Learning from traditional vaulted systems for the contemporary design. An updated reuse of flat vaults: Analysis of structural performance and recent safety requirements

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The Boveda plana is a particular solution for covering a quadrangular area that can be seen as a spatial vault in which the curvature tends to zero. The static behaviour is essentially based upon the connection among the different ashlars in the space, distributing the load in both the direction of the floor. The horizontal thrusts are very strong, and the solidity of the whole masonry is guaranteed only if horizontal displacements are prevented. Otherwise, the collapse shows all the features of brittle ruptures.

The aim of this research work is to develop a system for the horizontal structures made from a set of dry-assembled blocks. If we want to propose a contemporary structural system that is borrowed from these historical examples, it is important to overcome the outlined drawbacks. The work is focused over the following aspects:

— Analysis of the structural behaviour of the system. There is a serious difficulty in modeling structures that are naturally discontinuous. The ancient knowledge of blocky structures has been abandoned for a long time, and now very few methods of computation exist for discrete systems. Rigorous approaches are time consuming and computationally expensive. Equivalent continuous model are a rough approximation of the reality. Different possibilities will be explored and tested on the case study, with a particular reference to the use of Finite Elements with proper adjustment for the particular case.
— Updating of the system in order to prevent a brittle collapse, to endow the structure with a certain degree of ductility (that is nowadays a fundamental law requirement). Reinforcement bars have been introduced, and the shape of the blocks has been accordingly designed. Formal and structural evolution of the system is examined.
— Analysis of two possible solutions for the cables (pretensioned or loosen), considering the question of the installation procedures: direct assembly in the yard or pre-assembly and pretensioning of the whole slab, that is later positioned over the supports by using a crane.
— Use of alternative materials such as reconstructed stone, brickwork, and synthetic resins in order to optimise the weights and the structural performance. The spin-off on formal design of ashlars will be analysed.
— Problem of the structural joints, with an attention to the box behaviour of the building and to the elimination of the horizontal thrusts.
— Testing on scale models of the flat vault, showing some qualitative characteristics of the structural response.
INTRODUCTION

This work is part of a wider research project carried out within the Faculty of Architecture of the Polytechnics of Bari, concerning the analysis and updating of traditional stone architecture, in view of an alternative, contemporary design within the Mediterranean area.

The research group has been recently developing a work on this subject, thanks to the «Young Researchers Grant». This project is aimed at the reuse of traditional arched and vaulted system (dry stone blocks) in historical contexts. The synthesis between modern exigencies and a sustainability of building actions is realized, according to us, through the updated use of traditional techniques. Rehabilitation, in this sense, means continuity of types, materials, structural conception. Of course, it is necessary to study ancient examples from an historical and geometrical perspective, and afterwards to use structural tools of analysis in order to verify the static performance of the elements according to the different texture, and to design new proposals.

One of the case study on which the group has been focusing the attention is the Spanish boveda plana, of which the historical development has been faced [1–5] and the existing example of the Casa de Mina de Limpia near the dam of Ponton de la Oliva has been surveyed and analysed [5]. The study consists of two phases: historical and typological analysis; drawing, modeling and structural comprehension of the investigated elements. On the basis of the results, the design of prototypes to be used in the reconstruction of historical elements is performed (the application is the reconstructive hypothesis for the Casa del Guarda flat-vault).

THE BOVEDA PLANAS: SOLUTIONS IN THE THEORETICAL STUDIES AND EXISTING EXAMPLES

The Boveda plana is a particular solution for covering a quadrangular area, and in spite of its planar configuration, is more similar to a spatial vault in which the curvature tends to zero. The static behaviour is then significantly based on the three-dimensional interlocking of the blocks, that establishes a three-dimensional lattice distributing the load on the supports, using a configuration that could be derived from the platband (fig. 1).

Many different geometric solutions are possible for the block shape, as the investigations performed over historical treatises have shown. The development of different solution is characterized by an increasing complexity in the cutting and, accordingly, in the structural performance.

In some cases, the reaction is lumped in particular points on the supporting walls, like in the early elaboration of Abeille ([1, 4], fig. 1).
In other examples, a continuous distribution is achieved, in accordance with the complexity of the blocks’ shape. It is worth noting that this last situation is reached for the more advanced and complex solutions. This is the case, for example, of the Truchet solution [1, 4], in which the ashlars are cut following quadric surfaces. It can be considered the most refined evolution of the system of the flat vault, both in the geometrical complexity and in the improvement of the static performance. Indeed, no practical implementation has ever been realized, or at least it hasn’t been discovered yet. Maybe now, at the end of a process of re-interpretation and reformation of this architectural system, it could be possible to make the proposal feasible. It is in fact necessary to make easy and serialized the cut of the pieces, also in the perspective of providing the system with proper steel reinforcements. The modern technologies of cad-cam will help us in this task, supporting the design.

