

# STRUCTURAL REHABILITATION OF MASONRY VAULTS

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## SUMMARY

Masonry vaults are one of the most common structural forms which are present in the architectural heritage of almost all of the world countries. Facing the evaluation of their actual bearing capacity there are still problems to investigate and to solve, as the role of spandrels and backfill. In this paper the contribution of these further structural resources is studied and intervention criteria, in line with the principles of conservation philosophy, are proposed.

## 1. INTRODUCTION

The evaluation of the bearing capacity of historical building vaults has to be frequently faced in restoration design, as vaults are one of the most common structural forms present in the architectural heritage. This problem deserves particular attention especially when the building's potential for alternative use has to be determined, as this requires an increment of the variable loads.

The vaulted structures are usually considered as an ideal system of many arches. Barrel vaults can be idealised as arches one beside the others, but also cross vaults or coved vaults or others of more complex shape can be outlined in a similar way, with a system of main arches which support the secondary ones. With this ideal scheme, in some cases, equilibrium can not be justified, especially when the loads are not uniformly distributed.

The arch stability has been broadly studied for centuries and an historic excursus can be found in [1, 2]. Recent research works about this problem [4, 5, 6] are generally based on Heyman's extension of limit design to masonry structures, and their goal is to find out the collapse mechanism of stone arches both under dead and live loads. At least for service conditions, the arch scheme is sometimes too simplified. First it does not consider the interaction between the

arches and the resources due to shell behaviour. Moreover the structural role of the vault extrados backfill and spandrels has always been neglected, while, it is well known, they stabilise the vaults.

Specific studies about the evaluation of these structural resources have been recently faced for arch bridges in [6], but the problem of the vault behaviour still deserves attention. Two fundamental aspects have to be faced: the first concerns the confinement of the thrust forces at the springs. In [7] the interaction between the vaults and the supporting surrounding walls was studied. The second aspect concerns the flexural behaviour of the vaults under loads. In [8] the first results about the role of the spandrels and of different kinds of backfill under dead and variable uniformly distributed loads were presented. In this research work the behaviour under live non symmetrical loads and the effects of the construction of a thin slab at the floor level are illustrated. These effects were studied with a numerical approach based on F.E. technique. The study was limited to the elastic range, which has to be considered as a first step, but however significant for service conditions.

## **2. BACKFILL, SPANDREL WALLS AND UPPER SLAB EFFECTS**

Backfill and spandrel walls behave as a sort of stiff diaphragms and influence the behaviour of the arch limiting bending. To investigate this effect a F.E. analysis in the elastic range was performed for spandrel walls and different kinds of backfill. The original backfill which can be found over the vault extrados is generally made of incoherent material, though it may reach a relative compaction with time. For this reason a strengthening intervention was proposed which consists in the substitution of the original backfill with a new coherent and light one with structural relevance.

The study is limited to one kind of barrel vault with the geometrical characteristics indicated in Fig.1. The following mechanical characteristics of masonry were assumed for elasticity modulus, Poisson's ratio and weight density respectively:  $E_m=5000$  MPa;  $\nu_m=0.15$ ;  $\gamma_m = 18.5$  kN/m<sup>3</sup>. Any spring horizontal displacement under vault thrust is considered as perfectly restrained. Furthermore first results related to dead and variable loads uniformly distributed were presented in [8].

In the present work the situation of live loads, lying on one half of the vault, and moreover the effects of a thin upper slab at the floor level were faced. Thin slabs are commonly built under the bottom surface of floors to spread live loads. Two kind of backfills, with different mechanical properties, were investigated. The first one ( $E_b=100$  MPa) ideally simulates a dense coherent soil having structural relevance. In a strengthening intervention made on vaults in an ancient monastery [8], the original backfill was substituted by a low density concrete of cement or mortar mixed with light aggregates such as expanded polystyrene. The adopted values of mechanical characteristics were:  $E_b=1000$  MPa;  $\nu_b=0.15$ ;  $\gamma_b=6$  kN/m<sup>3</sup>. The extrados spandrels were supposed made of masonry of 12 cm thickness and 100 cm spaced (Fig.1b), of the same mechanical characteristics of the vault and oriented as the arches.

