AN EVOLUTION OF "CATENA A BRAGA" IN THE CONSOLIDATION OF MASONRY VAULTS

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Abstract

In the consolidation of arches and vaults, if tie-rods cannot be placed at the intrados to contain the horizontal thrust, one possibility is to work on the extrados.
Widely used in the past, the so called "catena a braga" is based on transferring the effect of an extrados tie-rod to the haunches, using diagonal struts called "braghettoni". However, this system is not able to effectively prevent the triggering of the pier rotation, since the tie-rod tends to flex.
In the 19th Century, G. A. Breymann improved this technique replacing the flexible tie-rod with an horizontal beam, more stiff and effective (Breymann 1885). This technique has been proposed again by one of the authors under the name of New Clamp Method (NCM) and it has been applied in the consolidation of several historical buildings.
The article concerns the dimensioning and some applications of the methods described above.

1. INTRODUCTION

Arches and vaults transfer to their supports not only vertical forces, but also horizontal ones, whose intensity depends on the geometry of the arch itself and on the applied load.

Such supports can be either pillars or walls that generally behave as slender elements along the discharge direction of the arch. Depending on the geometric constraints imposed by the boundary conditions, abutments can be considered as shelves, clamped at the base and loaded at the free-end by a vertical and an horizontal force. In historical structures, pillars and walls are generally made of brick or stone and they are characterized by a low modulus of elasticity and a limited tensile strength. Therefore, the supports of the arched or vaulted structures generally offer a low rigidity towards horizontal translations. As a consequence, the rotation of the abutments can cause negative effects on arches and vaults, up to the collapse of the structures if 4-hinges occur (generally 2 hinges form at the abutments, 1 in the middle position and 1 at the base of the pillar).

In case of arches and vaults that present a static instability due to the translation or rotation in the plane of abutments, the consolidation should prevent the activation of a collapse mechanism through the imposition of an appropriate confining system. Therefore, the consolidation requires elements that are able to avoid the mutual displacement or rotation of the supports, making pillars or walls working mainly in compression and reducing the bending moment.

The simplest solution to solve such problem consists in the insertion of chains at the intrados (usually made by steel or iron, even if in the past also wooden element were adopted, as shown in Figure 1), to connect the arches spring point. This type of intervention, although structurally efficient, sometimes may not be appropriate, due to some aesthetic reason or due to the fruibility of the space, which in some cases can be compromised. Therefore, it’s possible to raise the position of the chains, at mid arch or even at extrados, although this solution is not totally suitable from structural point of view.

In fact, chains placed at the extrados can lead to the modification of the collapse kinematic of the arch-pillar system, generating plastic hinges on the piers, where the horizontal thrust of the structure acts. Chains placed at the extrados provide an adequate action to contain the thrusts only in presence of high vertical load on the piers, counteracting the rotation mechanism of its upper portion.

Figure 1 – View of the magnificent cross vaults of Sant’Anastasia church (Verona, Italy) with wooden chains (left) and iron chains in the central nave in San Giacomo Maggiore church (Bologna, Italy) (right).

2. *“A BRAGA”* CHAINS

As previously mentioned, the extrados chains, even if they respond to some aesthetic matter, are less effective than the intrados ones, because the action they exert is decentralized with respect to the horizontal resultant thrust of the arch or vault.

In order to solve this problem, two inclined iron elements called *braghettoni* were often inserted to intercept the horizontal thrust of the vault as close as possible to the spring involving also to the kidney area. Architect Carlo Francesco Dotti, in the 18th Century, in *Examination on the strength of the braga chains* [1], through geometric schemes showed that the braga chain was not able to guarantee the containment of the thrust of the vaults because it was extremely deformable (Figure 2). In fact, the horizontal tie, stressed by the inclined braghettoni, is subjected to flexural bending moment, thus losing its effectiveness.

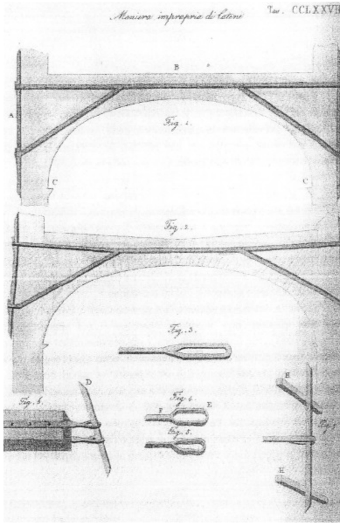

Figure 2 – Drawings from Dotti’s manuscript on the braga chain, showing the elevate deformability of the horizontal element.

