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The vaults in "Sistani's House" in Bam Citadel (Iran): Construction principles, shape geometry and design for reconstruction

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The aim of the reconstruction of the vaults is to achieve a maximum of fidelity to the original, which must not be limited to the appearance, but has to regard also the structural character, the "microstructure", and especially the traditional building procedure. The Persian art of vault construction is unique and deserves to be preserved and recorded as cultural heritage, apart from the structures themselves. On the other hand, security and serviceability of the building have to be guaranteed through a design process at the state of the art, including especially the prediction of structural behaviour and seismic response, by means of numerical modelling. Both features, i.e. traditional construction and modern planning, are crucial for a successful reconstruction, hence, their integration is the principal objective of the design of the vaults and the research illustrated in the following.

As in general in vaults which are constructed without formwork, in the vaults in question there is a close relationship between the construction process, the microstructure of the masonry fabric, and the shape of the vault itself (Wendland 2004, 2007, forthcoming). Therefore, both for the surface description (essential for the planning process, namely the structural modelling) and for the design of the construction in detail, it is necessary to take in account this interrelation.

1 The vault in "Room 12"

The type of vault over this room has been described as "voûte a trompe d'angle" (Besenval 1984; Wendland 2007, forthcoming). It is characterized by its building process, starting from the four corners with self-supporting masonry courses. The assignation of this type to the room in question is due to the available documentation, including aerial photographs before destruction; similar vaults have survived in other parts of the complex and were widely used in the entire Citadel. Generally, this type of vault is very frequent in the traditional Iranian architecture. The vault starts from a plain rectangular plan, 3.75 m long and 3.07 m wide. It spans in all directions, i.e. all four walls act as abutments.

1.1 Shape and construction

In this type of vault, characteristically the shape is particularly determined by the construction process. This is first of all due to the fact that these vaults are built entirely free-handed, without any formwork or centering at all – hence, in the absence of any geometrically determined elements (Fig. 2). Moreover, the requirements which arise from the construction process have a dominant influence on the vault shape (Wendland 2007, forthcoming). Therefore it can be stated that the shape of the vault surfaces is almost entirely depending from the construction procedure, and that it can be influenced only through the boundary conditions of this construction process. This means that any requirement to the shape, namely for the structural behaviour, and therefore also the design of the vault to be reconstructed, must take in account this relation.

As the vault is built with arched courses starting from the four corners, the masonry apparatus consists of four systems of masonry fabric which are bound at seams along the longitudinal and transversal axis in plan (Fig. 3, 4). The surfaces of the beds within the masonry fabric are plane, these planes are diagonally inclined towards the inside; throughout the entire height these planes are parallel within every system. In this manner, the single courses describe curves; therefore every new course is stable as arch as soon as it is completed, and the units of the next course can be set on top of it.

The shape of the vault results from the building of the subsequent arched courses. In previous studies (Wendland 2007, forthcoming), the principal boundary conditions for the development of the shape could be formulated (Fig. 5). From the point of view of execution, the development of the shape is literally automatic. In geometrical terms, however, the surface is highly complex. The approach chosen by the author to achieve a surface description and a CAD model (Fig. 6-8) is based on a description in procedural terms.

Figure 1 A vault of the "trompe d'angle" type: historical example (Besenval 1984, after Pugachenkova). Note the courses of the masonry, which depart with diagonal inclination, forming arches over the corners of the vault.

Figure 2 Vaults of this type are built free-handed, entirely without formwork or centering (Besenval 1984, after Ward-Perkins).

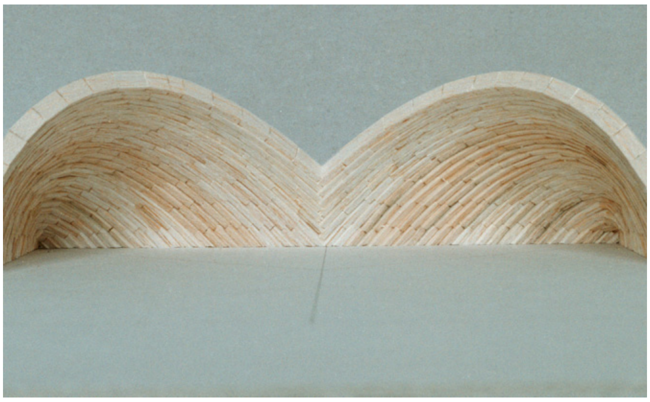

Figure 3 Simulation of the building procedure in a model, showing the masonry pattern shortly after connecting the systems from two adjacent corners (Wendland 2007).

