Load carrying capacity of multiple-leaf masonry arches

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ABSTRACT: Some Romanesque monumental buildings in the Italian alpine region present the covering structure carried by a system of round arches, built up adopting multiple-leaves masonry technology. Buttresses resist to the lateral thrust of the arches.
In time the buttresses can undergo significant displacements. As a consequence, the geometric features of the arches are modified, and many cracks open. The global static conditions of the structure are compromised, especially when there are losses of contact and even local separations between the masonry leaves of the arches, as it can be observed in *Basilica di San Fedele*, in Como.

The study presents the results of a numeric modelling of an arch assumed with reference to this structure, considering the presumptive initial configuration (XI century) and the present condition. The results indicate the progressive loss of bearing capacity due to the buttresses displacement and the worst contact characteristics of the layers.

In addition a possible restoration technique for this type of element is reported.

1 INTRODUCTION

For many centuries, up to modern building techniques, in order to cover large spans in constructions, there were two possible solutions: the use of wood beams or wood trusses, and the use of arches and arch shaped structures (barrel-vaults and cross-vaults).

As wood is a material subjected to a relatively rapid degrade, and sometimes it is quite expensive, stone masonry or brick masonry arch structures were the technique preferred for important monumental buildings, as the medieval churches, built up to last in time.

Before the XVI century there was not a design method for the arches, they were built following empirical rules concerning the geometric features of the element. In the following times various methods based on equilibrium were developed, until the final formulation of Culmann in XIX century. Stone masonry arches have been adopted for important structures also in recent times, till the end of XIX century they were common for road and railway bridges.

Modern structural analysis gave many results about the behaviour of arches, but generally these studies are focused on arches made only of one structural material.

The presence of arches with two or three layers of different materials, in some monumental building in the alpine region, suggested the opportunity of a study in order to evaluate the load-carrying capacities of this kind of structural element. The study was performed taking into account an arch feature similar to that of the arches of "Basilica di San Fedele" in Como (Italy), which date back to the XI century, and is a typical example of the Lombard-Romanesque architectonic style. This monument presented a significant degradation in its multiple-leaf arches, which have been recently reinforced and restored.

The study performed is not a study of the effective mechanical behaviour of the arch structures of that monument, but a general overview of the resistance characteristics which can be expected from this kind of structural element, in comparison with some field observations on the reference monument, reported afterwards.

There is no document evidence explaining the choice of this unusual building technique. In the alpine region up to the XIX century almost all monumental constructions are built using only stone masonry, as good quality stone material was largely available, and the stone workers of that region were fairly famous (Magistri Comacini).

The addition of a brick masonry layer over the stone masonry arches of the central nave, seems a subsequent reinforcing intervention, although the early arches are made with good squared stones. Probably the intervention was needed for the developing of cracks caused by the subsiding of the buttresses foundations, or because the initial thickness of the arches seemed not fit to carry safely the large load of the roof. Generally in the alpine region the cover of historical buildings is quite heavy. In this church it is made by stone slabs 3-4 cm thick, over a frame of wood beams. The arches carry the roof in three points, by mean of horizontal girders.
A false barrel-vault along the nave leaves visible only the lower stone masonry layer of the arches, therefore it is not possible to observe the developing of cracks between the stone arch and the brick arch, and the local separation of the two structural elements.

The load carrying capacity of multiple-leaves walls, particularly in case of out of plane loading, is strongly dependent on the effectiveness of the joints between the different leaves. For multiple-leaf arches, therefore, a weak or locally null interaction between the leaves seems particularly dangerous.

This was the case of "Basilica di San Fedele", where significant displacements and a separation between the arch leaves were observed in some parts of the structures, particularly close to the keystone. In this situation the restoration of the church was aimed to eliminate the structural function of the arches, transferring the load of the covering from the arches to special steel trusses. This solution was possible because the steel trusses are hidden by the false barrel-vault.

