedge into position.
 11. History of Building (Jack Bowyer):
 Key to the ability to construct with stone was the ability to move the pieces into position after cutting. Levering machinery such as this was possible once pulleys were invented.
 Medieval method of moving a pillar by the common lever principle ($W = F \times d$)
 12. Greek Architects at Work (Coulton):
 Colossal stone transportation: isometric restoration
 - a. Metagenes' method c. 550 BC
 - b. Paconius' method (first century)
 Often stone not quarried at the building site.

IMPLEMENTATION: GREEK

13. Angle contraction in the Doric Order; elevation with oblique projection: illustrating the placement of the parts, centering and proportional distances.

Propylaia at Athens, east facade (c. 437-432 BC) exploded isometric view showing cantilevered frieze beams. Idea of cantilever in stone difficult as it is not designed to do this very well.

14. Greek Architects at Work (Coulton):

Features of early Greek monumental masonry: a) U shaped hole; b) dove tail clamp; c) band anathyrosis; d) orthostate; e) handling boss; f) preliminary dressing

15. Vitruvius: The Ten Books on Architecture (first century BC)

“All things therefore appear to be made up and produced by the coming together of these elements, so that they have been distributed by nature among an infinite number of kinds of things. Hence I believed it right to treat of the diversity and practical peculiarities of these things as well as of the qualities which they exhibit in buildings, so that persons who are intending to build may understand them and so make no mistake, but may gather materials which are suitable to use in their buildings.”

“The stone in quarries is found to be of different and unlike qualities. In some it is soft in some it is hard, as in lava quarries. There are also numerous other kinds. (Tufa as being noted as being able to be cut with a saw). All these soft kinds have their advantage that they can be easily worked as soon as they have been taken from the quarries. Under cover they play their part well; but in open and exposed situations the frost and rime make them crumble, and they go to pieces. On the seacoast, too, the salt eats away and dissolves them, nor can they stand great heat either. But travertine and all stone in that class can stand injury ... But since, on account of the proximity of the stone quarries of Grotta Rossa, Palla, and the others that are nearest to the city, necessity drives us to make use of their products ...”

“This we may learn from several monuments in the environs of the city, which are built of marble or dimension stone, but on the inside packed with masonry between the outer walls. In the course of time the mortar has lost its strength, which has been sucked out of it by the porousness of the rubble; and so the monuments are tumbling down and going to pieces with their joints loosened by the settling of the material that bound them together. He who wishes to avoid such a disaster should leave a cavity behind the facings, and on the inside build walls two feet thick, made of red dimension stone or burnt brick or lava in courses, and then bind them to the fronts by means of iron clamps and lead.”

16. Temple of Neptune at Paestum

Temple at Paestum showing the lintel construction, noting the Tuscan order of columns.

17. Temple of Hera at Paestum, noting the construction joints in the columns

IMPLEMENTATION: ROMAN

18. Roman Forum; note use of Ionic and Corinthian orders, lintel system

19. Roman Imperial Architecture (Ward Perkins):

Amphitheatrum Flavium (Coliseum), inaugurated in 80 AD.

Note use of different stone based materials, travertine where seen by important public, tufa for less important visual (infill material) and concrete for large structural masses.

20. View of Coliseum: note arches and pilasters and holes in exterior where the iron was removed: note barrel vault

21. Interior of Coliseum
22. Roman Imperial Architecture (Ward Perkins):
Basilica of Maxentius 307-12, completed by Constantine after 312 AD
The central nave measured 260 x 80 feet. Of note are the coffered barrel vaults used to lighten the weight of the structure.
23. Roman Imperial Architecture (Ward Perkins):
Pantheon, c. 118-128 AD
24. Roman Imperial Architecture (Ward Perkins):
Axonometric view and section. The stippled area in the section (here shown slightly exaggerated) represents the masonry added below the structural intrados of the dome so as to complete the visual curvature of the coffering. Coffering done to lighten the weight of the dome.
The Architecture of the Roman Empire (MacDonald): Pantheon cross section
25. The Architecture of the Roman Empire (MacDonald) Pantheon, plan
The structural system of the Pantheon between level II and III
26. Palladio Four Books of Architecture:
Partial front section of the Pantheon. Palladio did numbers of engraving studies of the buildings of antiquity during the Renaissance and published in his treatise on Architecture.
27. Pantheon interior view: the formal scheme of the rotunda is a circular drum half the height of its own diameter (142 feet) surmounted by a hemispherical dome, the crown of which is thus, in accordance with the precepts of Vitruvius, exactly the same height above the pavement as the diameter of the building.