No relative displacements at the vault-spandrel interface were supposed. At the four corners of the vault the displacements in the three directions x, y, z are not allowed, while along the edges of vault constrains are applied in direction y, z (Fig.1). Plate-shell elements were adopted for the vault, membrane and brick elements for spandrels and backfill.

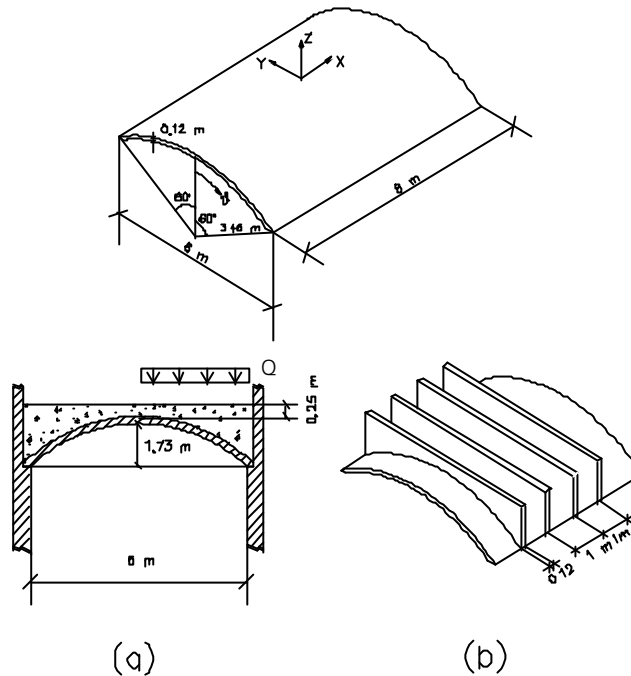


Figure 1 : Geometrical characteristics of the vault, of the backfill and of the spandrel walls.

### 3. RESULTS

Some significant results of the numerical analysis, which illustrate the structure behaviour, are here presented. In particular stresses  $\sigma_{\theta}$  and  $\sigma_x$  are plotted along the middle section of the vault ( $x=0$ ), starting from one edge to the other ( $\theta = \pm 60^\circ$ ) (Fig.1). Stress  $\sigma_{\theta}$  is significant for the arch type behaviour: both membrane and flexural stresses are reported.

In Fig. 2 the eccentricity of the compressive force is plotted under uniformly distributed dead and live loads [8]. It is possible to note that only the backfills with mechanical properties ( $E_b > 100$  MPa) and the spandrels are able to force the resultant inside of the central kern of the section.

Figures 3, 4, 5 refer to the vault with a compacted backfill with low mechanical characteristics ( $E_b = 100$  MPa), under live loads of different entity, lying on the right half of the extrados. The membrane stress  $\sigma_{\theta m}$  does not differ very much at the growing of the loads, while the bending effect is much more significant, as it is possible to see observing the results of the bending stress  $\sigma_{\theta b}$  and of the eccentricity (Figs.4 and 5). Of course the curves which are out of the range  $\pm h/6$  refer to an ideal tensile resistant material. Shear stress  $\tau$  along the arch-backfill interface is also neglectable (maximum value  $\tau = 0.002$  MPa).

As a consequence of the above reported results it is proposable a strengthening intervention where the original backfill is substituted with a new one of better mechanical properties, such as a low density concrete of cement or mortar mixed with light polystyrene aggregates ( $E_b = 1000$

MPa). In alternative new masonry spandrels can be constructed. Moreover a thin slab ( $E_{\text{slab}} = 10000 \text{ MPa}$ ), can be proposed at the floor level.

Figures 6, 7, 8, 9 illustrate the behaviour under a live load of  $6 \text{ kN/m}^2$ , lying on the right side of the vault extrados, after these interventions. The results with the slab were obtained by considering the effects in accordance with the construction phases. In the first one the slab acts as a dead load, in the second one, when live loads are applied, the slab acts as a structural element.

The backfill, the spandrels and the slab limit the bending of the ideal arches constituting the vault (Fig.7) and also the membrane stress decreases remarkably (Fig.6).

The resultant compressive force lies out of the central kern in some sections near the key (Fig.8), but if the maximum compressive stress is calculated neglecting tensile resistance of masonry and considering a triangular distribution, the values result very low and broadly under the mechanical maximum resistance of the material.