Nevertheless a study on the carrying capacity of this type of arch seemed important, as it is present also in other monuments of the region. It was carried out, focusing the attention mainly on the influence of the mechanical properties of the joint between the two leaves. This multiple-layered structure cannot be studied with the mechanical assumption used for arch structures made up with only one material, just for the presence of the weak intermediate joint. The analysis was performed by means of a distinct element code, in this case UDEC2D, which allows the assessment of collapse conditions and can follow the dynamic behaviour of the blocks up to the complete collapse of the structure.

2 NUMERICAL MODELLING

The structure considered is a round arch with an inner free span of 10 m, made up with a lower arch of quite good stone masonry, and another arch over that of brick masonry. The two structural elements are connected by a mortar layer of about 4 cm.

The thickness of the stone masonry and that of the brick masonry in the model were assumed 40 cm, representative of an average model of the arches in the church. In reality there are arches with a little bit less mean values for stone masonry thickness, and sometimes also the brick masonry arches are thinner.

The masses of the three materials were set to the average values of 1900, 2000 and 2300 kg/m^3 respectively for the mortar layer, the stones and the brick masonry. The structure was modelled by means of deformable blocks, whose dimensions for the stone masonry arches are similar to those of the real stones. The intermediate mortar layer is of quite poor quality; as its thickness cannot be disregarded, it was modelled by means of 4 cm thin blocks.

The properties assumed for the joint mechanical behaviour (Coulomb model) are reported in Table 1, they are taken from literature as plausible values for these type of structural elements.

Table 1 : Joint mechanical characteristics.

	Cohesion (MPa)	Friction angle (degrees)	Tensile resistance (Mpa)
Stone masonry	0.5	30	0.2
Brick masonry	0.2	25	0.1
Intermediate mortar	0.2	25	0.1

3 RESULTS

The aim of the analysis, to obtain indications on the global load carrying capacity of these types of arch, was carried out in three main steps. The first step regarded a brief modelling of the behaviour of:

- the stone masonry arch by itself
- the composite structure with very weak or null effectiveness of the intermediate joint.

The second step considered the load carrying capacity of the composite material arch subjected separately to external vertical loading and to the displacement of a base pillar.

Finally a third step considered a possible set of joints characteristics that give a structure resistant to the previous load conditions acting together.

The first analysis performed regards the structural behaviour only of the stone masonry arch, without the brick addition. This structure is a quite slender element, the free span is 25 times the thickness assumed, and probably from the beginning the builders considered the opportunity of a reinforcing.

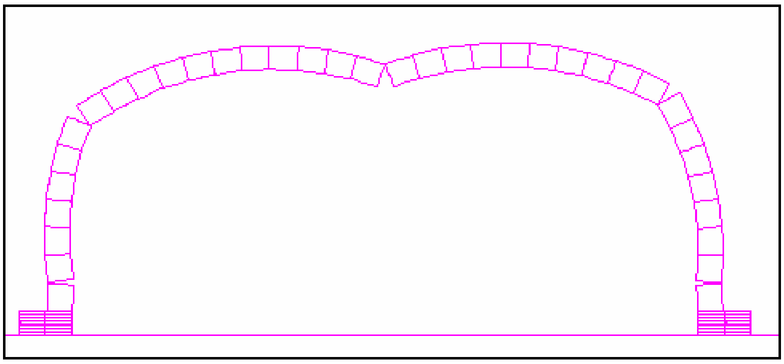

Figure 1 : Collapse of the stone masonry arch.

Figure 1 represents a stage of the collapse of the structure, subjected to three loads of 10 KN in the same zones (keystone and the two arch sides) where the girders of the covering transfer the load to the arch. The load carrying capacity of the modelled arch can be assumed about 30% less than the applied 10 KN load, and seems anyway not fit to the quite large load of the cover.
The results obtained depend obviously on the values of the joint mechanical characteristics assumed in the model.

The following models performed regard the carrying capacity of the composite structure. Assuming a quite weak intermediate joint (cohesion 0.1 Mpa, 20 degree friction angle and almost no tensile resistance), without applied external loads, the arch is not equilibrated (collapse is represented in figure 2.