In the system of the boveda plana, the horizontal thrusts over the supporting elements are strong, and the stiffness and solidity of the whole masonry is guaranteed only if every horizontal displacement is prevented. If the masonry panels are rigid enough and well scarfed to form the masonry box, the floor is very stiff. Otherwise, the collapse of the structure is sudden and unexpected, showing all the features of brittle ruptures: neither warning signs nor large deformations arise, and a snapping collapse takes place. Once the sliding over the contact surfaces of the blocks are activated and the hooping action of the walls is no more able to contrast them, the structure cannot find an equilibrated configuration. It is evident that in these cases very high safety factors are required.

Since the aim is to propose a contemporary structural system that is borrowed from these historical examples, it is important to overcome this drawback.

**Historical masonry structures: modern interpretation of the structural behaviour**

From a methodological standpoint, a preliminary historical characterization of the architecture, the materials and the structural elements is very important, and do assume a central position within the structural analysis. By integrating these instruments of knowledge with more advanced numerical and modelling tools, it could be possible to obtain a Contemporary approach to the Design and the intervention on historical building, that does not break with the past, but rather assimilate the tradition.

The analysis of the historical elements and the proposal of updated elaborations have been guided by the idea that the texture (that represents often the decorative pattern) is a central point in the design with structural stone, and could be advantageously exploited in order to improve and optimise the structural response.

**THE CASE STUDY OF THE PONTON DE LA OLIVA**

The first part of the research work as been devoted to the study of the historical examples as they were described in the treaties of stereotomy of the Seventeenth century, and in the survey and analysis of one of the few existing examples of flat vaults: the little service building near the Dam on the Lozoya River, at the Ponton the la Oliva.

The building yard of the Dam and the outlying service buildings represented an experimental and scientific «laboratory» of construction. The designers were actually scholars of stereotomy, and taught in this subject at the University of Madrid. The stone masonry building technique was very advanced and refined in Spain, as witnessed by the high level achieved in the studies on stone cutting in the seventeenth century (formalized in the historical treaties). This well-established and long tradition is an important element in the analysis and comprehension of this unique example of hydraulic plant, in which out-of-plane loaded masonry is masterly used, experimenting daring technical solutions for dry cut stone masonry. In the dam, the sophisticated texture of the blocks, designed according to severe stereothomical rules of cutting that can be recognized in the historical treaties, introduce an important improvement in the mere gravity/frictional mechanism. The use of the dovetail joint improves the interlocking of the blocks, enhancing the strength to the mutual sliding and to the rotation induced by the overturning pressure. The structural performance is strategically committed to the texture of the wall. The conveyance of the water pressure to the abutments is
so achieved through the combination of two mechanisms: the classical gravity reaction and the frictional interlocking among the blocks establishing a spatial platband-behaviour similar to that of the Boveda Plana explained in the book of Frezier [1].

Indeed, the structural problem to solve was the same: the loads act in the direction perpendicular to the «plate» (out of plane actions), and have to be absorbed—and then conveyed to the restraints—by means of a plane structure made up by no-tension materials and relying only, if conventional solutions are adopted, on the development of the friction reactions. The closeness of the two structures seems to be validated by the presence of the little space, intended for containing the technical equipment, located nearby the dam wall and covered with a Boveda Plana (fig. 2—indeed, this is one of the few examples of flat vaults ever realized). Maybe, it was a divertissement of the designers who wanted to apply the theoretical solutions described in the treaties, and the presence of a yard specialized in stone cutting made it possible the implementation of extremely complex geometric configurations. Certainly, they had to solve a tricky problem for the dam construction, and used all the tools and knowledge available at that time. The little and fascinating Boveda Plana witnesses the high level reached in the building techniques, and the care for details in order to guarantee a well-done construction.

Figure 2
The flat vault of the Casa de Mina de Limpia near the dam of Ponton de la Oliva

The role of stone blocks’ shape in the structural performance

For the Boveda Plana, the mechanism of the work can be schematised through the simple system shown in figure 3 (beams organized in a celtic fashion arrangement). Each of the four beams has one perfect constraint on one side and is elastically constrained on the other by the following one, and is then loaded by the previous.

Figure 3
The spatial platband scheme of the boveda plana

Revision of the constructive system of the flat vault according to contemporary structural needs and ductility requirements

While re-proposing stone as building material, and developing a system for the horizontal structures
made from a set of stone or stone-like blocks dry-assembled, it is necessary to justify them in terms of feasibility and convenience.

Besides the static safety, it is then important to guarantee functionality, economic convenience, and standardisation of the building process (in particular by focusing on quality). Speaking about structural stone, it is evident that costs regarding materials become relevant, in particular with regards to characteristic thickness of these structures. Secondly, the cutting of stone needs high skilled hand workers, and this could be an unsustainable making a common and wide use of stone practically impossible.

