Traditional building methods: the scope for their present use - The flat-tile vaults.

G. Tardella, M. Lemma, R. Gulli

Istituto di Edilizia, Facoltà di Ingegneria - Università degli Studi di Ancona, via Brecce Bianche - 60131 Ancona - ITALY
Tel. 071-2204783, Fax 071-2204582

Summary
Research work on self-supporting light vaults made of flat-bricks with no centering is currently underway at the Istituto di Edilizia of the Faculty of Engineering in Ancona.
This type of horizontal span needs to be critically analysed, given the scope for its application in such fields as building rehabilitation, improvement of the overall quality of new constructions, use in developing countries. This research work is divided into two sections. One section is devoted to a historical and critical analysis of the works of those masters who used these construction techniques (Gaudì, Le Corbusier).
The second, experimental section involves a laboratory construction of life-size mock-ups. The characteristics and the performances of this element are in the mock-ups checked, according to a range of parameters. This paper illustrates the preliminary results of this research. The technical and building feasibility of one mock-up built in the laboratory of the Istituto di Edilizia are discussed.

1. Flat-tile vaults interpretation by two masters of architecture.
The use of traditional building techniques by two masters of modern architecture provides several clues for a critical study.
The first case-study considered is the analysis of roofs made with flat-tile vaults. This kind of roofs is rather widespread, in different interpretations, throughout the Mediterranean area.
A special version of this vault was studied: the so-called "Catalan vault". It can be found throughout Spain, and it has been used by Gaudì in his time and, with a later interpretation, by Le Corbusier.
Gaudì frequently used the catalan building technique to make vaulted floors. His many projects included the cellar's vaults of Güell Palace (1886-1888), the floors of the Episcopal Palace in Astorga (1889-1893), the roof of the Theresianus College (1888-1889), the ceiling of Colonia Güell crypt and Santa Coloma de Cervellò (1908-1917).
When Le Corbusier travelled to Barcelona, in his notebook he drew a sketch of the "cascadas bovedas", which characterize the roof of the Sagrada Familia School built in 1909 from A. Gaudì's project.
As usual, Le Corbusier synthetically analysed the typical features of the building deriving valuable informations. These latter were used much later (around the beginning of the '50s) when he introduced a newly designed Catalan vault in many of his projects.
Le Corbuser's interpretation of the Catalan vault focuses on a geometrico-formal aspect, a building aspect and choice of materials. In many projects (village de gouverneur Chandigarh, 1950), maison Jaoul (1952), maison Fueter (1950), maison Sarabhai (1955), maisons des peons, the vaults' span size follows the rules dictated by Modulor, while the rise is defined as required by the individual project. Analysing the flat-tile vault structure of the Maison Jaoul, we can see that the first ring of tiles is built with gypsum, as dictated by the traditional Catalan technique. The next ring is made with 2" (5.08 cm) thick hollow tiles, combined with lime mortar, and arranged with their holes parallel to the vault generatrices.
The filling is made with clay-containing lightweight concrete on which a reinforced concrete slab is laid with a metallic mesh.
Le Corbusier, therefore, revisits the Catalan building technique by using products derived from a more modern building technique.

2. The experimental mock-up
This study is organized in two phases: the analysis of Le Corbusier's work, dealing with texts and historical documents, drawings and autographic notes found at the Le Corbusier Foundation.
A careful reading of the original tables showing some of the Catalan vaults designed by Le Corbusier (and associated comments) enabled to obtain information on the geometrical configuration of the vaults (span/rise ratio), materials and building technique adopted.
Conversely, the second phase of the study focuses upon the real scale of the mock-up as results from the indications found in the main documents.
Then, a short outline of the experience made in laboratory is presented from three standpoints:

- geometrical characteristics;
- choice of materials;
- building techniques.