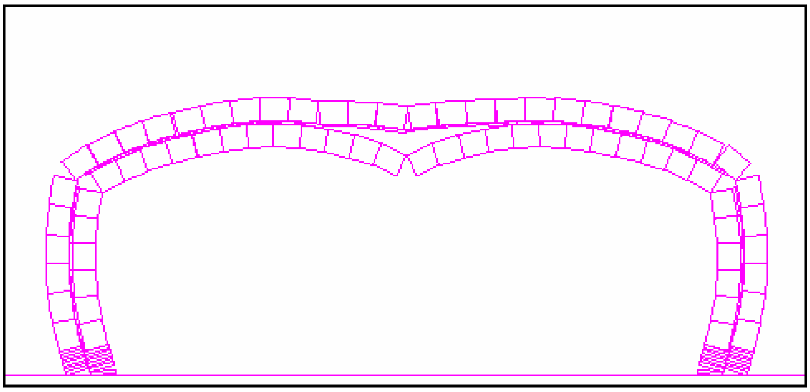

Figure 2 : Collapse of multiple-leaf arch with weak joint

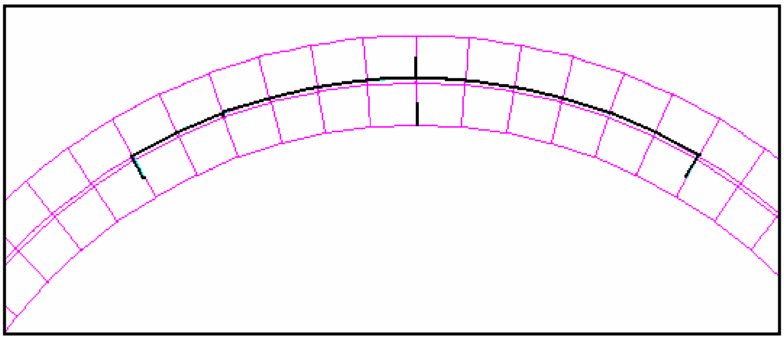

Figure 3 : Joint fracture in the upper arch part

This model represents a limit situation, which has weak joints also at the bases of the arch, at the connection to the pillars, therefore the horizontal thrust that can be applied is low and the resistance to the opening of cracks at the base is quite small. In this case the upper brick arch behaves especially as a load. The structure can reach equilibrium only assigning to the brick masonry one half of its mass. Assigning a 0.1 tensile resistance to the mortar joint, equilibrium is reached, but in the upper zone, at an angle ± 30 degrees from the keystone, the joint is fractured, as it is represented in figure 3 (the thick line indicates the joint fracture).

Considering the more realistic joint characteristic of table 1, the load carrying capacity of the structure was investigated assuming two separate stress conditions: external load transmitted by the girders of the covering, as in the previous stone masonry arch, and a sinking of the right base pillar.

The analysis performed gave a limit value of the load about 30 KN, more than three times the load estimated for the stone masonry arch by itself. It should be pointed out that this value is an estimate of the largest loading for the convergence of the numerical model. The block assemblage is shown in figure 4.

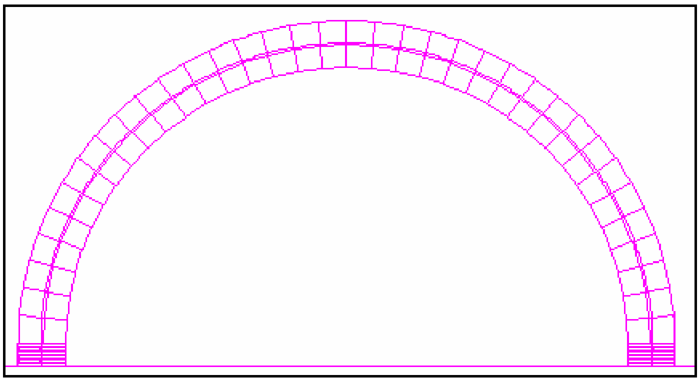

Figure 4 : Block assemblage of the multiple-leaf arch

The obtained final structure anyway shows widespread fractures and opening of the joints. The transfer of this result to reality should be made with caution. However a clear indication on the effectiveness of the brick masonry reinforcement is obtained.

