The heritage of stereotomy, and new perspectives for building in a sustainable way

Francesco Bergamo & Gabriella Liva
IUAV University of Venice, Italy

Stereotomy, or the art of cutting solids as it applies to cutting stones, gathered the dignity of a discipline when Philibert de L'Orme published his *Le Premiere Tome de l'Architecture*, in the Renaissance era. The projective questions found a coherent geometrical solution only with Gaspard Monge, but by then the golden age of Stereotomy had already been almost forgotten by architects and builders. Later, Rationalism, Modernism, and steelworks finally led architects and engineers towards totally different conceptions, and shapes. Today we're beginning to see some strong assumptions in the direction both of a renewal of the interest towards this heritage, which demands to be preserved, catalogued and studied, and of new declinations for that knowledge, made possible and necessary by the new digital technologies, also in the direction of building according to sustainable principles, while matching the cultural architectonic request for complex spaces where finally form and structure will match each other again.

1 STEREOTOMY AND CUT STONE IN THE WESTERN WORLD.

Since the Stone Age, and more considerably starting from the Neolithic, mankind has been shaping part of her world by working local stone, one of the most precious natural resources both for making tools, and for building architecture. Egyptians chose stone as their privileged material for cities, monuments and ornaments: the blocks were squared and smoothed for a better performance, while ingenious techniques for their transportation and assembly were invented. Also in the Ancient Greece, the most notable achievement for architecture has been switching from precarious wooden structures to massive and sophisticated stone buildings, whose material allowed them to survive partly even until today, and gives us precise indications about how they looked like at the time of their maximum splendor.

A major improvement took place in the Middle Ages, when the process of cutting stone was planned with high precision, and executed with new techniques and tools; one of the most precious evidence of the medieval art of building is Villard de Honnecourt's sketchbook, dating back to the early XIII century. It is also by studying these drawings that Martin Kimpel (Kimpel, 1977) says that stone cutting in the medieval constructions can be considered an early form of 'serial' production, concerning a sort of standardization of the blocks for certain architectural elements, with a technological evolution during the whole Middle Ages which reached its apex in the Reinaissance and especially in France - for example in Philibert de l'Orme's barrel vault and hemispherical dome at the castle of Anet, where the structural and the ornamental patterns perfectly match each other, and are obtained by repeating the same identical elements within each course. The Italian masters of the Reinaissance, instead, preferred employing complex brick patterns - in the tradition of the Roman architecture and civil engineering - , like what we find in
Brunelleschi's masterpiece Dome in Florence, or in Bramante's helical staircase in Vatican, thus contested by de l'Orme.

As Robin Evan clarifies (Evans, 1995), it's not easy to determine a precise moment of birth for stereotomy - or the art of cutting solids, as it applies to cutting stones with architectural purposes, so to form a geometrically complex and coherent structural element without the need of mortar or glue : it relates to different 'major' disciplines, arts and crafts, and it can fit different declinations according to different techniques and historical periods. The word stereotomy - from the Greek, composed of stereós (solid) and tomé (cut) - has been written for the first time, from what we know, by Curabelle in his pamphlet *Examen des ouvres du Sieur Desargues*, which severely criticized Desargues' geometrical methods. Thus, applying this word only to the field of architecture can be reductive, since it could be extended more widely to any material (for example it is less know, but anyway interesting, the stereotomy of the wood), and any discipline where a complex spatial configuration needs to be 'cut' or subdivided into manageable pieces; but, nonetheless, by means of the weight and durability of stone and of gravity, architecture has been led by this specific approach to produce incredibly complex structural and formal configurations, as in the exceptional case of the vault of the Hôtel de Ville in Arles, by Jules Hardouin-Mansart and Jacques Peytret, who in the second half of the XVII Century not only designed the shape, but also the constructive process. According to Pérouse de Montclos, what begun to be codified during the Renaissance was a sort of elaboration, according to some new projective devices, of some older works in the southern France, like the Pont du Gard, the Temple de Diane, and the arenas of Nîmes and Arles. But even the Eastern cultures, and more specifically the Syrian buildings seen by the Crusaders, might have influenced the French approach of building with cut stone, according to Eugène Viollet-le-Duc.