One century later, also architect Giuseppe Valadier advised against the use of this structural system, since it was not considered to be more effective than a simple extrados chain. Thus, in order to have an effective braga chain system both agreed that the horizontal element should not deform under the action of the braghettoni.

At the end of 19th Century, Breymann improved the braga technique, as described in his *Civil Building Treaty* [2]. Breymann’s solution consisted in the insertion, already during the construction phase, of vertical iron posts within the arch support walls (Figure 3).

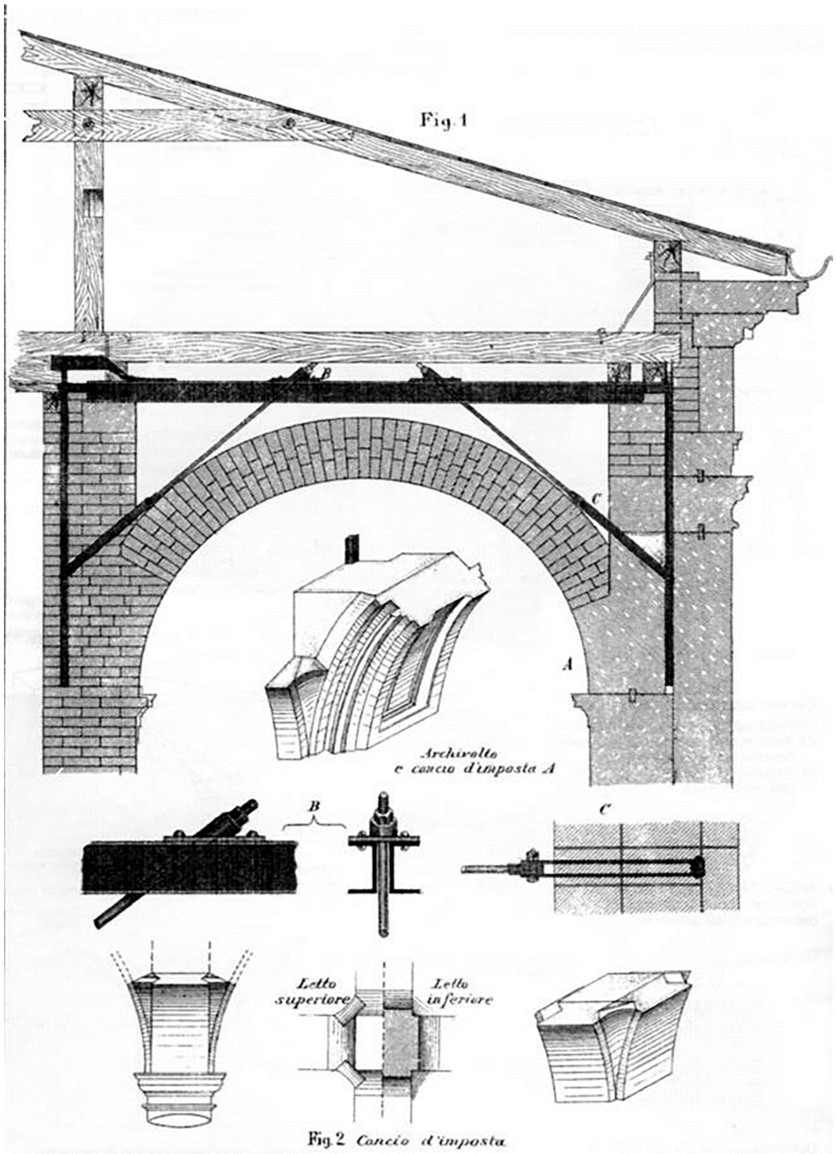

Figure 3 – Breymann’s enhancements of the braga chain.

These posts reduce the horizontal thrusts from the arch to the lateral supports, by means of two inclined ties connected to a metal stiff beam placed at the extrados of the vaulted structure. Breymann used such vertical elements inside the masonry to act on the arch springs, without compromising its continuity. This technique allows a reduced inclination of the diagonal ties with respect to the horizontal beam; as a consequence, the vertical components of the forces transferred to the beam is reduced and bending is minimized too. It has to be said, however, that the real distribution capacity of the metallic vertical element in the Breymann system is not completely guaranteed, due to its reduced sectional inertia. It follows that the pillars/walls will be still subjected to bending, even if smaller than what would happen in total absence of a confinement system. The technique described by Breymann comes from older construction experiences. A similar solution, in fact, was used for the vaulted roof of the secular church of San Nicolò in Verona. In that case, the reinforcing system consists on diagonal iron ties inserted into the masonry at the base of the vault, which are connected to the overlying wooden trusses (Figure 4). The wooden chain is subjected to flexural bending moment and it can offer sufficient stiffness.