Figure 4 Model of complete vault; note the rather long courses in the lower and central regions (Wendland 2007).

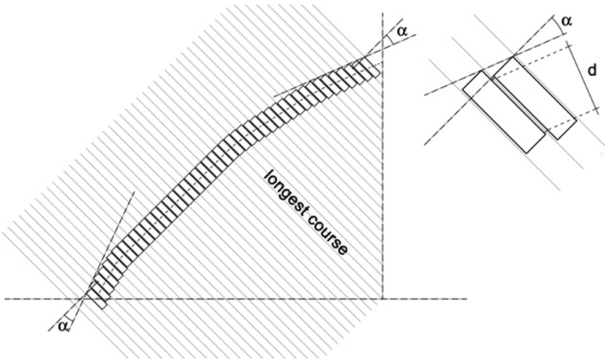

Figure 5 The shape of the "trompe d'angle" vault in relation to the arrangement of the courses (diagonal cross section along the groin) (Wendland 2007, forthcoming).

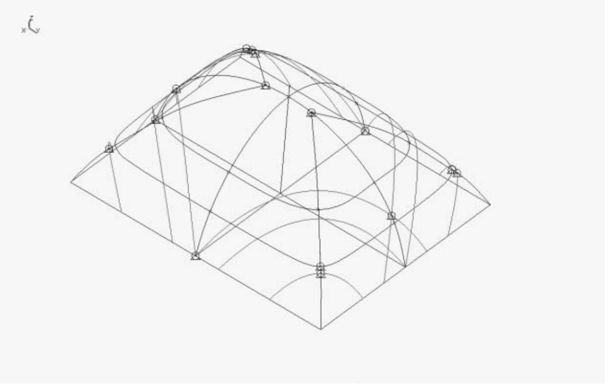

Figure 6 Development of a CAD model, based on the boundary conditions given by the construction process (author).

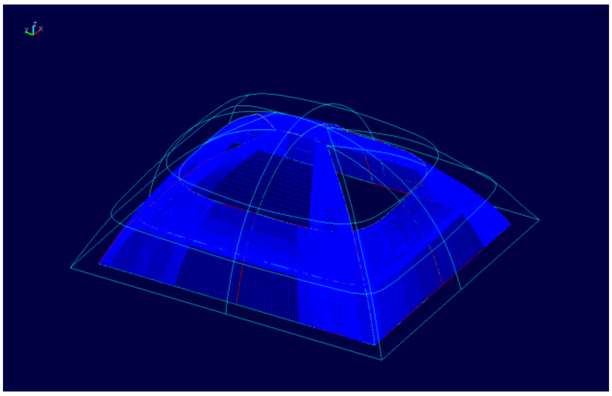

Figure 7 CAD model with surface description, tailored for the purpose of numerical modelling (author).

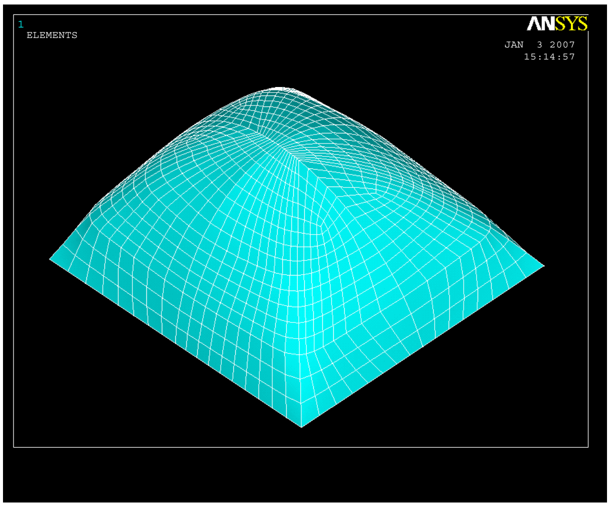

Figure 8 CAD model imported for Finite Element modelling (author; solid and mesh generation by T. Bakeer)

1.2 Construction details and reinforcement

The construction details correspond to the traditional building technique which is dominated by the workers on site. Typical details will be supplied in the execution design.

To improve the structural performance of the vault, the most important measure to be taken is the construction of a frame on its abutment (see the section 6.3 of this report), preventing the thrust of the vault from pushing the walls aside. Additionally, major improvement will be due to the use of fibre-reinforced adobe units.