Stereotomy got the dignity of a specific matter of study, merging mainly Construction Science and Projective Geometry, when Philibert de L'Orme wrote and then published his theoretic and applied knowledge, a sort of magnificent implementation of the most advanced Medieval stone masonry, in his *Le Premiere Tome de l'Architecture* (1567), published for the first time in Paris. Until then, the method of the trait (with the specific meaning of preparatory geometric drawing) had not been applied 'scientifically' to the stone cutting, which earlier relied upon a corpus of orally transmitted knowledge that de l'Orme knew very well, being he the son of a master mason, but that still missed the link with the tools given by Euclidean geometry.

If the projective questions found a coherent mathematical and geometrical solution only with Gaspard Monge in the late XVIII Century, by then the golden age of stereotomy was already almost forgotten by architects and builders, even in its homeland France. Rationalism, Modernism, and steelwork then definitively shifted the interests of architects and engineers towards totally different conceptions, and shapes.

2 PRESERVING AND LEARNING FROM OUR HERITAGE.

Except for the bare fact that it's 'almost been forgotten', why should we start studying stereotomy again? Is its heritage worth, and can it teach something to the planners and designers of today, who face a quickly changing technological world and are required to build in a sustainable way? First of all, we should notice that there is still much to do about preserving, understanding and transmitting to the next generations the heritage that we have at disposition. The fact that stereotomy is not studied anymore in most of the schools of architecture doesn't mean that it could not provide planners with important theoretical and practical instruments for building with more awareness, even reducing the waste and excesses of materials, and employing sustainable, natural or recycled substances. In the second instance, the word stereotomy is nowadays employed with different shades by some architects and designers who are interested into exploring the possibilities of the digital technologies, without ignoring their cultural and multidisciplinary implications, and while trying to overcome the mismatch between form and structure that is so evident in the architecture of Frank O.Gerhy and many other 'Deconstructivist Architects'. The researches of Philippe Block, for example, aim at building in a sustainable and coherent way, and their starting point is thus studying the 'classic' stereotomy, plus other systems like the Catalan vault, since the purpose is that of building very complex shapes, where the surface is also the structure.
2.1 The case of Philibert de l'Orme's stereotomic inventions in the Castle of Anet.

The underrated and partly unknown architecture of the Anet complex is an important indicator about the danger of losing this heritage: there we find the first important innovations introduced by Philibert de l'Orme, with the construction, around the half of the XVI Century, of the Castle for Diane de Poitiers and Henry the II. De l'Orme concentrated in this site four stereotomic masterpieces: the first big dome, a vis de Saint-Gilles staircase, a cryptoporticus, and the famous trompe. The cryptoporticus’ geometric and configurative analysis here presented is based upon the integration of different sources – written, graphic, and coming from a survey made by dott. Lisa Martini –, in order to explore the hypothetical surfaces shaping the vaulted space. We think that a 3D laser scanning survey could provide more information, and more precise, for building and verifying the virtual clone of this structure. Anyway, confronting the available informations (what remains, and some drawings) and guided by Projective Geometry, it’s been possible to draw the Mongian projections of what should have been its original aspect, according to de l’Orme's intentions. This first analysis shows how the cryptoporticus’ conception grounds upon a repetitive game, in plan, of circular periodicity. Also in the elevation, circles and ellipses are used again to trace the outline of those arcades which enter the different vaults. The cryptoporticus, edificated between 1549 and 1552 and mostly destroyed during the French revolution (Fig. 1), is a longitudinal space delimited, in its heads, by two overhanging lateral pavilions, connected to each other by means of a balcony, above the cryptoporticus itself. This long gallery is completed on its extremities by two apse spaces, each covered by a lowered half-dome (Fig. 2); but the most fascinating part of the cryptoporticus is its connection with the monumental staircase, whose vault is designed according to the vis de Saint-Gilles, its impost plane consisting of an helical surface.
In the digital model, here presented through its renderings, the *épure* proved to be a useful tool for cutting also the 'digital stones', while the master mason used to trace them in their real dimensions on the ground, or on a wall surface wide enough. By means of 3D modeling softwares a digital clone of the lost structure has been created, for reproducing its configurative problems, and for contributing to save its heritage, either in the case that someone will decide some day to restore it (starting from the 3D model, it would be possible cutting the stones automatically with CAD-CAM operations), or simply to make it virtually explorable by anyone interested. The aim of this research was the stereotomic definition of the cryptoporticus’ most meaningful parts. For the cut of the spherical surface’s stones, thus double-curved, it’s been adopted the principle of ‘reduction’ of the sphere to a set of coaxial cones circumscribed to it, permitting to the develop the vault’s horizontal courses, which consequently grants with sufficient approximation the definition of the different *panneaux* (panels). The problem of developing a surface on a planar panel might appear obsolete today, since we have CAM machines milling or founding complex surfaces, which are subdivided into and approximated with small polygonal areas - as for the STL interchange file format -, but was of course relevant when the *panneaux* were the main reference for the stonemasons’ work in a complex construction like this. Besides the *panneaux*, other indications consisted in the metric and angular dimensions of the stone ashlar’s contours, drawn upon the block, previously squared.