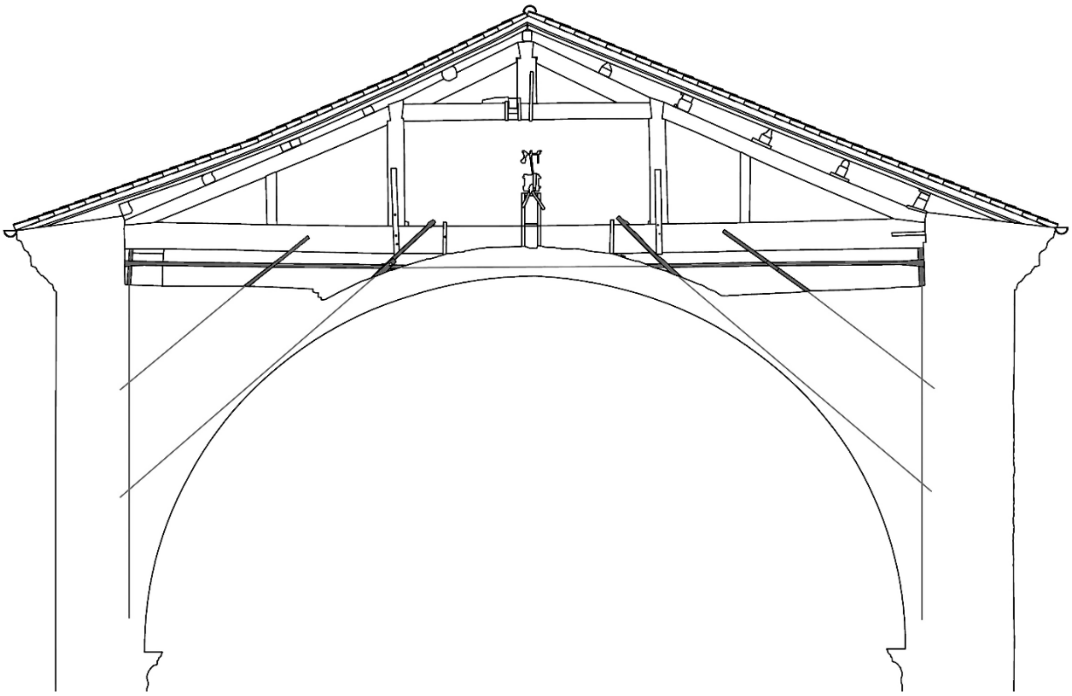

Figure 4 – Consolidation with the braga chain of the vaulted roof of San Nicolò church in Verona.

Two possible critical issues of the above described solution in San Nicolò could be mentioned. First, under snow or wind, the wooden truss deflects and thus the contrast offered to the diagonal tie rods is reduced. Second, the wooden truss exhibits a viscous behaviour under constant loads, that makes the system less efficient. It follows the need to disconnect the covering truss from the contrast system of the vault, so as to obtain a structure whose effect is constant over time and under every load condition.

2 THE *GRAFFETTE* OR "*NEW CLAMP METHOD*"

An alternative solution that exceeds the limit of the braga chain is the so-called *Graffette* or *New Clamp Method* (NCM) technique, improved by one of the authors as a consolidation technique in case of the impossibility to work with chains at intrados [3]. The NCM system is essentially composed of:

- a steel beam, placed at the extrados of the vault to be consolidated, simply supported by the pillar of the arch/vault;

- two symmetrical and diagonal tie-rods that start from the beam and reach the two abutments of the arch.

In the system shown in Figure 5, the inclined tie-rods are anchored through grouting mortar inside the wall at one end, and through a contrast plate at the other one. A nut allows the post-tensioning of the tie-rod. As a consequence, the internal forces in the reinforcing system result as reported in Figure 6:

- the tie rods are subjected to tension;
- the extrados beam is subjected to bending, due to the vertical component transferred by the tie rods and, in the central part, it is tensioned because of the horizontal component of the same tie rods forces;
- the wall portions between the support of the beam and the anchoring points of the tie rods are subjected to additional compression;
- the horizontal thrust induced by the arch is wholly or partly eliminated, depending on the force imposed to the diagonal tie-rods.

