Construction History and Experimentation

Joël Sakarovitch

“Those who only master theoretical geometry are usually rather clumsy, while a craftsman who only understands experimental geometry is a narrow minded worker…” wrote Diderot in his *Plan of a University for the Russian government* (1773). Similarly: “it is difficult, not to mention impossible, to take practice further a field without speculation, and reciprocally to speculate without practical experience”. The necessary alliance between theoretical knowledge and practical know-how in teaching is therefore not a novelty as such and was very much part of the Enlightenment philosophers’ thinking. D'Alembert in the *Encyclopaedia* (for example, the item "Application") or Condorcet in his report on public education, which he presented to the Legislative Assembly in 1792, defended the same idea. But although the law, which was drawn up in accordance with Condorcet’s intentions, was voted for by the Convention in 1794, it was in reality never implemented. Thus, if the idea is not new, neither is the failure to apply it, at least in France.

Seeking, as it were, to train architects that would be neither “clumsy” nor “narrow-minded”, a number of lecturers and professors in French schools of architecture fought for about 15 years to establish a place that would allow the old dream of the Encyclopaedists to be realised – at least with regard to the teaching of construction. Without having to trace its origin back as far as the 18th century, the idea was to set up an interactive form of construction teaching in architectural schools, in the lineage afforded by the Bauhaus in the Thirties or the teaching promoted by a few pioneers such as B. Fuller, R. Le Ricolais or F. Otto, i.e. by combining the quest for theoretical principles and the execution of innovative constructions. Thus the opening, in January 2002, of the “Grands Ateliers de l'Isle d'Abeau », or GAIA for short, about 30 km from Lyon (France), rooted in a long tradition of pedagogical intentions that were, for the most part, never put into effect. This centre for experimentation on construction practice is common to five schools of architecture, 3 engineering colleges, and 3 art schools, and is also supported by industrial partners. However, the project was mainly developed by staff from the research laboratories in architectural schools, who were keen to see large-scale experimentation used as a means to carry out research experiments and to teach construction.

Personally, as I do not teach construction *per se* but the history of construction, I somewhat diverted the prime objective of this experimentation centre, with the graceful complicity of the GAIA directing team. Indeed I proposed subjects that belonged entirely to my own field of research and involved both historical and constructional problems. In the six five-day workshops that I have supervised since GAIA was opened, I have used large scale experimental projects to try and place students in situations where the history of techniques, of materials, of mathematical modelling, of geometry, of spatial representation might be serially or simultaneously applied, while never losing track of the relationship with the history of construction and architecture. The topics chosen were always vault or dome constructions, with or without the use of mortar.

I followed the same organization pattern in all the workshops:

1. To begin with (approximately half a day), the subject and relevant historical references are presented,
2. Then the construction stage, which takes two and a half to three days; for practical reasons, and given that the school is far from our school in Paris, this phase cannot really be extended,
3. Followed by a period testing static behaviour,
4. And finally, disassembling the construction and putting away the building material.
5. Back in Paris, the students review and analyse their experiments and prepare a written summary.

STEREOTOMY WORKSHOPS

The very principle of decomposing dry-stone vaults into small-size elements makes stereotomy one of the areas of choice to analyse the way problems of geometry, statics, construction and aesthetics are articulated. Erudite dry stone architecture is probably one of the first examples of constructive geometry in terms of the relationship between the characteristics of the material used, and its capacity for constructive efficiency. Stereotomy also provides an excellent example to make people understand that, in architecture, there is no “geometry without material”, which is to say that one cannot build without prior drawing nor draw without prior knowledge of the material and how it is to be used. Indeed the drawing of each panel does not only depend on the geometrical shape of the arch-stones, but also on the way each stone face is cut.