The same approach has been adopted also to define the geometric-configurative components of the second element: the staircase (Fig. 3). The theme had been developed by de l’Orme starting from the very first years of his profession, when he reached the apex of the art of trait both for the complexity of its design, and for its formal richness. The staircases of Anet, of Fontainebleau and of the Tuileries testify this richness by themselves. He previously studied the solution used in the helical staircase in Vatican, credited to Bramante: here the helical ramp, supported by a barrel vault, yet diverges from the *vis de Saint-Gilles* because its core is substituted by a colonnade that, allowing the presence of a central void, also allows the light to penetrate in the stairwell. Although Bramante isn’t directly quoted as an inspiration, his lesson is clearly un-
understood by Philibert de l'Orme, who based the program of his work upon matching the Belvedere staircase's shape with the geometry of the *vis de Saint-Gilles*.

The staircases upon the vault, unfortunately, have been completely destroyed, and it’s thus difficult to imagine the exact configuration, and the consequent ornamentation, adopted by de l'Orme. However, it is possible to advance at least one hypothesis about the style: by studying the staircase from a purely geometric point of view, through the Bougeois drawings, the first evident surface is the one ruled by the helix; upon this surface, the overhanging staircase stands. The *vis de Saint-Gilles*, the most interesting configurative element of the staircase block, is here found in the vault’s intrados, below the helical stair: we’re dealing, more specifically, with a vault whose impost surface results to be helical, whose generatrix is a round arch, and with a cylindrical helix as directrix. The stairwell is delimited by two cylindrical parts whose directrices are curves composed of mutually tangent circular arches. The openings, in these walls, are obtained by intersecting a number of cylinders with horizontal axes, and whose directrices are rampant arches. The stereotomic reference is that of opening an arch in a cylindrical tower: it’s a surface know also as conoid, having a quartic arch as curvilinear directrix. Once we’ve understood the praxis of Philibert De L'Orme and how he delighted in exercising his imagination and the *trait* science, it’s necessary to understand what creative process led him to think that, against the commonly apparent laws of equilibrium, the *vis de Saint-Gilles* could stand without the central core and remain - as it was in fact - hanging in the void. The development of a ring vault is obtained by considering the surface as enveloped by a series of cones, just like the domes' ease. We realize that this vault, also called vault *en bercou tournant*, comparable to a vis de Saint-Gilles but without sloping, could be described, as we said earlier about the dome, by the development of the correspondent cones. The sphere and the ring (or toroidal) vault are both double curvature surfaces, and the transition from the shape of a dome to the one of a vault *en bercou tournant* is essential to understand the geometric-configurative character of the *vis de Saint-
The analysis of the shape makes him ‘discover’ that the vis de Saint-Gilles is morphologically closer to the sphere – with which it shares, as said, the characteristic of a double curvature – than to the barrel vault: this structure needs a keystone, while the first one stands simply by its geometric configuration.