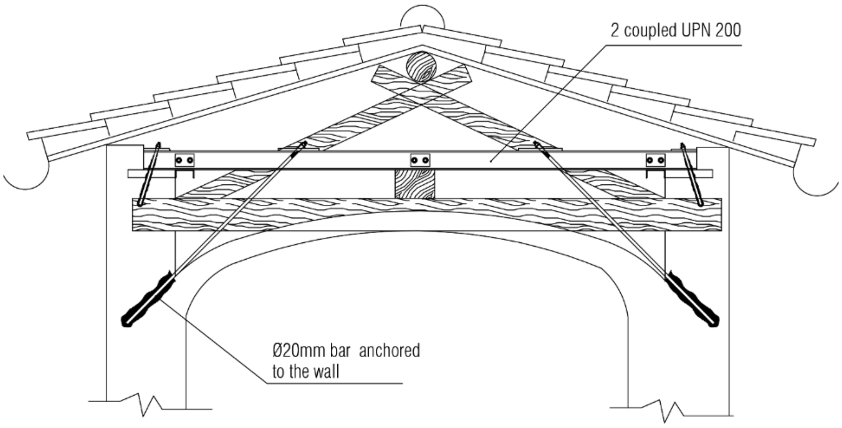

Figure 5 – Graffette method for the consolidation of a barrel vault.

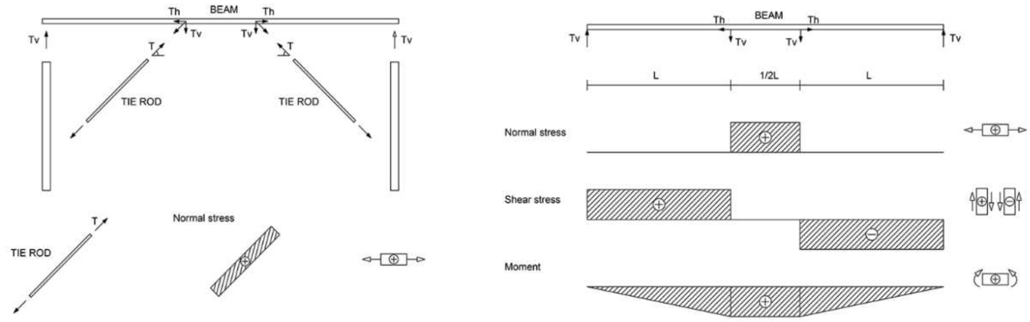

Figure 6 – Distribution of stresses in the clamp system elements.

3. CASE HYSTORIES

In this paragraph several cases in which the NCM system was adopted are presented. The new clamp technique was used by the author L. Jurina for the consolidation of the vault of *Palazzo delle Carrozze* in *Masino* Castle, Caravino (Italy), owned by FAI (Fondo per l'Ambiente Italiano). That barrel masonry vault was supported by a retaining wall on the left side, that could be considered fix, and by an un-constrained wall on the right side. This last one presented some cracks due to a global overturning, even if some braga chains already existed. Thus, the necessity raised to reinforce the vault and to prevent the overturning of the right support, without the possibility to work from the intrados, since the height of the room was not enough to allow the insertion of new chains. Therefore, a non-symmetric NCM was adopted as a reinforcing system, anchoring the overturning wall in ten different points along the vault. In order to have a more widespread confinement of the side wall and to avoid excessive local concentrations of the stresses, the clamp method was adopted by introducing three inclined tie-rods for each couple of HE profiles, positioned at the extrados. The connection of the diagonal bars to the masonry was guaranteed by steel contrast plates, positioned on the external facing, in small holes under the plaster (Figure 7 - 8).