Finally, the aim of the stereotomy workshops is also to allow stone to be rediscovered as a construction material. A noble constructional form from Antiquity until the 18th Century, erudite dry-stone architecture was not only what Claude Perrault described as, “the most refined and artistic form in architecture”, but also represented the “high tech” of construction, at any rate between the sixteenth and eighteenth centuries in France and Spain. In view of the variety of covering surfaces erected, the use of cantilevers and the span this allowed, this construction technique remained unrivalled until the advent of iron and concrete.

For all these reasons, I decided to propose large-scale experiments in stereotomy as part of the GAIA projects. For students of architecture, therefore, certain aspects of the stereotomy workshop belong to the realm of knowledge archaeology, which involves discovering the tools as well as the drawing and cutting techniques of stone craftsmen. But this workshop also includes a prospective feature. Thanks to new extraction and building procedures, stone might also recover a place in contemporary construction, if contracting authorities and leading contractors are willing to relearn to use it in situations other than restoring historical buildings and cladding façades. The possible reuse of stone also requires resolving the difficulties encountered in justifying the very specialised building of dry stone vaults by calculation sheets, and to work out the multidirectional distribution of stress. As with all "traditional" forms of construction, there is to date no satisfying theoretical justification for this construction technique, which therefore excludes it from European norms of construction. The experiments run in the stereotomy workshop also aim at participating in the elaboration of such norms.

The three stereotomy workshops that I supervised focused on the building of flat vaults **(figure 1)**. The flat vault on a square plane, this little marvel of statics and geometry, borrows from the principle of the sedan chair, applied so as to obtain a frame of the herringbone type. Conceived at the end of the 17th Century by the French architect and engineer, Mr Abeille, the principle of this technique was published for the first time in a treatise by Frézier (1736). The only known example of this belongs to Spanish 19th Century stereotomy (see Rabasa, 2000).

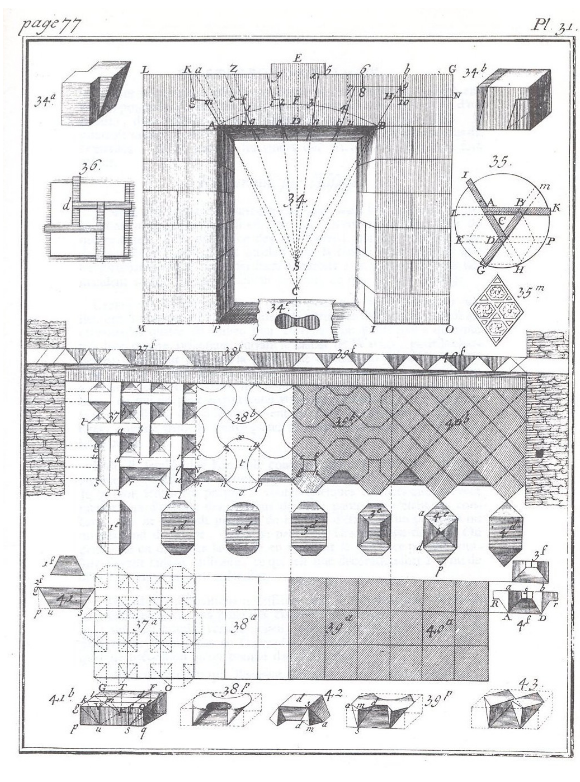


Figure 1. The principle of the flat vault Frézier, 1736, *Des voûtes plates* , Tome II, pl.31, p.77.

This initial exercise in stereotomy was chosen for three reasons: first of all, the relative simplicity of the arch stones allows the central stones to be cut at the quarry, which is useful given the small amount of time available (two and a half days for stone cutting), leaving one with the sole task of cutting the edge voussoirs. Furthermore, while the shape of the voussoirs is simple, their assembly is clever and the static behaviour of the whole structure is *a priori* surprising. Finally, the aesthetic effect is interesting and the possible prefabrication of such vaults could make them marketable.