Additional improvements to the vault itself can be the following:

- moderate alteration of the vault shape (invisible to the viewer) for better structural performance, based on the results from numerical modelling
- fibre meshes inserted in the bed joints
- a system of fibreglass bars and fibre meshes applied to the intrados and extrados prevents the debris from falling to the floor in case of collapse, providing a minimal survival space

Neither of these elements alters the appearance and the structural character of the building.

1.3 Process of reconstruction and form control

The execution design will be based on the surface model confirmed through numerical modelling (Fig. 8). On this model, the masonry pattern can be generated in detail (Fig. 9). As this model is basically developed in relation to the traditional construction process, the reconstruction can take place in the traditional manner, just verifying the accordance to the design shape (Fig. 10).

The information supplied for the reconstruction in traditional technique regards:

- the boundary conditions, especially the inclination of the bed joint planes
- the curves described by the courses at the intrados
- curves along typical sections of the intrados surface, to be verified during construction
- CAD surface model for random tolerance control

The reinforcing elements mentioned above can be easily integrated in the traditional construction process.

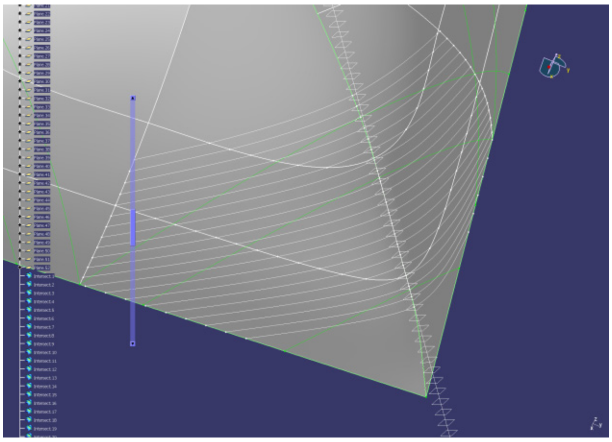

Figure 9 Generation of the curves described by the courses, on the vault surface modelled upon the revision after the structural analysis (author).

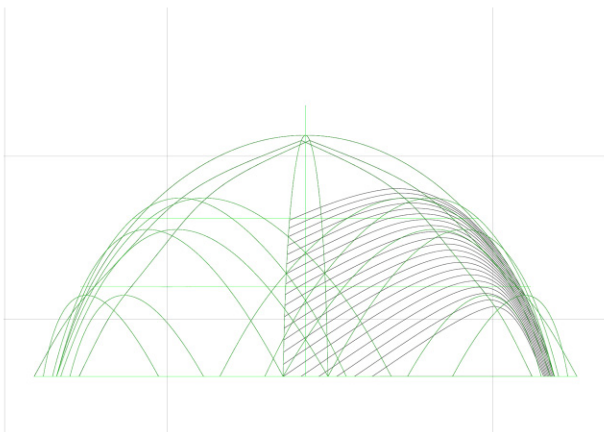

Figure 10 Geometrical data for shape control during reconstruction: typical sections and single masonry courses, on the intrados (author).

2 The vault in "Room 11"

The ceiling of this room consists of inclined barrel vaults spanning between diaphragm arches, which are embedded in the vault surface (Fig. 11). There is no evidence left on the remains of the building, except for some traces of the lower portions of the niches; nevertheless, the architectural typology could be identified through the available documentation. Several other rooms of the same building were also covered with this type of vault, and in some cases remains could be examined; similar vaults still survive in fragmental state in other buildings in the Citadel. Moreover, the typology and the general outlines of the design are also described in existing literature (Cejka 1978; Zamarshidi 1998).

The span of the arches is 3.57 m; the longitudinal extension of the vault is ca. 5.30 m. The thrust of the vault is concentrating on the springing of the transversal arches, hence, on the long walls (east and west sides) of the room.

2.3 Shape and construction

The shape of this vault surface, in contrast to the one described before, is strongly determined by elements with geometric design, defined and traced prior to construction. These elements are on one hand the transversal arches, on the other hand the arches of the niches along the longitudinal walls which serve as formeret arches for the vault. The surface of the barrel vaults between the arches, is also subject of the rules of free-handed vaulting, thus, its development is more complex from the geometric point of view.

