In the latest years there is a growing interest for the revaluation of the European tradition, culture and constructive natural materials (i.e. stone), and for the elaboration of a new rehabilitation strategy in the light of a sustainable management and preservation of cultural heritage.

In the European area, characterised by the generalised use of load-bearing masonry systems with an organic character in traditional construction, the typological and constructive reform of traditional vaulted systems is a central question. The importance and cohesion of this cultural area, but also the extremely diffuse use of stone techniques, enables us to propose their reintroduction into contemporary restoration and constructive practices.

For many years the architectural research has been dominated by the use of «new materials» and the interest on vaulted systems (especially made in stone), has been relegated only in the direction of historical studies and in that of surveys and reconstructive analysis.

The complex examples of vaulted systems contained in the historical treatises on stereotomy, have been basically «ignored» in the architectural and engineering practice in favour of an exemplified and reductive «modernist» formal repertory.

In the next years, architects will be mainly involved in a complex work of re-assessment and renovation of both historic landscapes and of the urban environments, and the recognition of the intrinsic qualities of traditional materials and techniques (in terms of durability, performance, aesthetic quality, etc.) is self-evidently urgent, such as the elaboration of updated architectural solutions for stone vaulted systems.

A first attempt in this regard is represented by the model of a reinforced «flat-vaulted» system, specifically elaborated for the reconstruction of the Casa del Guarda covering system, at the experimental construction site at the Pontón de la Oliva (Spain, 1851–58), that could also be regarded as a remarkable example of a stereotomical application in hydraulics. In fifties it was substituted with a reinforced concrete roof.

The project of the earth dam at the Pontón de la Oliva at the beginning of the Canal Isabel II (the channel which still provides water to the city of Madrid), reflects the social and productive situation of the country during the last century. In Spain the long tradition of stone techniques, achieved in the previous centuries and formalised in the Spanish historical treatises, was utilised for solving the problem of resisting the water pressure force by means of a cut-stone masonry structure.

This well-established and long tradition is an important element for the comprehension of the formal and constructive characters of the interesting solutions realised within the site, such as the unique and original example of the «flat-vaulted» system at the «Casa de Mina de Limpia». 
The analysis of the survey data of this dry-assembled stone masonry flat-vault was the preliminary condition for the elaboration of the reconstructive hypothesis.

The great problem before the «modern era of concrete» was the use of no-tension materials (such as clay and mud or masonry) to face flexural out of plane actions, to which these materials are not able to react appropriately. For this reason specific tectonic knots, solutions of contact surfaces among elements and of chain and supporting elements had been elaborated and improved.

Therefore the paper intends to highlights the tectonic principles and the traditional syntax, and to explain the complex passage from the geometrical model to the real model of the «flat-vaulted» system, throughout the graphical one (which also involves a reflection on the updating of traditional stonecutting methods, i.e. cad-cam processes).

**Stone Techniques for the Nineteenth-Century Territory’s Infrastructures: The Project of the Canal Isabel II**

On 16th July 1851 the Administrative Council of Canal Isabel II appointed four engineers of the Cuerpo de caminos, canales y puertos for the redaction of the executive project of the canal derived by the Lozoya river, that, in the following years, had to almost duplicate the water supply of the city of Madrid (Fig. 1).

**Figure 1**

Planos generales del Canal Isabel II (1851). Archivo Central del Ministerio de Fomento. (supplied by J. J. Gonzales Reglero)

The project of Canal Isabel II was a political and technological event. On the one hand the President of the Government, Juan Bravo Murillo, strongly promoted the realisation of a modern service for the expanding city of Madrid as a reply to the crescent needs of pure water for both domestic and industrial purposes. On the other hand Spain did not lead the scientific and technological knowledge, developed in industrialised countries in the same period, and the scientific and technological situation of the country was quite backward.

The Government, then, decided to politically support a project, which reflected and demonstrated the technical competence in public works already achieved by Spanish technicians.