On the other hand, certainly in time the arches have undergone some displacements at the base. In this modelling only in plane displacements can be examined, but in reality also some relative displacement out of plane were observed.

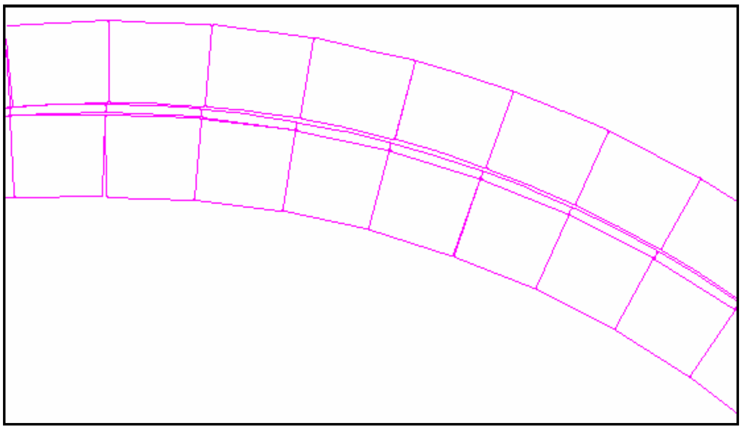

Figure 5 : Separation between the arch layers

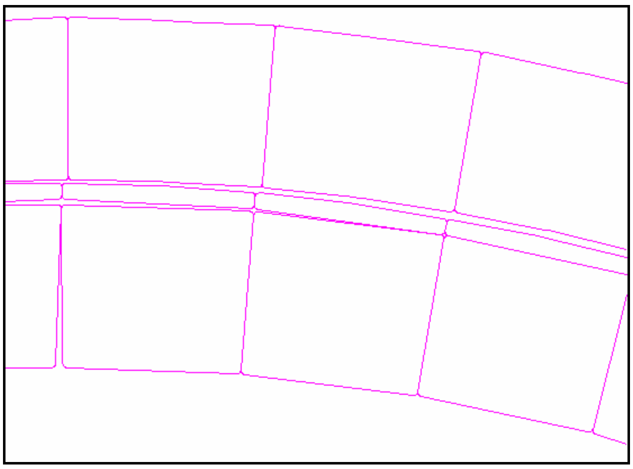

Figure 6 : Separation between the arch layers close to the keystone

Taking into account only the self-weight load, and considering a translation of the right base pillar horizontally and downward of the same quantity, the limit load condition is a 10 cm down and 10 cm right displacement.

The results obtained are interesting because in the models a 2-3 cm joint separation between the two arches appears in a wide area in the upper zone (figure 5 and figure 6). A similar joint separation was verified in the real structure.

An enough large different sinking of the arch base pillars is very realistic: the city of Como, particularly its centre, is in a lake valley, with generally soft soil.

Also a different kind of displacement was considered, that is a small rotation of the right base of the arch, in addition to a horizontal displacement, obtaining similar results with regard to the intermediate joint separation. Figure 7 refers to a limit situation with an 8 cm horizontal displacement and a 3 to 5 cm vertical displacement of the right base.