IMPLEMENTATION: GOTHIC

28. The Gothic Vault (Acland):
Romanesque and early Gothic masons used small split rubble stones for the panels of their vaults. Layout was a rough and ready affair with only a few controlling lines or templates. The masons butted their coursing together at the groins, only occasionally keying their stones in alternate projections. They relied upon a heavy coat of plaster to make up irregularities. Evidently it was advantageous to first build a masonry rib as a support and as a cover for this erratic line of intersection. The problem could have been solved by carefully designing each voussoir stone at the groins as a seven sided wedge keyed to the panels of vaulting to make a hidden rib. Eventually this was to be done during the Renaissance but it did involve a disproportionate outlay of time and energy on complex stereotomy or stone cutting. The vault had to be planned and laid out in advance, by the use of three dimensional projective geometry, as a complex of precisely shaped and fitted stones. This was beyond the technical capacity of masons during the Middle Ages. Roughly shaped fieldstone or rubble, broken along the cleavage planes into elongated cubes slightly larger than a brick, was the basic constructional material, restricting their use of cut stone to facings in piers and walls.

External apparatus of the thirteenth century Gothic structural system: shell vaults concentrated loads to the ribs and then to the piers. Vertical loads were carried down the nave piers and thrusts spread through the flying arches to the mass of the buttresses, outside the sheathing wall.

- Thirteenth century Gothic masonry engineering in the nave wall of Notre Dame, Dijon c. 1225 (after Viollet-le-Duc)
29. At Chartres cathedral after 1194 a three tiered buttressing arrangement let the clerestory expand to carry large windows.
 30. Chartres Cathedral, view of ceiling of nave, noting vaulting and ribs expressed. Gothic architecture was later perceived of a structuralist as the architectural expression was in the structure of the building Chartres Cathedral, interior. The change in the attitude of society in respect to the Church and the desire to have the character of the space god-like and upward lifting lead to experimentation in the shape of the arch. These types of arches could be constructed with greater span and height than standard round arches, and the flying buttresses supported the walls to permit glazing, the ribbing in the vaults concentrating the load away from the glazed area.
 31. Notre Dame Cathedral, Paris used flying buttresses which stretched the technique to its maximum potential.
 32. St. George's Chapel, Windsor Castle, William Vertue, 1506-1511
St. George's Chapel, strictly speaking the Windsor vault is not a real fan vault, the ribs did not develop from a conoid surface. William Vertue cut the elaborate interlace of liernes from a thin masonry barrel constructed of carefully interlocked large stones. (Acland)
 33. The Gothic Vault (Acland)
The architect in coordinating the construction of a Medieval cathedral church had to draw upon the skills of many trades and the technical capacities of specialist artisans. Note the use of centering and hoists.
VIA 7 The Building of Architecture:
Illustration of Wood Centering for stone vault construction from the Encyclopedie of Diderot and D'Alambert.
 34. On Adam's House in Paradise (Rykwert)
Sir James Hall, the origins of Gothic Architecture: Small variations in the joining of the willow rods provide the models for the varieties of arching and vaulting. Hall assumes the complexity to have been progressive: so the pointed arch, the clustered column, the branching roof, "the three leading characteristics of Gothic Architecture" have been accounted for. Hall's motive in going through this elaborate exercise is his conviction that before the rise of Gothic Architecture proper, its principal features had appeared in "a more ancient style", and he hopes to restore to Gothic architecture its due share of public esteem" by showing how it derives from a simple timber original, and is consequently systematic, "its authors have been guided by principle, and not, as many have alleged, by mere fancy and caprice."
- Georg Wilhelm Friedrich Hegel: The stones and beams obey the laws of gravity, press downwards, and so high walls are carried up. Thus the elements are made use of according to their nature, and yet cooperate for a product by which their operation is limited.
35. Antonio Gaudi (1852-1926): Sagrada Familia, Barcelona (begun in 1884).
Executed in a Gothic style under the influence of Art Nouveau but elaborated with absolute originality. Sagrada Familia uses images of tree forms on windows -- these calling the image of the bent willow forms that were speculated to form the origins of the shape of the Gothic arch. The frontal columns use tree forms with the benefits of engineering knowledge in order to cant them. Gaudi left a model at 1:25 of the proposed