#### 4. CONCLUDING REMARKS

The present study aims to focus the behaviour of a barrel vault in the most unfavourable service conditions when variable loads are not symmetrical. The results show a very important collaboration between the vault and the backfill, and the vault and the spandrels. The structural interventions based on substituting the original backfill gives evident benefits. As a matter of fact both membrane and bending stresses along the ideal arches decrease. Particular static improvement is obtained when the intervention is based on the construction of a thin slab at the floor level. The present numerical analysis, even if performed in the elastic range, is acceptable for service condition. In fact, for every kind of the examined collaborating backfill or spandrel walls, no appreciable tensile stresses occur. Furthermore the compressive stresses have so low values, both in the vault and in the backfill or spandrels, that the elastic behaviour can be well justified.

#### 5. REFERENCES

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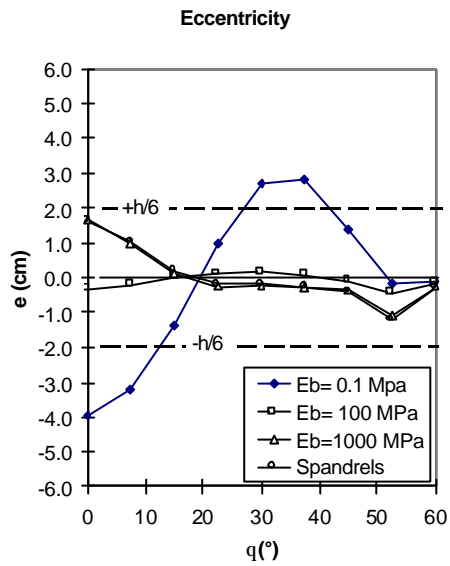


Figure 2: Eccentricity of the arch axial force under dead and live loads [8].

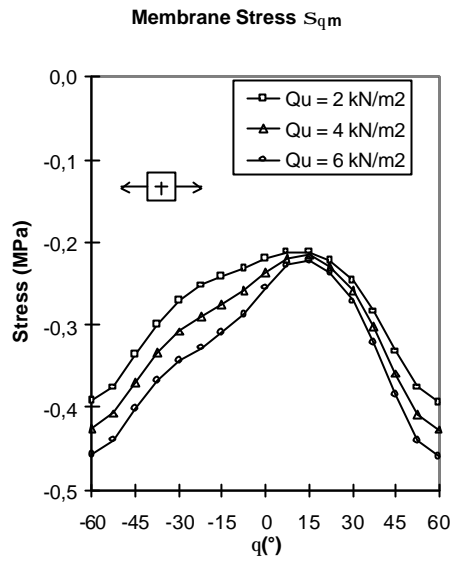


Figure 3: Membrane stress  $\sigma_{\theta m}$  along the masonry vault.

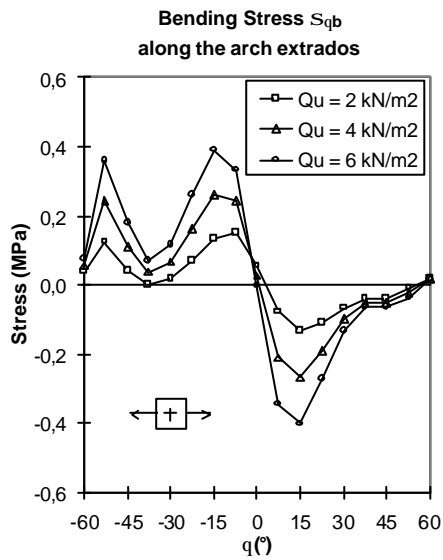


Figure 4: Bending stress  $\sigma_{\theta b}$  along the masonry vault extrados.

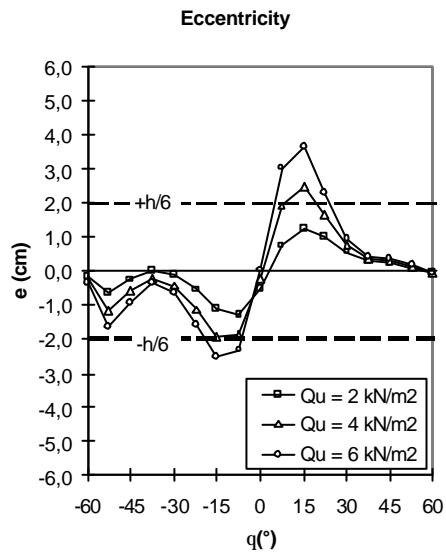


Figure 5 : Eccentricity of the arch axial load.