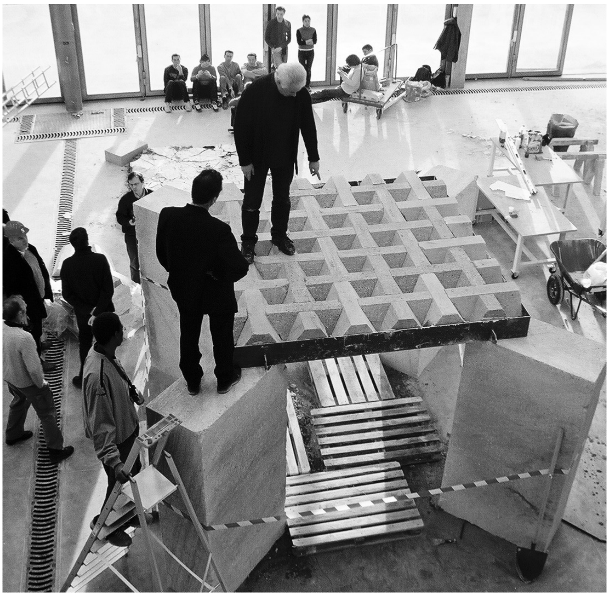
The flat vaults built at GAIA, on a square plane with sides of 2.4 to 3 m, comprised 36 to 81 voussoirs (of about 60 x 30 x 20 cm), cut in soft limestone (third choice so as not to be too expensive) from a quarry near the Pont du Gard Bridge. At the first congress on construction history in Madrid in January 2003, I ended my introductory talk on stereotomy by a brief presentation of this first vault (with sides of 2.4 m), assembled in a metallic frame **(figs. 2-4)**.

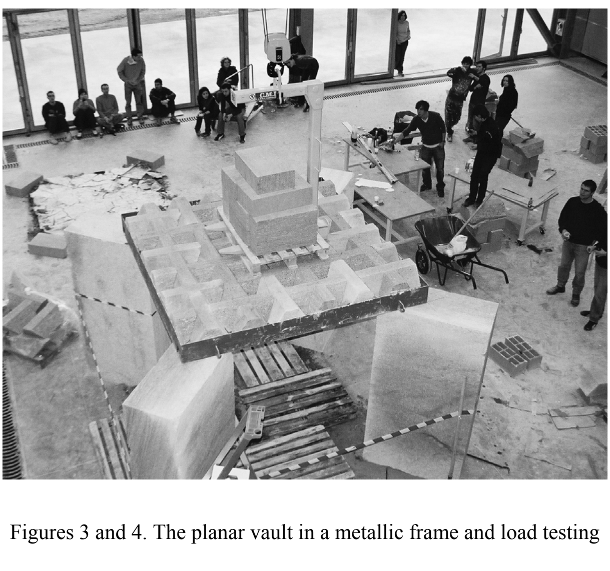
Figure 2. Cutting of voussoirs

Emboldened by this first success, we attempted to conduct a second experiment with an additional double objective:

1. Increasing the breadth of the construction to about 3 x 3 m in order for it to attain "useful", habitable proportions.
2 Achieving something we had not been able to do during the first experiment, which was to measure the lateral pressure exerted by the vault

Furthermore, we tried a "stone only" presentation and conceived a scheme to avoid using a metallic frame. After having installed supporting blocks at the periphery, the stones were first assembled on the ground to be checked and then placed on a formwork 2 metre above the ground. Detectors were installed to measure the distortion due to the lateral thrust exerted by the vault, after which we removed the formwork. A “slippery soap effect” appeared, the edge voussoirs started to slide and lift up, thereby causing the vault to collapse. As any failure, this example was very instructive. It is also rather hard to accept, both for students and teachers, but it is a risk inherent to teaching that involves experimentation. When restricting vault representation to computer imaging, the risk is certainly not as great.