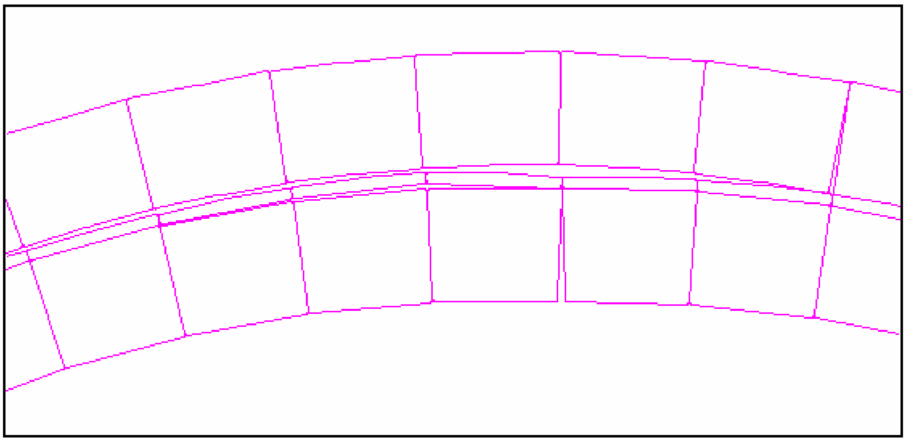

Figure 7 : Separation between the arch layers near to the keystone, due to base rotation

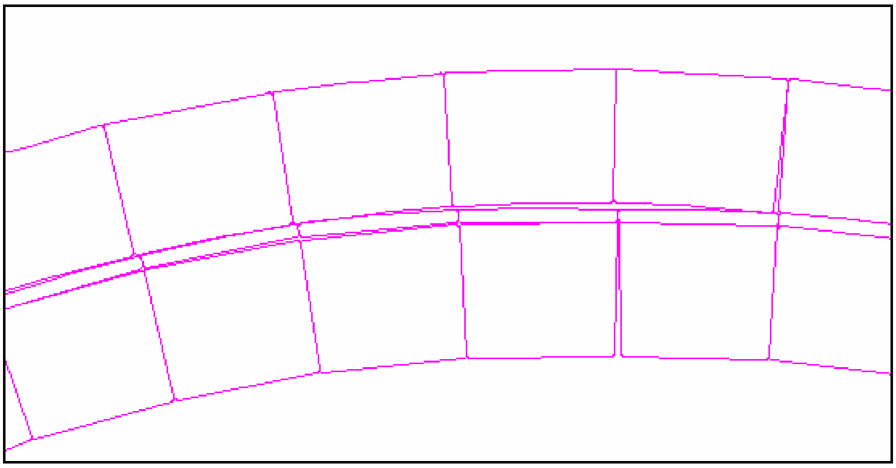

Figure 8 : Separation of layers at the keystone due to base rotation

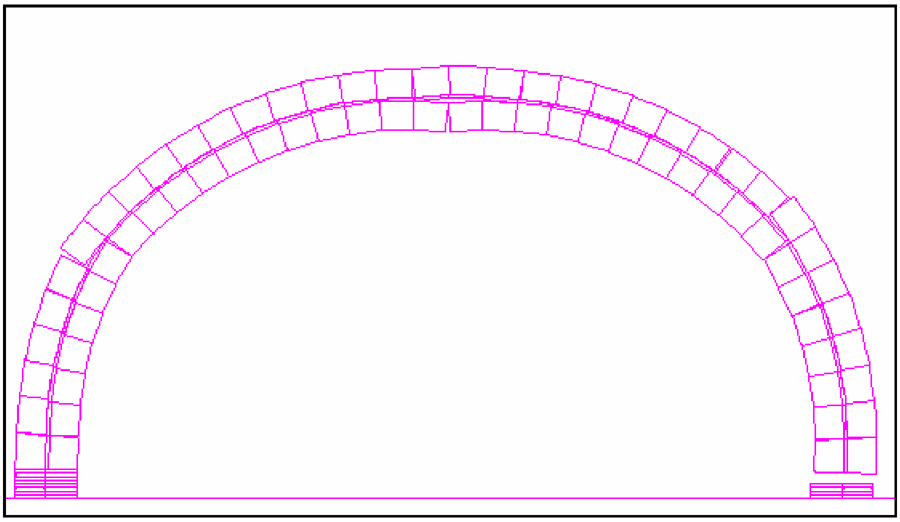

Figure 9 : Beginning of collapse due to arch base horizontal displacement and rotation

Increasing the rotation of the base, assigning as an example a 3 to 7 cm vertical displacement, equilibrium is reached only with no horizontal displacement. Figure 8 shows the joint separation between the two layers and the shear block displacements determined near the keystone.
The addition at the base of a small horizontal displacement causes the collapse of the structure; its first stage is represented in figure 9.