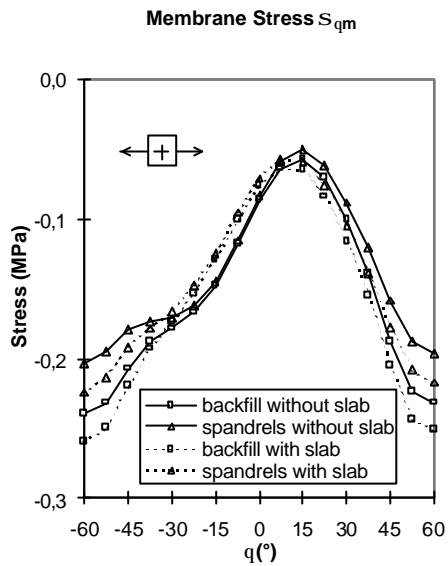


Figure 6: Membrane stress  $\sigma_{\theta m}$  along the masonry vault.

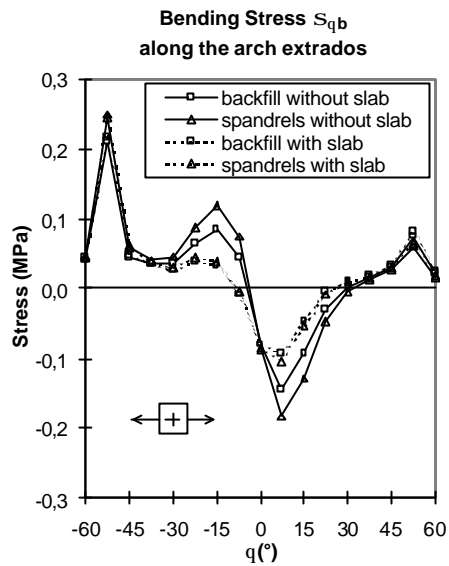


Figure 7: Bending stress  $\sigma_{\theta b}$  along the masonry vault extrados.

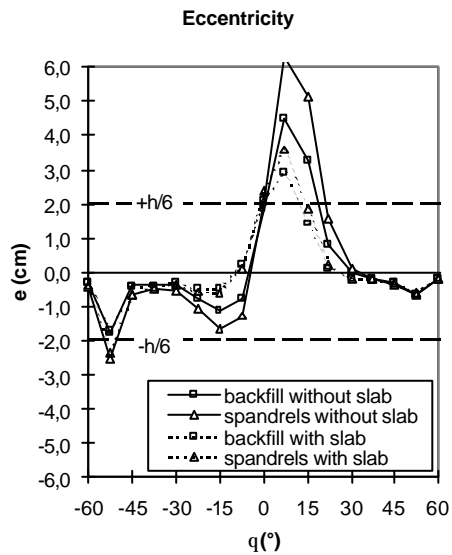


Figure 8: Eccentricity of the arch axial load.

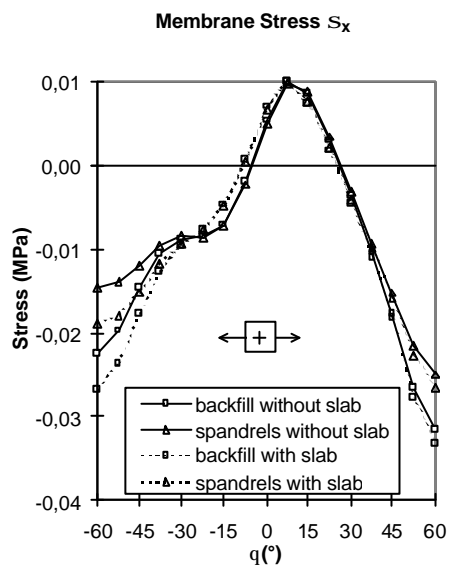


Figure 9: Membrane stress  $\sigma_x$  along the mid section of masonry vault.