The structure of the vault is likely to be very similar to that in "Room 04", where traces of transversal and niche arches are still evident, and also that in the adjacent "Room 09" which is documented by photographs prior to the destruction. The system can therefore be resumed as four transversal arches, two of them pasted to the front and back walls of the room and two spanning freely in between, and longitudinal arches along the longitudinal walls (formeret arches), which are all rising from the pillars which separate the niches on the longitudinal walls of the room. All arches are springing from the same level.

The geometric definition of the arches (see the architectural drawings in section 6.4, based on the geometric definition suggested by the author, Fig. 11) has been reconstructed in a comparative study based on the available documentation, a geometrical analysis of the remains of a similar vault in the same building, and the relevant literature (Cejka 1978; Zamarshidi 1998). All arches are pointed arches, traced with four circle segments each.

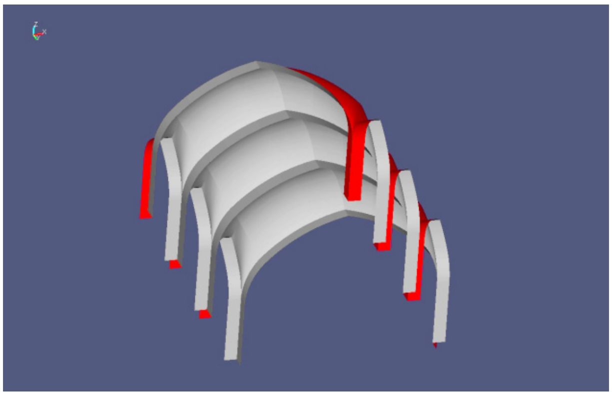

Figure 11 Surface of the vault intrados, showing the general composition of the vault. Major difficulty for modelling the surface of the caps is the geometrical complexity due to the fact that the vault surface tends to be smooth, while the boundaries are described by pointed arches (author).

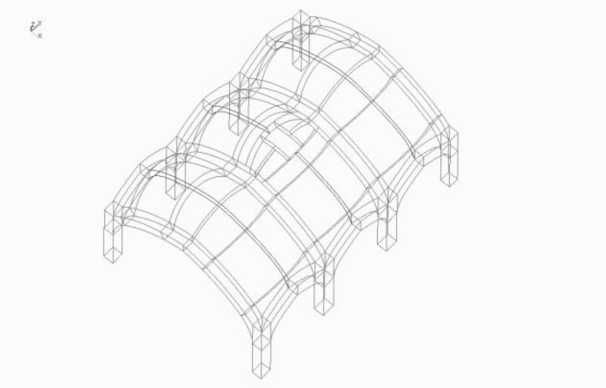

Figure 12 CAD model for the purpose of numerical modelling of the structure. The shape of the caps has been developed in relation to the construction process (author).

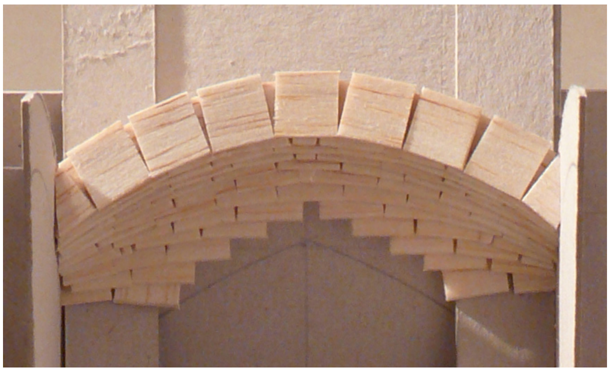

Figure 13 Model study of the vault masonry, built with self-supporting courses on nearly vertical bed joint planes. A particular difficulty for the surface description and modelling is the transition from the pointed formeret arch to the smooth main portion (author).

2.3.1 Construction details

In the original structure, the formeret and transversal arches were constructed with vertical masonry courses, which allowed building them without centering. In case of the formeret arches, the brick tiles of the first course were glued to the wall with fast-setting mortar, and the following courses were successively glued to the preceding ones. For the transversal arches, gypsum templates were prepared and placed in vertical position, and the courses of the arches were glued to them in similar manner.

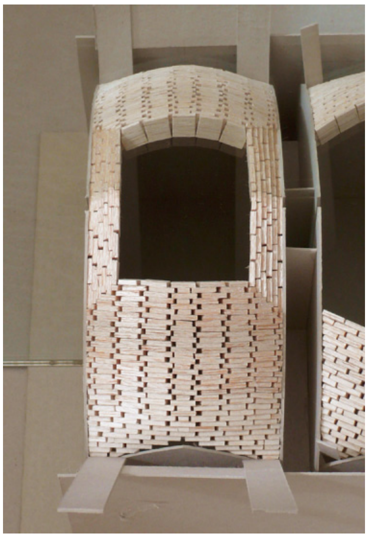

Figure 14 The central portion is closed with courses running alternatively along the four sides of the bay (author).