The redaction of such an important project was entrusted to engineers of the Cuerpo de caminos, that was the most prestigious technical institution of the country.

The engineers responsible of the project had a proved experience in previous public works, and in particular in the construction of canals, streets and ports in masonry: José García Otero, economic and optional Director of the work, but also architect and inspector general of the Canal Isabel II, architect ingeniero jefe de segunda clase (general Director of Obras Públicas from 1851); Juan de Ribera y Piferrer, ingeniero jefe de segunda clase; Eugenio Barón Aviñón, and Constantino Ardanaz ingenieros primeros.

All of them directed or participated to the redaction of many project for territory’s infrastructures (retaining walls, earth dams, bridges, ports, etc.) all over Spain (Valencia, Sevilla, Madrid).

Some of them had also a solid career as professors of the Esquela de Caminos Canales y Puertos: García Otero taught Principios de Arquitectura civil y Dibujo (tercero curso); Lucio del Valle was firstly professor of Geometria Descriptiva (primer curso) and later on of Geodesia; finally Juan de Ribera taught Arquitectura y Estereotomía (segundo curso) at the same school.

The technology adopted was mainly cut-stone masonry, because of their perfect knowledge of stereotomy and of its application to civil architecture and public works.
The Experimental construction site at the Pontón de la Oliva (1851–1858)

The ceremony for the laying of the foundation stone of the masonry dam took place at the Pontón de la Oliva on 11th August 1851. The earth dam, that corresponds to the first section of the Canal Isabel II, would be inaugurated on 24th June 1858 (Fig. 2).

The site is 65 km away from Madrid, and is comprised in the administrative municipality of Patones (province of Madrid) and Uceda (province of Guadalajara) on the North of the capital.

This terrific natural site was chosen in August 1851 as starting point of the Canal Isabel II, that in a few years would conduct the water of the Lozoya river to Madrid. Lucio del Valle and Juan de Ribera were the engineers responsible for this section of the project. The labour was composed of 2000 prisoners, and 1500 workers (stone-cutters) for the different operation of the construction site.

The building yard of the dam includes some outlying service buildings: the prison barracks, the house of compuertas, the house of mina de limpieza, covered with a flat-vault, the casa del guardia, the auxiliary buildings dedicated to iron-work, wood-work, stone work, mortar fabrication, and a brick furnace.

The stone employed for the construction of the dam and the annexed buildings was excavated in different quarries: the white stone of the dam derives from Redueña y Patones; the yellow limestone of the surrounding buildings, canals, and inspection points, was obtained from quarries on the two margins of the river.

The construction site at the Pontón de la Oliva could be regarded as an experimental and scientific «laboratory» of construction. Firstly expert stone-cutters had to train prisoners to the art of stone-work: soon after they became a qualified labour that had to be employed in the following public works all around Spain. Secondly it could be possible that the construction site had been visited by scholars during the summer, in order to study practical applications of stereothomy: this is probably the reason why the project presents some stereotomical «games», and peculiar vaulted masonry systems, such as that of the boveda plana (flat vault) at the Casa de Mina de Limpia.

The masonry dam at the Pontón de la Oliva was an impressive work for the period (Fig. 3–4–5–6): it could contain 3,000,000 m³ of water, and has a coroner 70 m long, and 27 m high; the cross section has a trapezium shape with the lower base of 51 m width and the top of 6.5 m. For the dam’s construction the Administrative Council destined 4,174,659 reales.5

The flat-vaults at the Casa de Limpia: aesthetic quality of cisterns and inspection points’ coverings

There great ability of the stone-cutters, who worked at the construction site, is proved not only by the terrific results obtained in the masonry dam, but also
in some minor examples and architectural details that could be found in the surrounding buildings.