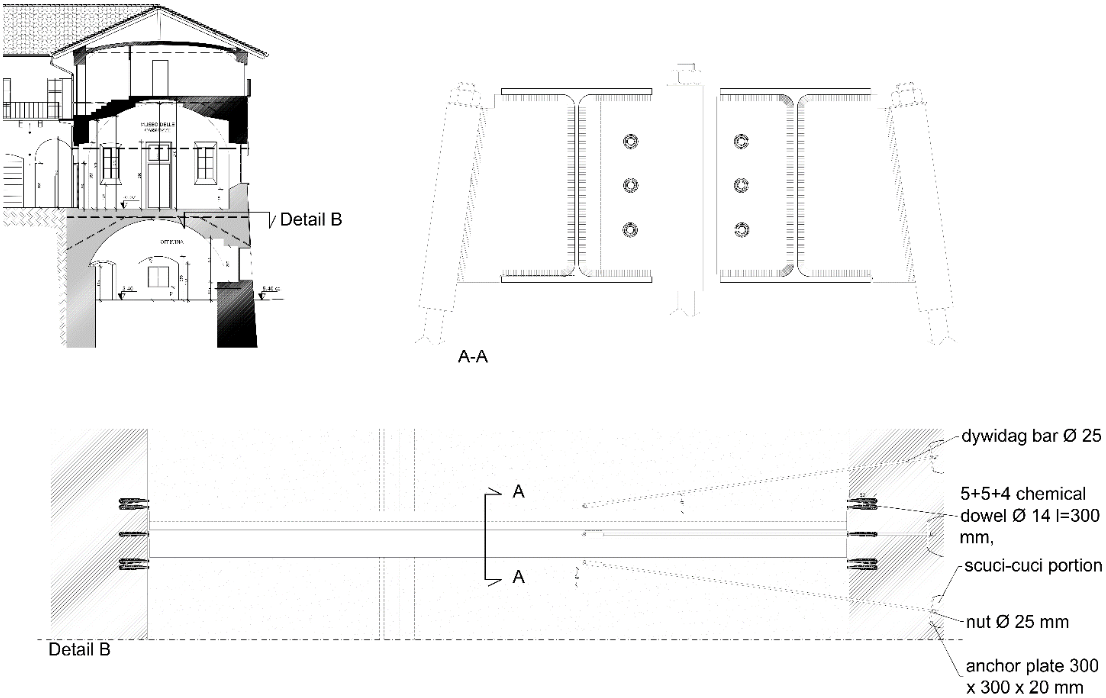

Figure 7 – Details of the consolidation with the new clamp technique on the vault of Palazzo delle Carrozze in Masino Castle, Caravino (Italy).

The steel extrados beams of the clamp technique, in many cases, can be also useful for supporting the floors above the vaulted surfaces, so that the distributed live and dead load are transferred directly to the perimeter masonry through the new structures. In the case of *Palazzo Cattaneo* in Cremona (Italy), the clamps, placed at a step of 2.5 m, worked as support elements for a continuous wooden floor placed under the roof, used for maintenance of the roof and as a support for UTA-air treatment units (Figure 9).

Figure 8 – Details of the intervention on Palazzo delle Carrozze in Masino Castle, Caravino (Italy): steel supports of the horizontal element (left) and overview of the intervention from above (right).

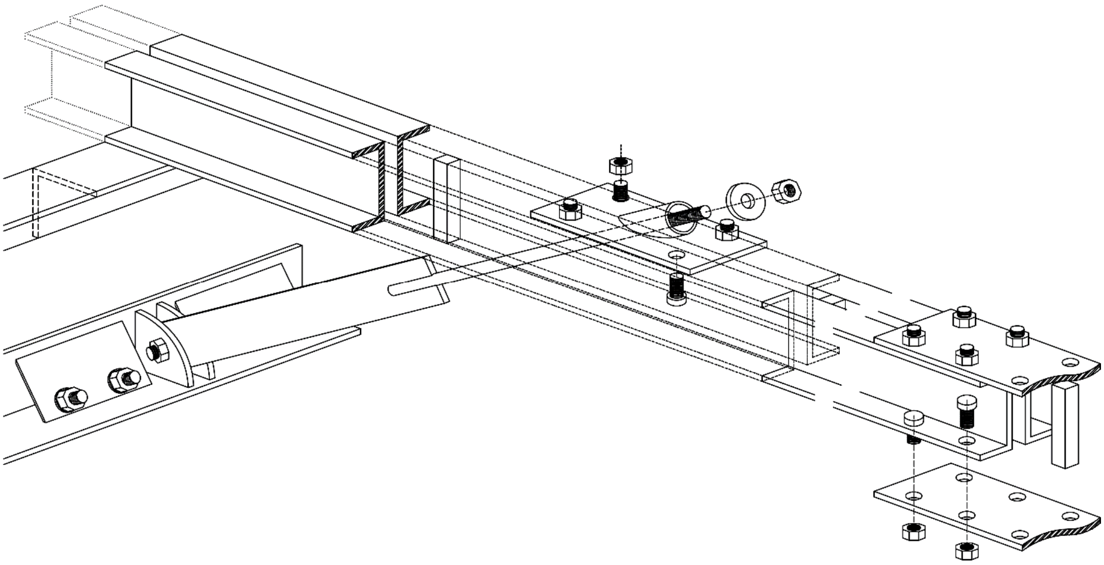

Figure 9 – The metal clamp used in Palazzo Cattaneo in Cremona (Italy).