Figures 3 and 4. The planar vault in a metallic frame and load testing

Not wanting to remain with a feeling of failure, we programmed a third flat vault of intermediate size (8 x 8 voussoirs, instead of the 6 x 6 for the first and 9 x 9 for the second). We returned to the principle of a surrounding metallic frame. The result was equally “intermediate”: we were able to lift the vault, but could not run a load test even though the vault was very well adjusted and locked in its frame. The metallic frame had not been made according to the plans that had been sent. Instead of using H-shaped iron sections, which offer good resistance both vertically and horizontally, U-shaped iron sections were assembled, which offered good vertical, but inadequate horizontal resistance.

One can easily see on the photograph **(fig. 5)** that the frame is beginning to bulge and that the vault is sagging. The problem with this type of vault is that as soon as it begins to sag, the sharp angles of the stones disintegrate - and even more so when the stone is not of prime quality. We were nonetheless able to test the vault in both directions since one of the characteristics of the flat vault is that it can be assembled both ways, with the alveoli serving either as intrados or extrados.

Figure 5. The underside of the vault, showing the frame beginning to bulge.

MASONRY WORKSHOPS

Alternating with stereotomy workshops, I also organised three masonry workshops.

The Byzantine Dome

During the first workshop **(figs. 6- 8)**, we built a pendentive dome flanked with a brick *cul-de–four*. In order to be able to recuperate the building material, we used clay mortar. This exercise was in fact supervised by Patrice Doat from the Grenoble School of Architecture, who first devised this type of large-scale clay experiment a long time ago. Before GAIA was opened, he would use the basement or the parking lot of the Grenoble School. Another objective of GAIA is to promote exchanges between teachers and allow others to benefit from the experience that some of us have acquired in the field of building experiment.

The dome was assembled with mortar made up of 80% sand and 20% clay, which allowed the disassembly and reuse of the bricks and the mortar itself. This technique, whereby materials are completely recycled, was painstakingly worked out by the CRAterre Laboratory of the Grenoble Architectural School and its use enormously reduced the cost of each of the construction experiments. It represented a great advantage since the costs of this kind of exercise can quickly become prohibitive. The construction began by mounting arcs on formers that are prepared in advance, then adding the pendentives and finally the dome itself, using a measuring rod. To allow more students to work simultaneously, we flanked the dome with a « *cul-de-four* ».

Figure 6. A pendentive cupola flanked with a *cul-de–four,* and exercises of dry brick assembly, without mortar

One of the problems in the management of such exercises is to give all the students something to do throughout the workshop. For example, when the building of the dome is not far from being finished, few students are able to work simultaneously. For this reason, in parallel with the construction of the dome, various manual exercises of dry brick assembly were proposed, such as the construction of trulli and pointed or chain arches using mortar only for the keystone, on which we conducted crash tests.

Dome "à la Brunelleschi"

The following masonry workshop is a cross between the preceding one and Salvatore Di Pasquale's analysis relative to the construction of the Florence dome (Di Pasquale, 2002). Di Pasquale's essential idea is that in order to build the Florence dome without a centering, Brunelleschi erected it like a revolution surface dome, even though it is traced out on a polygonal plane. This very seductive construction hypothesis about *Santa Maria del Fiore*, provides an excellent subject for experimentation.

Figures 7 and 8. The construction of the cupola with clay mortar

We built a dome **(figs. 9 -10)** of approximately the same size as the previous one (about 3 m in diameter) on a hexagonal base. I chose a hexagonal rather than an octogonal base in order to exaggerate the difference with a round dome. We then placed exterior guides in order to follow the curve of the cylinder portions of each facet and used an internal measuring rod to erect the dome as if it were a revolution surface. Having reached a certain height, one can easily see that the bricks festoon and follow the cone/cylinder intersection curves. An opening in the drum was created after the construction was completed. Demolition was achieved by lifting part of the dome with a rolling bridge, which allowed destruction of the dome without breaking too many bricks.