The last step of the analysis was a general improving of the joint characteristics in the intermediate mortar layer and in the stone masonry.

The aim was to estimate values giving a structural element able to carry at the same time the ultimate external loading and the ultimate base sinking evaluated previously.

The values obtained are reported in table 2.

Table 2 : Good mechanical joint characteristics

	Cohesion (Mpa)	Friction angle (degrees)	Tensile resistance (MPa)
Stone masonry	0.5	30	0.2
Brick masonry	0.4	30	0.2
Intermediate mortar	0.4	30	0.2

Only for the case of base rotation displacement, the external ultimate load is a little lower than the former weight (30 KN).

In this third step the multiple-leaf structure is quite similar to a strong single material element; as it can be seen from the almost uniform important value of cohesion and of tensile resistance.

4 ARCH RESTORATION

Restoration activity depends on the supervision of the Italian state department "Soprintendenza Regionale alle Belle Arti", which impose the observance of the rules of "Carta del Restauro" and mainly the reversibility of the intervention.

Afterwards some indications on the restoration choices are reported, as they seem proper to be applied, when possible, to similar situations.

Considering the degrade of the intermediate joint, in some parts completely open, and considering the presence of cracks, the absence of chain restraints and the displacements of the buttresses, the arches seemed not suitable to undergo possible additional stresses, due to accidental loading as other base displacements, small seismic loads, etc.

Therefore the main purpose of the intervention was the reduction of the loads on the arches, and a consequent lowering of the horizontal thrust on the buttresses. This result was obtained by means of steel trusses arranged at the two sides of the arches. Naturally this option is favoured by the presence of the false barrel vault, which hid the steel trusses and the covering frame.

The separation of the two arches in some parts of the intermediate mortar joints, the presence of significant cracks between the blocks close to the keystone, and the alteration of the arch curvatures indicated the necessity of the restoration also of the arches themselves. Besides the replacement of the degraded mortar, the stones in the central part of the lower arch were connected to the upper bricklayer by means of a system of stay bars contained in the arch section.

5 CONCLUSIONS

The numerical model performed was not aimed to model the real behaviour undergone in time by the considered structure. The model is taken from a mean geometric example, and the mechanical characteristics are plausible values from literature, probably quite similar to the real values, but they are not obtained from experimental evidence in that monument.

The steps performed give a general survey on the structural characteristics of the element and of its load carrying capacity, taking into account separately the ultimate load conditions due to external loads and those due to the sinking of foundations.

In what regards the support displacements, the order of the base displacements, which spend completely the resistance resources of the modelled arch, is about 1/100 of the free span.

The stone masonry arch by itself probably appeared unfit to carry the loads of the covering very early to the builders, as it is suggested by the results obtained.

The addition of a second brick masonry arch can be a suitable reinforcing, but the effectiveness of the connection between the two structural systems must be assured. With larger value of the mechanical characteristics of the joints, or rather with similar characteristics of the joints for the whole structure, the two elements behave like a single arch with a good load carrying capacity.

An important problem in this kind of structures, is the effectiveness of the connecting intermediate mortar layer, that generally, as large part of ancient mortars, degrades in time. This effect can cause a significant lowering of the load carrying capacity.

Another important item is the resistance to horizontal thrusts at the basis of the arch: chain restraints are not present, but buttresses in Romanesque architecture are used. Nevertheless in the resisting mechanism at the base should be considered the influence of the mechanical characteristics of joint between blocks at the base of the arch and also in the buttresses. In the study performed, this effect is in part taken into account assigning at the base of the arch the joint characteristics of the intermediate mortar layer, but only when the external load is applied.

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