The same technique was applied in *Corridoio delle Grottesche* at the *Castello della Manta*, Manta (Italy), which had a worrying cracking situation due to the horizontal thrust of the barrel vault, that was not confined by any chain. In fact, due to the overturning of one not constrained perimeter wall (only the external one was free to rotate), an evident arch-shape crack appeared on the painted vault (Figure 10).

The clamps were supported by long steel profiles, with an L section, placed on both sides of the vault. Even in this case, due to the necessity to prevent the overturning of only one side wall, the NCM system was applied in a non-symmetric configuration. Furthermore, the rectangular fields between clamp and clamp were integrated with diagonal cross cables, so that the whole system became an effective reticular beam in the plane of the roof, useful in presence of seismic loads (Figure 11).

Figure 10 – Decorations at the intrados of the vault of Corridoio delle Grottesche in Castello della Manta in Manta (Cuneo, Italy). Overall view (left) and detail of a remarkable crack on the corner (right).

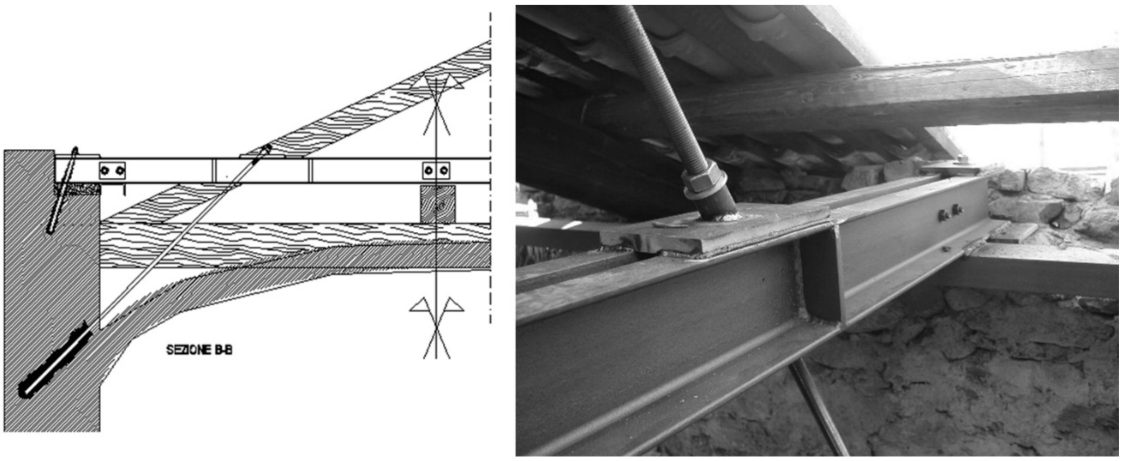

Figure 11 - Intervention with the new clamp technique on the Corridoio delle Grottesche’s vault. View of half span as drafted (left) and realization (right).

The efficiency of the consolidation with the clamps method of te Corridoio delle Grottesche was studied by means of a finite elements numerical model, that allowed to determine the post-tension to be applied to the inclined tie rods, demonstrating a noticeable improvement both in terms of stress and deformations. It should be noticed that the desired confinement effect was achieved by operating exclusively from the extrados and preserving the precious frescoes of the corridor.

Another consolidation intervention in which the clamp method was adopted was the matroneum of *Cremona Cathedral* [4], next to the main nave. In the matronea a long three-dimensional truss girder beam was laid out, measuring 60 x 8 x 1 m, acting as a “seismic diaphragm”. The diagonal bars, which fall tangential to the arches in order to limit the thrusts on the lower columns, were anchored directly to this truss girder, which works exactly as the horizontal steel beam, mentioned in the previous example.

4. PARAMETIC ANALYSIS THROUGH NUMERICAL MODELS

FEM analyses have been recently performed by the authors, to further investigate the behaviour of the New Clamp Method and determine its optimal configuration with respect to the geometry of a given barrel vault.