In this paper, the question is faced with a particular reference to the case study of Ponton de la Oliva, and to the proposal of the reconstruction of the Casa del Guarda flat-vault (for further details on the formal, typological, and constructive elements of the blocks and of the system see [3]).

The first aspect to be examined is the prevention of brittle collapse. Not only it is necessary to provide a sufficient margin of safety with respect to collapse, but also a control on the modality of the collapse itself is required. The structure should be endowed in fact with a certain degree of ductility (that is nowadays a fundamental law requirement), a sort of an emergency supply that, in case of a failure, averts devastating effects.

This idea is well established in the field of r.c. and steel constructions, and for masonry buildings is a more delicate question.

It is wrongly believed that masonry is not able to develop any ductility. The experience as shown, instead, that a well designed and executed building can have an excellent behaviour even under unexpected and strong stresses (like during seismic events), and perform a good ductility and hysteretic dissipation. An essential premise is that a good connection is realized among the different supporting elements, both horizontal and vertical.

In this way, a box-like behaviour is induced, and a beneficial effect is recalled: the shear resistance of those panels positioned in the most favourable direction is recalled.

In accordance to these principles, after studying the flat vaults in their historical and formal evolution (pointing out the interesting static and expressive possibilities), different updated solutions have been elaborated, in view of a rational contemporary proposal. To improve the system (in the sense that has been just precised), the use of reinforcement bars is foreseen, and the shape of the blocks is accordingly designed.

The ties (that could be pretensioned or even loosen) can have three different functions:

- eliminating the horizontal thrusts over the supporting walls that would disarrange the masonry box and cause the overturning—and collapse—of the system;
- supplying the floor toothing to the walls (if the anchoring is brought outside) and providing an horizontal bracing;
— Improve the shear mechanism of mutual contrast (increasing the friction effect, and by a pin-effect);
— Constituting an emergency safety net able to retain the blocks in the case of a sudden and unexpected collapse.

The possibility of developing the above-mentioned phenomena will depend on the particular solution adopted: introduction of the pre-stress; position of the bars with respect to the block. In particular, the position of the bars is related to the technological choice. If a stone cut piece is to be used, grooves on the sides of the blocks should be foreseen. If a prefabricated, reconstructed stone is designed (that could use a resinic binding agent or a cementitious one), the moulding procedure allows the use of built-in holes.

An example is hereafter given (fig. 5), where the reinforcement cables are positioned in the lower part of the blocks (the example in the pictures shows the case of lacunars that are on the extrados of the floor, but it is possible to invert the situation by simply reverting the slope of the faces of the block and turning upside down the system).

In this case, there is the possibility of applying compression prestress through the ties in the lower part of the section. In this way there is a direct action that compensates the effect of the vertical loads. Of course, there is a formal problem in the management of the cables, positioned in groves that are visible on the ceiling, even if they are sealed with mortar.

The choice of a system that is cast from artificial stone would completely solve the problem, by shifting the bars in the interior of the block, and allowing the centring of the contrast plates with respect to the section (fig. 7).

The question is then to evaluate the contribute of the introduction of reinforcements into the system. If the cables are not pretensioned, the only function would be that of tying the system and eliminating the overturning thrust. The same result, however, could be as well achieved by placing ties only in the outer walls. However, a safety function in retaining the blocks during the collapse is played, and a small contribution to the shear transmission of the forces is provided by a pinning effect. Much more relevant is the global effect if a prestress is applied (fig. 6). Infact, under this hypothesis, it can be shown that the load-bearing capacity is improved, thanks to the increasing of the frictional resistance on the contact surfaces. This also contributes to raise the energy dissipation in case of limit situations, enhancing the plastic resources of the system.

Another solution is presented in picture 8, in which, even without cutting the hole within the block, it is possible to lower the ties as much as possible. So the elements can be more easily realized in stone too, taking advantage of the prestress benefits and preserving the integrity—and decorative pattern—of the ceiling.

In this brief exposure of solutions for a contemporary use of the system of the flat vault (the occasion could be the reconstruction hypothesis in the historical context of the Ponton de la Oliva), only the
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Figure 7
Reinforcement placed at the center of the section

Figure 8
A solution suitable for stone cutting, with quasi-centered ties

...geometrically simplest case have been shown, that have allowed an easier positioning of the reinforcements and comprehension of the possible effects attained.

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REFERENCES

3. «Learning from stone traditional vaulted systems for the contemporary project of architecture. The experimental construction site at the Ponton de la Oliva (Spain, 1851–1858): survey of the small boveda plana of the Casa de Mina de Limpia, and reconstructive hypothesis for the Casa del Guarda flat-vault», E. de Nichilo.