Figures 9 and 10. A polygonal cupola erected like a revolution surface dome :
the bricks “festoon” and follow the cone/cylinder intersection curves

This experiment is an important example for me in more ways than one:

1. The idea is derived from an analysis pertaining to the history of construction.
2. The construction principle that Di Pasquale attributes to Brunelleschi, according to which the outer form does not necessarily explain the construction mode, is not only simple to

illustrate experimentally with a single example, but also very general and enriching pedagogically.

3. The Byzantine dome exercise made it possible for the pedagogical team of the Paris-Malaquais architectural school to acquire a first experience in clay mortar manipulation and in organising this type of construction work, and to take advantage of all the experience accumulated by Doat and his laboratory. Without this first experience, I would have never been in a position to think about the possibility of building a dome in the style of Brunelleschi. But the Byzantine dome remains rather elementary from the geometrical point of view, whereas in the latter example, the brick beds, which follow cone/cylinder intersection curves, already have a sufficiently unusual geometry for the students to find them difficult to visualize.
4. It is easier (for students) to build the intersection curve physically than trace it on a sheet of paper when asked to make a drawing of it. As with the square-cutting technique for stone, the student is placed in a situation where he/she can build an element that is more complex geometrically than what he/she would have been able to draw let alone imagine and there are good reasons to think that this type of experience provides very valuable training in spatial visualization.
5. Like its geometry, the statics of the vault is also richer in this second example. The keystone effect of each row is indeed all the more striking in this case for being unexpected, whereas it is very natural not to notice it in a revolution surface dome,

Thus history of construction, constructive geometry, statics, materials science and building site experience are closely interwoven in this example.

Catalan Vaults

The last example of masonry vaultwas built following the technique used for Catalan vaults, the construction of which is quite remarkable given the great simplicity of execution for a competent mason in relation to the complexity of the surfaces generated. The characteristic of this construction is that it is achieved without centering, merely owing to the properties inherent to the plaster and flat brick materials, which are quick-setting and light, respectively. This association allows the formation of a cohesive structure that is different from the stone arch structure, which is based on gravitation. This session was made possible by the participation of Riccardo Gulli and Giovani Mocchi, who had already built such vaults, run similar building experiments with students at the University of Bologna, and published several works on the subject (see for example 1995).

Three vaults of very different size were built in this workshop. The main vault was a tunnel/barrel vault of 2.5 m wide and 3 m long, with a circular oculus overhead. It was built with three layers of flat bricks (25 x 20 x 2.4 cm) and assembled with quick-setting cement. The construction work began with the building of guides and quick-setting cement dosage experiments. Two rows were erected in full respect of traditional Catalan vault craftsmanship, without a former or guide **(fig. 12)**.

However, in order to facilitate and accelerate construction – and given the simplicity of the shape of the main vault – the other rows were layered using a guide.

Figure 11. Catalan vaults

In parallel to the construction of the main vault, and because all the students would not have been able to work simultaneously on the same vault, we launched the construction of two subsidiary vaults: a conoid vault, which formed a lunette to the main vault and the under-face of a staircase. These vaults were built with two layers of 14 mm-thick 12 x 16cm flat tiles that were re-cut if necessary.

For the conoid vault **(fig. 14)**, a wire guide was set up, which allowed the shape to be followed but could in no way serve as a former, unlike the guide used in the main vault, which had an in-between ambiguous role. Load tests were conducted on the conoid vault (approximately 350 kg) without pursuing the tests until it collapsed. The staircase under-face was built by leaning it on a rapidly erected dry stone wall onto which it was attached, as well as two wooden cheeks forming a chain-like formwork **(fig. 15)**. On this formwork, and following the perpendicular to the lateral chain work, a shape was placed to generate a double-curvature intrados in the vault.

Like the “Brunelleschi dome”, the Catalan vault session perfectly illustrates the interweaving of history of construction, constructive geometry, materials science, and construction work. Something specific to this particular session was the great freedom this construction technique offers: the subsidiary vaults were practically improvised, the students choosing examples among those that had been shown to them during the introductory talks. The students really appreciated this freedom of choice, as they were able to influence the subject of what they were about to build, which was not the case in the sessions described earlier. Finally, from a structural point of view, these examples demonstrate very well how shape influences resistance and provide spectacular illustrations of varied spans and covers achieved using very simple and low-cost building techniques.