It is the case of the small boveda plana that covers the Casa de Mina de Limpia (Fig. 7), that is one of the few realised examples of flat-vaults composed of serial elements with a polyhedral shape.\(^6\)

The flat vault, mainly indicated and described as a geometrical game, could be regarded as a direct quotation from A.F. Frezier's *Traité de Stéréotomie* (1737–39), one of the most important treatises of stereotomy.

The solutions designed by Frezier\(^7\) started from the analysis of the original model elaborated by Abeille (1669?–1752?), described in Pl. 31 Fig. 37, and quoted the existence of two later solutions by Sebastien Truchet (see Pl. 31, Fig. 38). He then describes his original new variants (see Pl. 31, Fig. 39 and Fig. 40) that could be considered as simplifications of the fine, and also complicated Truchet's solution,\(^6\) in order to reduce and clarify the process of execution. These successive variants could be regarded not only as a geometrical game but mainly as an attempt to improve the static performances of the system.\(^5\)

The model, realised probably for the first and last time at the Pontòn de la Oliva (Fig. 11), was designed by Lucio del Valle and/or Juan de Ribeira with a direct reference to Frezier's solution contained in Pl. 31, Fig. 39 (Frezier, 1737–39).
The vaulted system and its supporting elements are modular and prevalingly symmetric (Fig. 8). Moreover the original units of measurement (Spanish feet) have been converted into metres in order to better understand the proportioning process of the ashlars.

The small *boveda plana* covers a rectangular space (dimensions 310x380cm) which accommodates an inspection point. The overall dimensions of the flat system at the extrados are 397 cm x 328 cm, and its thickness is around 21 cm.

The form, geometry, proportions and dimensions of the elementary ashlars inform the entire composition:

- the square at the lower base is very small (around 35 cm side), and its composition designs an intrados' texture made of 9 per 11 squares;
- the top base is a polyline figure, and the circumscribed rectangle has overall dimensions of 35 x 51 cm (Fig. 9).

Frezier’s rules for a correct execution of a flat-vault system, and its identical ashlars are respected. The process for their realisation is quite simple: too acute angles are avoided, because they constitute points of frailty and rupture; the projection of the bases and of the sides in order to obtain the *patrones/panneaux* that guide the execution are direct and do not require complicated geometrical constructions; the stone-cutting proceeds according to planar cuts.

The inclination of the sloping sides follows an angle of 67° (comprised between 45°-75° and 34°), and there is a very small utilisation of mortar so that the flat vault could be considered dry-assembled.

The solution is characterised by the continuity of the intrados and extrados, that offers a better resistance to the collapse (Fig. 10–11–12–13).

There are also interesting constructive solutions adopted for contrasting the horizontal thrust of the system that can hardly be recognised from the intrados: the L shaped massive blocks in correspondence of each corner (Fig. 14–15–16–17), that are replicated with few variations in the elements that compose the parastas of the closing walls, creates a chain mechanism that avoid the collapse.
THE HYPOTHESIS OF RECONSTRUCTION OF THE FLAT-VAULT AT THE CASA DEL GUARDA:
AESTHETIC QUALITY, TECTONIC KNOTS, STEREOTOMY, AND DRY-ASSEMBLY METHODS FOR UPDATED «FLAT-VAULT» SYSTEMS

In fifties some restoration works interested the earth dam and its surrounding buildings. In this occasion the building destined to the Casa del Guarda was deeply modified with the demolition of the rooms at the first floor and the substitution of the intermediate floor with a reinforced concrete structure (Fig. 18).

The analysis of the archives’ data (original project: plans, sections and frontal views; period pictures, etc.) and the presence of recurring constructive and architectural details (the same L shaped massive blocks in correspondence of each corner, identical parasitas of the closing walls for the chain mechanism, etc.) suggest the existence of a second flat-vault system corresponding to the intermediate floor, now demolished (Fig. 19–20–21–22).