The trompe of Anet has been destroyed too, but it is probably the most studied and well known object designed by Philibert; and, luckily, both the barrel vault of the castle and the dome of the church are still existing, displaying an astonishing coherence between the ornamental system, and a sort of ‘prefabrication’ where the many stones are cut with the smallest amount of épures. As we said, for de l'Orme, and for many after him, stereotomy is articulated around an element of fundamental relevance: the panneaux. As Philippe Potié proved, the modular technique employed to organize the stones – where the decorative pattern is an essential component of their design – is chosen in order to reduce to the minimum the number of the required silhouettes: in fact, for the barrel vault only the panels for ten shapes of stones are needed for realizing the whole vault. In this way, the productive sequence offers, through the panel, the common module articulating the vault's orthogonal appareil and the decorative interweaving, which creates a wisely cadenced counterpoint.

2.2 Watching at the heritage through the lenses of digital technology: towards sustainability.

Among the reasons why the interest towards stereotomy has almost disappeared in the past two centuries, after being more and more often relegated to treatises of geometry or civil engineering, one of the most relevant is for sure related to the new materials and techniques spread by the Industrial revolution. The right angles and an average lowering of the complexity of the surfaces is partly due to iron beams and pillars, glass panels, and prefabricated elements. Concrete offered and offers the possibility of being shaped as it were a 'liquid stone', but very few are the planners who use it in this sense. Even Mendelsohn, in his celebrated Einstein Tower, is forced to compromise with difficulties and to build it partly in bricks. If cast concrete already marks a shift toward a 'stereotomy of the surface', because of the necessity of designing the surfaces of the formworks, Semper's conception of stereotomy as 'building massively' is definitely subverted by Preston Scott Cohen, who goes back to the projective origins of this art, matches it with perspective deformations and skiagraphia - especially recovering Brook Taylor's theoretical apparatus about perspective, and making of it the basis for his permutations (Scott Cohen, 2001) -, and finally turns it into a strategy for designing architecture according to the contemporary condition and the technologies of today, but focusing mainly on the surfaces, like what happens in the project for the Torus House, where the characteristics of the ancient villa are deconstructed around a revision of the toroidal surface where a topological continuity persists, cohabiting with the folds of the rhizome clinging to the landscape.

Besides the formal and geometric approach, we think that digital technologies and their new tools would enhance (and be enhanced by) the study of stereotomy, and could suggest on its base new ideas for building in a sustainable way. As we introduced earlier, this second reason of interest (or looking at the future with the tools of the present), and without forgetting the heritage of the past, is clearly shown in the recent researches conducted by Philippe Block. The Catalan vaulted system - especially as applied by the Gustavino's in Boston - and the principles and examples of stereotomy - such as the fan vaults of the Lady Chapel in the Westminster abbey - served as a starring pint to develop an innovative method for the structural analysis, called Thrust Network Analysys and based upon a geometrical analysis (in Rhinoceros) leading to an automated computation in MATLAB. Not only he and his team built huge vaulted systems, very resistant, with very thin sustainable bricks, but he's also now experimenting with stone, for a more complex spatial configuration. And, if Block considers CAM machines an opportunity to build a vault out of unique complex pieces, Kengo Kuma, following his philosophy, employs simple squared elements for building the texture, which is also the structure, of his Stone Pavilion, or the Chokkura Plaza.
CONCLUSIONS

We see at least two important reasons to start studying and teaching stereotomy again: the heritage we have at disposition, which has still much to be taken care of and being understood in depth, and a renewed interest of architecture towards complex configurations one side, and sustainable building on the other, also trying to solve the mismatch between form and structure introduced for allowing the construction of deformed and warped spaces (Vidler, 2000).

New widespread technologies like the softwares for 3D modeling, laser scanners, CNC machines and rapid prototyping are showing their versatility by serving everyday new applications, and according to us they constitute a third important reason for researching about stereotomy from innovative points of view (for example, topology already introduced interesting conceptual innovations about generating complex shapes by deforming simpler ones, cfr. Fig. 4). Moreover, these tools can improve the accuracy of the control upon the final configuration, in the planning phase, and guarantee a precise finished product, somehow redeeming the loss of the artisans stonemasons, with the advantages of a serial production even when manufacturing unique pieces. It will be interesting to see if this approach will be proved to fit the conceptual and formal demand of planners for today's society, and how they will greet it; in the meantime, and in order to get an answer, it would be useful making them aware of its existence.

REFERENCES