Figure 15 Alternative pattern for the vault masonry, simplifying construction in the earlier phase (author).

The caps or inclined barrel vaults were built free-handed with vertical, self-supporting courses between the transversal arches, starting from the formeret arches (Fig. 13). In the central portion, the masonry pattern probably alternated to courses parallel to the transversal arches, closing the last remaining open portions from four sides (Fig. 14). At the beginning, possibly some courses were set diagonally to allow an easier connection to the boundaries of the vault surface.

In the reconstruction, the performance of the transversal arches can be significantly improved by a different masonry pattern, laying the courses in normal direction to the curve of the arch. This alteration requires for the use of centering for the free arches, in addition to the gypsum template. Such centering arches are easily produced; their employment is advisable also to accelerate the construction process. This alteration is fully compatible with historical construction.

The barrel vaults can be reconstructed according to the original, allowing following reinforcement measures:

- moderate alteration of the surface shape (invisible to the viewer) for better structural performance, based on the results from numerical modelling
- fibre meshes inserted in the bed joints

- a system of fibreglass bars and fibre meshes applied to the intrados and extrados prevents the debris from falling to the floor in case of collapse, providing a minimal survival space

Neither of these elements alters the appearance and the structural character of the building.

Additionally, alternative vaulting patterns for the caps are being studied: flat tiles ("timbrel vault"), with one or two layers of bricks for weight reduction and the possibility of reinforcement, or diagonal courses (Fig. 15) which might easier to build. These solutions can be executed without formwork and will not alter the shape and appearance of the building.

2.3.2 Process of reconstruction and form control

The arches are supposed to be reconstructed on centering, as mentioned above; the caps will be rebuilt free-handed in the traditional manner. The geometrical definition will be supplied for the tracing of the arches in full scale in situ as well as for the production of the gypsum templates and the centering arches on the site. For the caps, the curves of typical sections will be supplied to be verified during construction.

Note

This report describes a practical application of the research contained in the author's doctoral thesis, supervised by Prof. Dr. phil. D. Kimpel, University of Stuttgart, Institut für Architekturgeschichte, presented in 2007. The outlines of the reconstruction project for the vaults have been prepared for a pilot project executed by Jäger Consulting Engineers Ltd. within a training programme funded by the UNESCO and the Japan Funds-in-Trust for World Cultural Heritage in collaboration with the Iranian Cultural Heritage Handicraft and Tourism Organisation ICHHTO and the Recovery Project for Bam's Cultural Heritage.

References

Besenval, R. 1984. *Technologie de la voûte dans l'orient ancien* (Synthese no. 15, 2 vols.). Paris, Éditions Recherche sur les Civilisations.

Cejka, J. 1978. *Tonnengewölbe und Bögen islamischer Architektur: Wölbungstechnik und Form*. (Diss.) München, Techn. Univ.

Godard, A. 1964. *Die Kunst des Iran*, Berlin, Herbig.

Hejazi, M.M. 1997. *Historical Buildings of Iran: their Architecture and Structure*. Ashurst Southampton: Computational Mechanics Publ.

Pope, A.U. 1968. *Persian Architecture: The Triumph of Form and Color*. New York: Braziller.

Wendland, D. 2004. Some considerations on the shape of the caps of vaults. In Proceedings *4th International Seminar "Structural analysis of historical structures"*, Padova 2004, edited by C. Modena, P. Lourenço, P. Roca, vol. 1, 111-120, Leiden, Balkema.

Wendland, D. 2007. *Lassaulx und der Gewölbebau mit selbsttragenden Mauerschichten. Neumittelalterliche Architektur 1825-1848* (Diss.), Univ. Stuttgart.

Wendland, D. forthcoming. Traditional vault construction without formwork: Masonry pattern and vault shape in the historical technical literature and in experimental studies. In *International Journal of Architectural Heritage: Conservation, Analysis and Restoration*.

Zamarshidi, H. 1998. *Mi'mari-i Iran: ijra-yi sakhtiman ba masalih-i sunnati* (Persian Architecture: Building with traditional Materials). Tehran: Intisharat-i Zumurrud.