The hypothesis of reconstruction followed some preliminary conditions:
— among the different possible flat-vault solutions it was selected a lacunar ceiling, obtained overturning the Abeille's original solution;
— the inclination of the sloping sides had to follow an angle of around 60°;
— the thickness of the system has to be 23.22 cm (10 pulgadas);
— the overall dimensions of the intrados were 304.20 cm (11 piez) x 373.84 cm (14 piez and 4 pulgadas);
— the overall dimensions of the extrados were 348.30 cm (12 piez and 6 pulgadas) x 417.96 cm (15 piez);
— the support tapering was around 22 cm (9 pulgadas).
The obtained flat-vault system is a rectangle with a extrados made of 12 per 10 squares. The dimensions of the serial element are the following:

- the lower base is a rectangle 58.05 cm x 11.61 cm (2 piez x 5 pulgadas);
- the top base is a square 34.83 x 34.83 (15 pulgadas x 15 pulgadas) with the same dimensions of the nearest realised example ashlars' intrados;
- the sloping sides, that follow an angle of 56°, are conformed with a mortise joint (tectonic knot) that improves the friction among the elements, contrasting the bedding thrust.

The Abeille's problem of the pyramidal holes extrados (that have to be filled in order to obtain a trampolining layer) is solved by the continuous square plot. However the preference for this architectural scheme, and for the aesthetic quality of such a lacunar ceiling (Fig. 23-24-25-26) involved the solution of important structural and technological problems. For these reasons the reconstruction hypothesis provides an flat-system improved with

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**Figure 23-24-25-26**

View of the intrados at the Casa del Guarda. Photo by the author (May 2002) and photomontage of the reconstructive hypothesis.

**Figure 27**

Abacus of reconstructed flat vault elements. Drawing by the author (May 2002).
reinforcements: the tie-beams, positioned in correspondence of the block central axes in both directions, represent a security stitch against plastic deformations and frail rupture of the flat vault. Moreover the special blocks in correspondence of each side of the overall structure receive the tie-beams with their anchor slabs, positioned in the corresponding cavities. The application of a pretension to the tie-beams involves some advantages in the management of the restoration site: the entire system, in fact, could be pre-assembled and set on the existent structure. The necessary contrast to the horizontal actions will be provided by both the tie-beams and the existent monolithic L-shaped blocks at each corner of the system.

CRITICAL REFLECTIONS ON THE CAD/CAM PROCESSES' APPLICATION TO THE ARCHITECTURAL ELEMENTS PRODUCTION

The twentieth-century generalised lack of experimentation in load-bearing stone construction has determined, not only a suspicious approach to the traditional repertory of vaulted systems (i.e. vaults, trompes, etc.), but also a great difficulty in finding expert stone-cutters for their execution.

Recently the on-going research field established by Prof. Claudio D'Amato at the Politecnico di Bari, has experimentally proved the potentiality of informatics' technologies (i.e. cad-cam processes) for the revaluation of the Mediterranean constructive tradition, specifying the application of cad-cam process to the realization of stone architectural elements. The elaboration of the reconstructive hypothesis for the flat-vault could be regarded as a critical reflection on the the traditional relationship idea-construction, expressed in the stereotomy treatises' repertory. On the one hand the 3D model and render images have been elaborated in order to analyse the texture of the stone system in the light of the ashlers' execution with CNC machines. On the other hand the 3D model could be easily imported by many structural engineers' programs for the description of the structural behaviour. It also provide a clear differentiation of supporting and supported elements. It could also be used for the elaboration of animations, that illustrate concepts that are not easy to depict by means of static images, and with the purpose of offering an important contribution to the comprehension of the construction and assembly process of the traditional stone systems analysed. They both exemplify the different phases for the ashlers' traditional/electronic execution to non-expert stone-cutters and architects, and clarify the system's construction process.