2.1 Geometrical characteristics.
The configuration adopted by Le Corbusier for the Maison Jaoul vaults is based upon Modulor rules. The size of the small vault (made in the laboratory) is as follows:
span = 2.26 m.;
rise = 0.53 m.,
skewbacks' height = 2.26 m.
The large vault differs only in the span size, 3.66 m., consequently featuring a smaller sweep.
The indications given in the textbooks of that time recommend a 1/5 - 1/12 span-rise ratio. In the small vault this ratio is not observed, and it is somewhat greater than 1/5 (53:226 = 0.23).

2.2 Choice of materials.
The materials and binders used for the mock-up are similar to those used by Le Corbusier With reference having to be made to current building engineering, there are a few slight differences between the size of materials used for the mock-up and the Maison Jaoul.
As for the first ring, 27x14x1.8 cm. Catalan tiles have been used. The second ring included three-hole 24x12.5x5.5 cm tiles. For the first ring, Le Corbusier used a 2 cm. thick tile, while for the second a 5 cm. thick hollow tile was used.
The vault's filling was made in expanded clay-containing lightweight concrete with a cement slab placed on top,as shown in the original charts.
As to binders, for the first ring three different mortars were used (experimented in the different phases): the first was gypsum-based, the second had quick-setting cement, the third mortar containing plaster of Paris.
The second ring was built initially with fluid cement mortar, then a prepackaged lime mortar was used (1 l. of water - 5 Kg of product).

2.3 The building technique.
The mock-up was built according to the following procedure:
-construction of two small lateral walls with bricks supporting two reinforced concrete beams secured with stays;
- construction of a centering (template) as thick as the tile lenght. The centering is made to slide along two lateral supports anchored to the reinforced concrete beams placed a few centimeters below the vault's skewback so as to ease sliding during construction. Therefore, a wooden wedge was added, to be removed every time the centering is displaced.
- first ring (sencillo):
the first four rings of the vault, made with continuous joints both along the generatrices and along the directrix, were built with gypsum paste mixed with water in a 1:2 ratio. This ratio was arrived at after performing a number of tests to determine the right paste consistence vis-à-vis execution modalities.
From the construction viewpoint, the first two rings were built with centering used as tile support during construction. The time needed for this operation (with the aforementioned mix) was about 15 sec.. Three tiles were positioned using a mortar mix (this was possible thanks to the presence of a support).
When no centering was used, the time needed to position every tile was about 30 sec..
As a result, in order not to change mortar characteristics as compared to the previous case, the amount of processable gypsum over this time period proves to be halved or so.
A further investigation concerned the degree of humidity of the tiles to be laid. Three tests were carried out:
- tiles laid under environmentally balanced conditions;
- tiles laid after submersion in water for a few seconds;
- tiles left into the water for about 30 min. before laying.

A roughness test carried out 24 hours after laying showed that tiles must be dry (or slightly damp) to provide good tiles and gypsum setting.
Two more tile rings have been laid using quick-setting cement mortar. The time required for laying is about the same as with gypsum mortar, since the longer setting time required for cement as compared to gypsum is compensated by the possibility to use a greater quantity of cement, thus reducing the number of mixing operations.
Lastly, a ring was made using mortar containing plaster of Paris. This binder allows very short setting time, while showing greayer toughness of both gypsum and quick-setting cement. This last ring was made without centering, and setting time for each tile was about 15 sec. (comparable to that needed for gypsum paste with centering). Moreover, given its short setting time, small quantities of mortar must be ready so that from time to time each single tile can be laid.
- second ring (doblado):

the second ring included three-hole 24x12.5x5.5 cm. tiles arranged with their holes parallel to the vault's generatrices, as shown in the picture of the maison Jaoul vault still under construction.
The reason why Le Corbusier decided to put the second ring with the ribs parallel to the generatrices instead than to the directrix, as it should be, has not been understood yet. It could be inferred that this choice aimed to create some ventilated air space, which, however, was never realized.
As for the binder, two procedures were followed:
to start with, a particularly fluid mortar was used, then the extrados of the first two rows of tiles was covered. Hollow tiles were laid starting from the two skewbacks and going simmetrically towards the keystone.
Once three bricks had been positioned for each skewback, the vault suddenly collapsed. The reason for such breackdown proved to be the loss of resistance of the gypsum when coming into contact with the cement mortar excess water.
This test was then performed again, however in the second instance the binder was a prepackaged lime mortar mixed with little water. No structural yield was observed.
Lastly, a jet of clay-containing lightweight concrete was added to act as a vault's retaining wall upon which the cement slab was subsequently placed.