nave; note the reference to trees and the forest ceiling. Construction slowed down after Gaudi's death and continues to this date. The nave area presently under construction following the completion of the towers (12 constructed in all).

IMPLEMENTATION: RENAISSANCE

36. Filippo Brunelleschi, Pazzi Chapel, Firenze (1430) Renaissance return to classical forms, dome, pendentive. Note plastered surfaces which do not require exact cutting of stones.
37. Andrea Palladio San Giorgio Maggiore (begun 1566) Combination of classical temple forms and round arches and vaulting. San Giorgio, interior view, dome and pendentive. Clean forms, little or no structural expression. Reoccurrence again of plastered surfaces not requiring exact cutting of stone.
38. Palladio Four Books of Architecture:
Palladio's treatise on architecture is in keeping with the Renaissance's reexamination of classical architecture, particularly a reflection on the writings of Vitruvius. Palladio does not prescribe anything new in stone wall construction, simply presents an analysis of all of the different types of construction he has 'discovered'.
Engraving of Palladio's illustrating the geometry of the capital and base of the Ionic column. The Renaissance illustrated an interest in architectural representation and drawing, in two dimensions, and in perspective, and in the areas of mathematics as geometry, that was key for further developments of the 18th century.

THE EFFECTS OF MENSURATION ON STONE:

The Development Of Stereotomy And Stereometry During The Enlightenment

39. Greek Architects at Work (Coulton):
It would seem that the application of mathematics and geometry (mensuration) to the art of stonecutting (stereometry and stereotomy) separated the activity of the masons from the ancients up to the Renaissance from the activities of the masons in the 17th century onwards.
40. Versailles, Louis Le Vau, Jules Hardoin Mansart, 1669-85
It was the Baroque era which brought about the introduction of mensuration, stereometry and stereotomy into the building industry.
Architecture and the Crisis of Modern Science (Perez Gomez)
The use of practical geometry for the tracing of walls and foundations (in order to ensure verticality or symmetry) is obviously as old as the building craft itself. Only toward the end of the Renaissance, however, did concerns with mensuration and topography become more dominant, as the theoretical universe of these sciences acquired greater specificity. The initial attempt to systematize these processes of measurement appeared in Leone Battista Alberti's *Ludi Matematici*. In 1565 Silvio Belli's *Libro del Misurar con la Vista* taught to measure using an instrument, the *quadrate geometrico*, employing the law of similar triangles. Cataneo's publication on mensuration in 1584 was a forerunner of Descartes's analytic geometry but showed how difficult it was to conceive mathematics as an abstract science, apart from reality.

Only toward the end of the 17th century did treatises on practical geometry begin to reveal an interest to relate it directly and effectively to actual problems of building. They

were used with unprecedented importance, becoming essential for the success of any building task.

During the enlightenment mathematics was seen only as a practical tool in texts concerned with building techniques, and its instrumental value in construction programs was recognized by most French architects. The general interest in technical problems and the quantitative methods needed to solve these problems increased considerably throughout the 18th century. Not used as extensively outside France. Began to be taught in the French technical schools during the second half of the 18th century.