There are several advantages in using cad-cam processes for the realization of the flat-vault ashlers (Fig. 28):

- executive precision: speedness of the realization process in comparison with traditional stone-cutting; rationalization and repetibility of cutting and finishing processes, in the light of a dry-assembly;
- predominance of «border processes» (cutting, bordering, drilling, etc.) towards «shape processes» (mainly used for the realisation of no planar surfaces), that implies a short time in the elaboration of the CN-file to be used by the CNC machining centre;
- elements' dimensions and proportions compatible with almost all the more common CNC machining centres at our disposal.

Figure 28
3D virtual Model of the reconstructive hypothesis: comparative analysis of mortise joints solutions. Drawing by the author (May 2002)
The employ of a CNC machining centre implies an enlargement of the expressive possibilities: firstly exclusive solutions (i.e. Truchet’s one) could be easily obtained with a CNC machine; secondly the cad-cam process could be elaborated for both the ashlars’ positive (i.e. the traditional natural cut-stone element) and their negative (i.e. their formwork in steel, polystyrene, etc.).

This opens new horizons for the architectural experimentation, in terms of use of different materials (such as reconstructed stone), and definition of new methodologies a high qualified prefabrication.

ACKNOWLEDGEMENTS

This paper summarises, in some aspects, the contents of an on-going research project titled «Typological and constructive updating of vaulted systems for the contemporary project in stone» (G. Uva; E. de Nichilo, A. Di Roma, G. Fallacara). The project has gained in 2002 MIUR Young Researcher funds and is being carried out at the School of Architecture of the Politecnico di Bari. One of the distinctive characteristics of the School resides in the research line on stone construction, under both traditional aspects and needs for its technological updating.

This is the general frame that has strongly supported the intensive and experimental work I have carried out in close collaboration with Giuseppina Uva. I am very much indebted to Professors C. D’Amato Guerrieri and M. Mezzina, Politecnico di Bari, for their precious suggestions. Prof. E. Rahasa Diaz, offered his extremely important comments, and enabled me to connect this study with current work on the history and theory of stereotomy. Finally I would like to express my gratitude to Juan J. Gonzales Reglero, Fundación Canal Isabel II, who was a true support during the survey at the Pantón de la Oliva (May 2002). He not only offered his technical suggestions, but also was very generous in putting his facilities and the material of the archive of the Fundacion at my disposal.

NOTES

1. The Council was instituted by the Government headed by Juan Bravo Murillo on 18th June 1851 with a Real Decreto during the kingdom of Queen Isabel II and her husband King Francisco de Asís. The structure of the Council included three representatives of the Government: Juan Fernandez de Cordoba, XIV conde de Sástago, who was also the President of the Council; José Solano Mata-Linares, marques de Soverano and deputy-President of the Real Academia de Ciencias Exactas, Físicas y Naturales; and Manuel Cantero, member of the Government in the Banco Español de San Fernando.

2. The Cuerpo de Ingenieros de Caminos, Canales y Puertos included technicians (soldiers and engineers) trained to the Real Casa de Caballería Pajes and later on to the Escuela de Caminos Canales y Puertos (reopened for the third time in Madrid in 1834). The Institution had a hierarchical structure: at the top there was a very limited number of inspectores generales, followed by ingenieros jefes de primera clase, ingenieros jefes de segunda clase, ingenieros primeros and segundos.

3. An important aspect to be considered is the role that stereotomy had in the nineteenth-century engineers’ training. Different application of stereotomy were taught in many courses at the universities, and the preliminary condition to follow them was the perfect knowledge of French. The French and Spanish treatises of stereotomy and military art, in fact, were used as textbooks. The engineers of the Canal had a great knowledge of these treatises and contained constructive models, proved by the adoption of many solution in the canal construction.