3. The scope for their present use

Another aim of this study is to further investigate how these elements will be used in the future.

- Building rehabilitation - the morphology and building materials of these vaults make it necessary to examine and restore them according to different criteria from those used when examining common vaults;
- Improvement of the overall quality of new constructions. This element greatly influences buildings architecture and has great impact on performances (spatial, acoustical , good arrangement for heating and electrical systems);
- use in developing countries - the construction of horizontal structures thus becomes possible, even when wood, iron, concrete, etc. are not available on the construction site for economic or technical reasons.

4. Conclusions

The first stage of the study has been completed. In this stage issues related to flat-tile vaults building modalities have been considered.
The building process has been reconstructed and reproduced, in both its technological (binders, materials, etc.) and ergonomic aspects (climate, processing stages, etc.).
Initially, the study investigated the structuures' static behaviour by defining a mathematical model capable of describing its operation as well as a series of measurement aiming at ascertaining its validity.
The behaviour of these structures will be further investigated, particularly in relation with a number of performances usually expected from floors and roofs of a residential building.
Lastly, in the third stage their future use will be analysed, also undertaking a typological and dimensional assessment.

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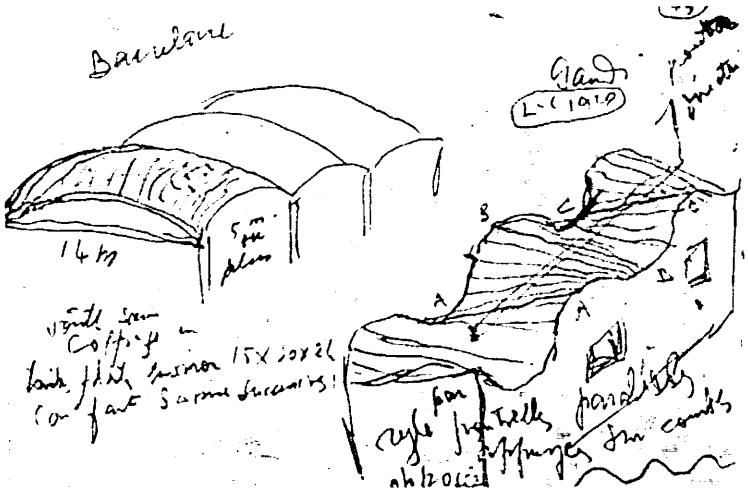

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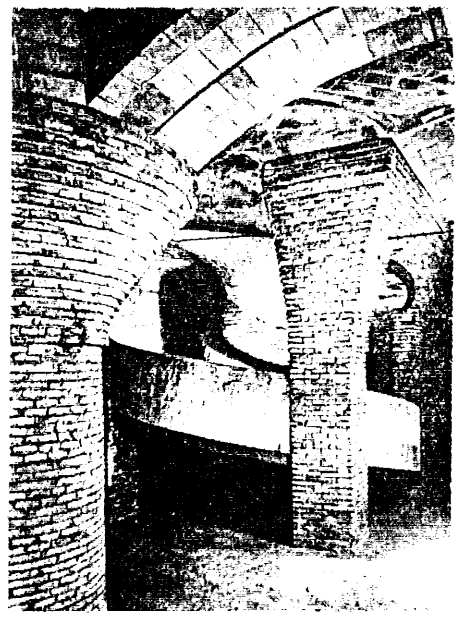