The models have been implemented by means of SAP 2000, by CSI software. The masonry barrel vaults have been modelled using 3D 8-noded elements (bricks), while the clamps have been simulated through simple 2-noded one-dimensional elements (frames). Linear elastic materials have been used, with average typical elastic parameters of both masonry and steel (E=1.200 N/mm^2 ; E=210.000 N/mm^2).

Since the aim of these simulations is only to investigate the distribution of stresses inside the masonry and compare it in the cases with and without the insertion of the clamp consolidation system, only linear static analyses have been performed. This allowed to apply the Superposition Principle to compute the effect of the clamp by only summing the “unconsolidated” vault case stresses with the effect of the clamp itself to get the final “consolidated” stress state. Therefore, these models do not include cracking phenomena, but they can be estimated by simply comparing the tensile stresses with a threshold cracking value, estimated from literature as f_t = 0.11 N/mm^2.

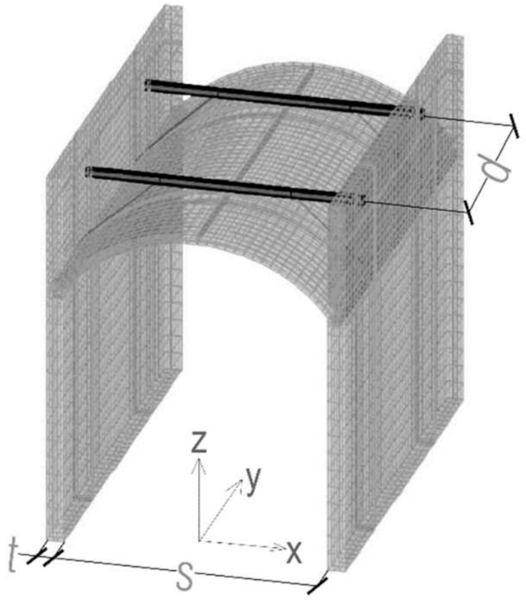

Figure 12 – Dimensions varied in the parametric analysis.

A parametric analysis has been performed, in order to determine the necessary tension to apply to the tie in order to recover an uncracked state in the entire masonry mass, by variating 3 geometric parameters: vault span (s), wall thickness (t) and clamps spacing (d) (Figure 12), for a total of 24 cases, as shown in Table 1. The thickness of the vault has been established for each case proportional to the span, with a constant thickness/span ratio of 0.0375. Also, the wall height depends on the vault span. The depth of the model is twice the clamps distance.

Vault span s [m]	Wall height [m]	Vault thickness [m]	**Clamps spacing d** [m]	**Wall thickness t** [m]		
4	5.78	0.150	**2**	**0.3**	**0.4**	**0.5**
	5.78	0.150	**3**	**0.3**	**0.4**	**0.5**
	5.78	0.150	**4**	**0.3**	**0.4**	**0.5**
	5.78	0.150	**5**	**0.3**	**0.4**	**0.5**
6	8.68	0.225	**2**	**0.4**	**0.5**	**0.6**
	8.68	0.225	**3**	**0.4**	**0.5**	**0.6**
	8.68	0.225	**4**	**0.4**	**0.5**	**0.6**
	8.68	0.225	**5**	**0.4**	**0.5**	**0.6**

Table 1 - Geometrical parameters used for the parametric analysis.

The clamp has been modelled always with a coupled UPN 160 as horizontal element, while the diagonal tie-rod is a Φ20 mm steel bar. The models are restrained at the boundaries in the longitudinal direction (y) and in the vertical direction (z) at the base. The loads applied are the self-weight (including a 14 kN/m overload simulating the roof centred on the top of the wall) and the tension of the bar, applied as an imposed strain. The horizontal element is simply vertically supported at the middle of the wall, so as to avoid unwanted moment/shear transmission to the wall. The bar is instead rigidly clamped inside the wall and hinged at its connection with the horizontal beam.

As expected, results show that the self-weight application, in the unconsolidated configuration, causes the occurrence of tensile stresses at the centre of the vault (at intrados) and at the impost of the vault, at the extrados, as shown in Figure 13 on the left (white colours represent tensile stresses). In these zones, where typically hinges arise, the positive principal stress exceeds the limit of tensile strength (f_t = 0.11 N/mm^2) and causes cracking. The application of the clamp, with the tension of the diagonal bar, causes a stress state that is opposite to the one caused by self-weight (central image on Figure 13), and therefore, by superposition, a final state with principal tensile stress in the uncracked field (right image on Figure 13) is obtained. To obtain this effect, the proper amount of tension to apply to the bar has been previously computed, based on the effect of a unit prestress. The results presented have the only aim to show the positive effect of this strengthening technique, since for more accurate results a non-linear constitutive model, that includes cracking, should be developed.