4. It is important to compare the Spanish situation with the coeval French and Italian ones. In Nineteenth-century the generalised request for new technical and specialised competences had two important, and contrasting consequences. On the one hand the need and the preference for practical aspects of the discipline explained the abandonment of the treatise in favour of the manual, that contained ready-to-use solutions. On the other hand, the strictly geometrical experimentation of some authors (i.e. Monge) led to the elaboration of stereotomical abstract models that lost their reference to the constructive reality. On the role and predominance of the «Art of building» in the French and Italian architects/engineers’ training see: RAMAZZOTTI, Luigi, L’edilizia e la regola. Manuali nella Francia dell’Ottocento, Edizioni Kappa, Roma 1984; and SAKAROVITCH, Jöel, Épures d’architecture: De la coupe des pierres à la géométrie descriptive XVI-XIX siècles, Basilea, Birkhäuser, 1998.

6. The small flat-vault at the Pontón de la Oliva is the study-case of the PhD thesis the author is carrying out, and titled Vaulted and domed architectural systems in dry-cut stone in Spain. Sixteenth-Nineteenth centuries. Sequences, tectonic knots and stereotomical techniques in comparison. Thesis supervisors: Prof. C. D’Amato. Politecnico di Bari - Dipartimento ICAR - Prof. E. Rabasa Diaz. E.T.S. de Arquitectura de Madrid. Departamento de Investigación Arquitectónica, Universidad de los Andes de Palermo, ciclo XIV. From the seventeenth century a formal and stylistic research field on flat-vaults had been developed in a limited number of French and Spanish treatises as evolution of the traditional vaulted systems. It is possible to divide the different flat-vault systems (voute plate/boveda plana) in two great families: the flat-vaults with converging cuneiform ashlars (such as the one realised by Juan de Herrera at the S. Lorenzo’s Monastery, Fasealda 1575); and flat-vaults composed of serial elements with a polyhedral shape. The solution realised belongs to this second family: its survey, conducted by E. de Nichilo, G. Uva and G. Fallacara in May 2002, has highlighted the presence of many interesting stereotomical typical details, and the differences with the abstract model described in the treatises.

7. Frezier A. F., Traité de Stéréotomie,[1737-39] 1980, pp. 68-79. The Abeille’s original solution was presented at the Académie des Sciences in 1699, and edited in Machines et inventions approuvées par l’Académie Royale des Sciences, Tom. 1, pp. 159, 1735). The serial elements had a polyhedral shape: the lower base is a square, the top base is a trapezium, and the sloping sides are trapeziums. It is possible to assembly the ashlars, alternating the directions of the placed pieces and obtaining the covering of a square space. The texture of the intrados has a square plot while the extrados presents polygonal holes that have to be filled in order to obtain a tamping layer. J. M. Perouse de Monteleon, in L’architecture a la francaise, does not mention any realised examples of the Abeille’s solution or its variants in France. E. Rabasa, in Forma y construcción en piedra, has documented one more small example of a flat-vault in Spain: the boveda plana of the Northern tower of Lugo Cathedral, designed by Julian Sanchez Bort (1727-1785). Here the Abeille’s system is poured and adapted to a rectangular plan. The central part was reconstructed in 1879.

8. A comparative analysis of the different flat-vault solutions contained in Frezier’s treatise, with reference to both geometrical characteristics and structural behaviour, was developed by the author and G. Uva, within the Research Unit of the Politecnico di Bari of the MIUR ex-40% funded research The typological and constructive reform of the Mediterranean house 1999-2001, (national and local coordinator: Prof. C. D’Amato, Dipartimento ICAR, Politecnico di Bari).

9. The conversion units utilised are:
  1 piec. (Spanish foot) = 27,863 cm
  1 pulgado = 2,322 cm
  1 piec. = 12 pulgadas


10. For the boveda plana structural mechanism see:


11. Since the beginning of Nineteenth Prof. Claudio D’Amato Guerrieri leads a more general but complex project, on the updating of traditional techniques of construction using cad-cam processes. The first impressive research result of cad-cam application to architectural elements’ production, was the 9/A capital replica of Apollo Epicurius Temple at Bassae, made of Carrara marble (120x60x60 cm) using numerically controlled machines (CNC machines), presented at 35° Veronafiere MARMOMACC in 2000.

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