Figures 12 and 13. Construction of the barrel vault without a former or guide.
The same with a guide

CONCLUSION

One cannot deny that students are very keen on this type of teaching. For the 24 places available per course, we get 80 to 100 applications. These figures are not in themselves proof of the relevance of this kind of approach, but other than being always pleasing for the teachers who propose the workshops, they undeniably show that the students are eager to have "hands on" experience and opportunities. There is good reason to believe that the more CADD, virtual images and paperless architectural studios are used in architectural schools, the more students will seek opportunities to be in contact will real materials and building sites.

> All the ostensible work involved will consist in graphical constructions and drawings. Such drawings and constructions demand meditation on the part [of students]; but there will be no time dedicated solely to such meditation; the latter will take place throughout the duration of construction and the student who will have simultaneously exercised his intelligence and manual skills, will gain from this dual work the exact description of the knowledge he will have acquired"
>
> (Monge 1795)

Figures 14 and 15. The construction of the subsidiaries vaults:
a conoid vault and the under-face of a staircase

With these words, Gaspard Monge was highlighting what in his eyes was one of the specificities of descriptive geometry scale drawings, and no doubt their main justification. The disappearance (or quasi-disappearance) of descriptive geometry teaching from the architectural schools no longer makes this discipline a possible basis for this pedagogical objective. But, while the basis has disappeared, the objective remains. And it is essential to find pedagogical situations that simultaneously allow the use of one's "intelligence and manual skills", constructions "that demand meditation [without there being] time dedicated solely to such meditation". The nature of the workshops at GAIA seems to me to be such as to be able to play this role, and probably more so than descriptive geometry classes, at least for the training of architects. By placing the construction work rather than drawing at the centre of pedagogical training, these workshops allow one to rediscover the complexity inherent to the multi-faceted act of building.

It is no less undeniable that this type of experience cannot replace theoretical and structured courses on construction or the history of construction. The great difficulty is in making such practical experiences hinge around a theoretical course in order to exploit the wealth of such workshops to the full. I must say, I find it difficult to articulate the two for the moment, especially since I do not teach construction directly. This difficulty is enhanced by the workshop organization itself, since there is a mixture of first- to fourth-year students, all sharing a moment designed to be a break from the normal curriculum. It is therefore not possible to work with all the participating students after the workshop has ended.

But whatever the reservations one might have, it seems to me the GAIA workshops such as the ones I have just described, or the ones organized by some of my colleagues, have profoundly renewed the teaching of construction in our architectural school by reintegrating a practical aspect that was cruelly missing and have initiated an original way of teaching the history of construction.

REFERENCES

Di Pasquale, S., 2002, *Brunelleschi. La costruzione della cupola di Santa Maria del Fiore*, Venezia: Marsilio.

Frézier, A.-F., 1736-39. *La théorie et la pratique de la coupe des pierres et des bois…*, Paris (reed. 1980, Paris : Jacques Laget).

Gulli, R. and Mocchi, G., 1995, *Bovedas Tabicadas. Architectura e construzione*, Venezia: Edistampa.

Rabasa-Diaz, E., 2000, *Forma y construcción en piedra. De la canteria medieval a la estereotomia del siglio XIX*, Madrid: Akal.

Sakarovitch, J., 2003, “Stereotomy, a multifaceted technique”, in Huerta, S., (ed.), *Proceedings of the First International Congress on Construction History*, Madrid: Instituto Juan de Herrera, pp. 69-79.

Archives de l'Ecole polytechnique

Monge, G., 1795, “Procès verbaux des séances du conseil d'administration de l'Ecole centrale des travaux publics” (Reports of the Administration Board Meetings of the *Ecole Centrale* for Public Works), 20 pluviose an III.