The culmination of this process only took place during the early half of the 19th century when the science of measurement and geometrical drawing, the two disciplines that could implement the reduction of the reality of building practices to two dimensions, had become sufficiently systemized.

Versailles, L'orangerie.

41. Architecture and the Crisis of Modern Science (Perez Gomez): Geometric projections applied to the stereotomic description of a vault, from F. Derand's *L'Architecture des Voutes* (1643). Stereotomic virtuosity in the vaulting of the orangerie in the Palace of Versailles, designed by J.H. Mansart (1681-86).
42. Stereotomy, the use of geometric projections in determining the shape and dimensions of stone or wooden elements in arches, vaults, trusses ' stairs ' and domes, was specifically a French concern. De l'orme, 1567, in his book devoted several chapters to illustrate the use of horizontal and vertical projections in determining in two dimensions the precise configuration of complex parts of buildings. The geometry implicit in vault construction and other stereometric marvels constituted both the structure of the work and the ultimate source of its meaning. G. Desargues, booklets 1640 and 1643, but not discovered until the 19th century. Recognized three aspects of any activity: first, the theory (a framework in which to invent and make rules of practice), secondly, the rules themselves as derived from the theory, thirdly, practice, the execution of the rules. Conscious of the fact that no one before 'him had reduced the art of stonecutting to a set of methodical and universal principles. Felt that the architect should provide the craftsmen with precise stereotomic tracings to cut every piece of the stone--to maintain control of the design.

Architects of the Enlightenment not interested in this subject.

THE PRACTICAL APPLICATION OF STEREOOMETRY DURING THE INDUSTRIAL REVOLUTION

43. The Rudiments of the Art of Masonry (Dobson): Published in 1863 (after the exhibition of 1851), one of a rather large series of books of a technological nature. Idea of projections and drawings illustrated in a simple straightforward manner finally so that anyone could understand them. Development of a surface projections to describe the vault.
44. Architecture and the Crisis of Modern Science (Perez Gomez):

Illustration of De la Hire's hypothesis applied to diverse problems in the design of arches, from F. Milizia's *Architettura Civile* (1781)

The creation of the field of engineering and the derivation of the study of Statics and Strength of Materials led designers to be 'more daring' in the design of stone and other buildings. Previous structures were over designed due to the inability to calculate exactly how large piers had to be (for example) to support the load. Now structures could be lightened up.

THE REINFORCEMENT OF STONE WITH IRON: SOUFFLOT

45. Jacques Germain Soufflot, Ste. Genevieve (Pantheon) c. 1770
Frontal view. Designed to be very different from churches at that time. Adopted the Greek cross plan, versus the latin cross plan. The knowledge of structures allowed the lightening of the structure to support the dome which brought on much criticism. The main support port piers actually did crack and in 1806 reinforcement was desired by Rondelet.
46. Claude Perrault. The Louvre.
47. Place de la Concorde. Ange Jacques Gabrielle. Reinforced stone.

MODERN USE OF STONE:

The structural use of stone in architecture has all but disappeared this century. Load bearing construction has been replaced by rain screen walls which apply thin sheets of cut stone to the faces of buildings. These are typically either hung from a steel or concrete structure using stainless steel anchors, or laid up in courses. New technologies have been developed to ensure the durability of this type of stone construction -- preventing water damage, corrosion to the ties and resistance to deflection as a result of wind. Virtually no use is made of the compression techniques developed by stone masons of the past.

The use of stereometry in the shaping of stone pieces is critical in ensuring accurate construction in the modern use of stone. Computers are now attached to diamond tipped blades used in the stone saws to shape intricate multi curved stone shapes.

48. Stone in Buildings: Its Use and Potential Today. Bonded ashlar walls.
Solid stone walls and windows.
49. Modern use of stone has largely been relegated to that of a cladding material. Stone is cut in thin veneers (25 to 75 mm thick) and is hung from the structure of the building using stainless steel anchors as a rain screen curtain wall.