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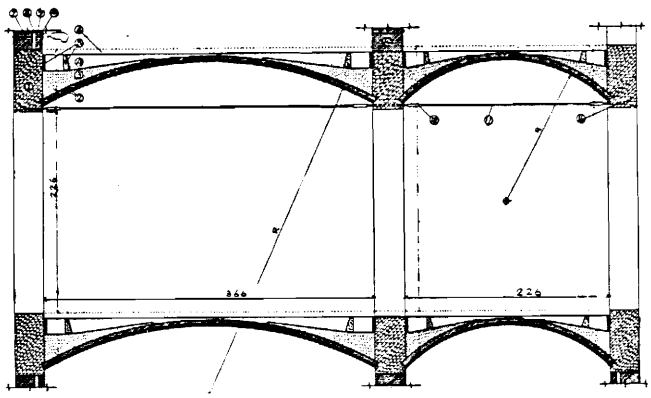

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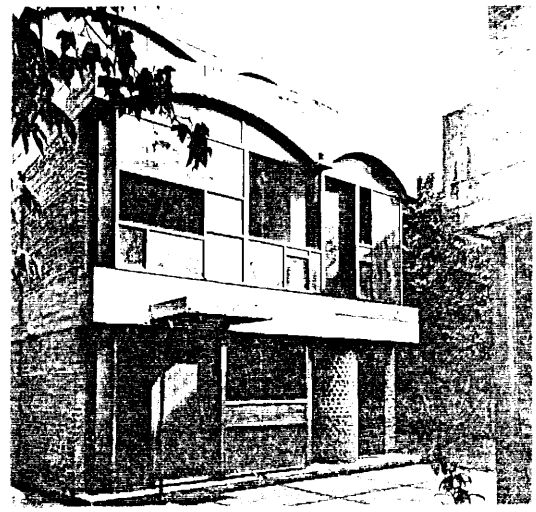

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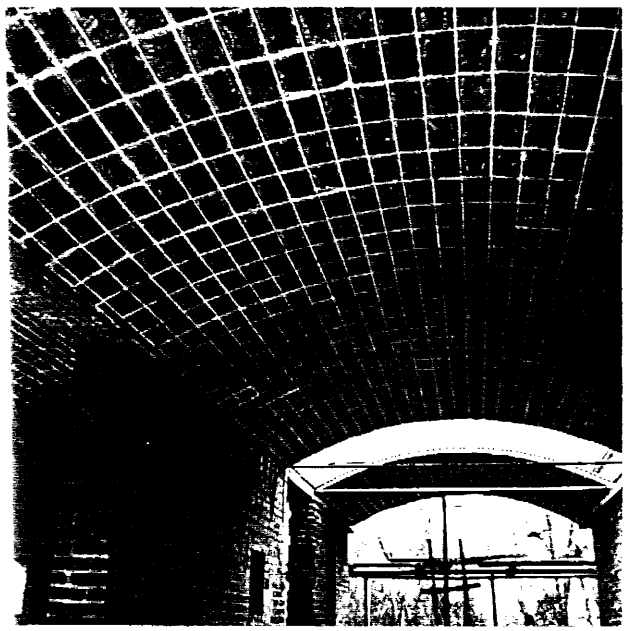

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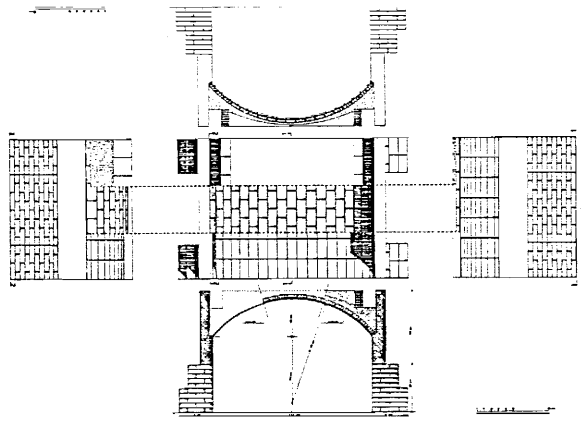

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1 - Le Corbusier's drawings of Sagrada Familia school's roof covering (1928)
2 - Güell building, stable (1985-'89)
3 - Jaoul house section (1951-'55)
4 - Jaoul house under construction
5 - Jaoul house facade
6 - Drawing of Jaoul house prototype