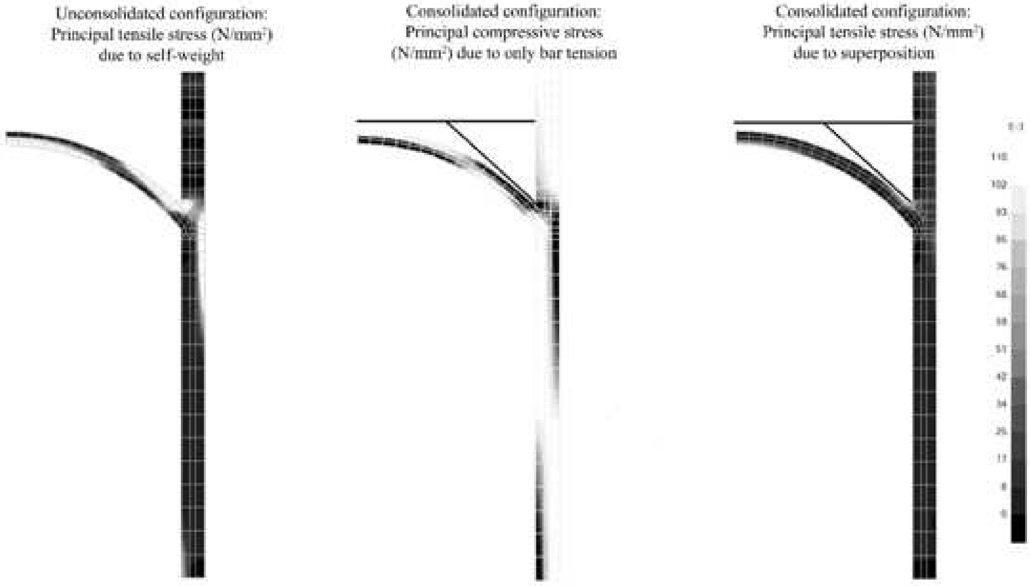

Figure 13 – Results on half transversal section of the vault, with the application of 72.5 kN on the diagonal bars.

It is interesting to notice how, in the final consolidated configuration, a sort of relieving arch mechanism develops inside the wall between the clamps. This also gives rise to unwanted tensile stresses at the extrados of the wall between the clamps and at the intrados of the wall at the clamps, shown clearly in Figure 14 and Figure 15 in white, where typically cracks arise.

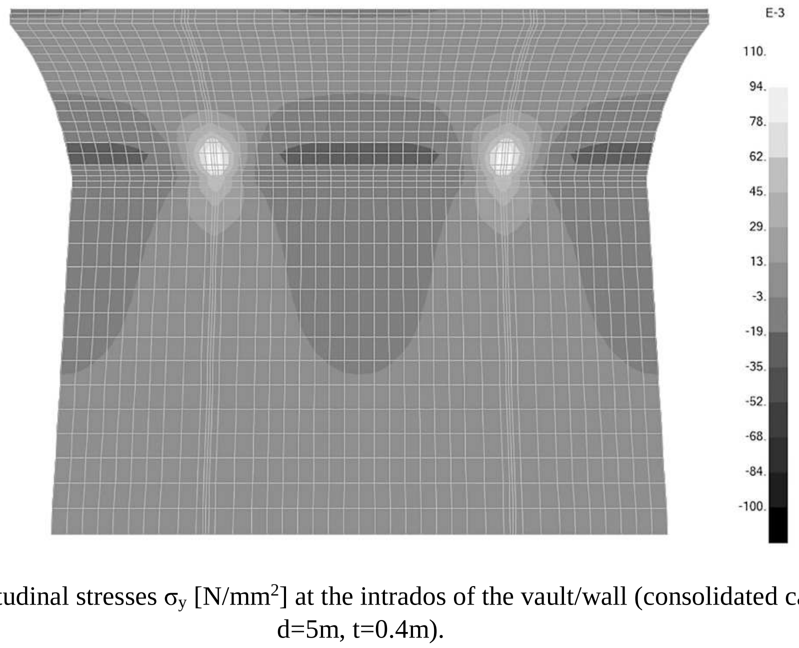

Figure 14 – Longitudinal stresses σ_y [N/mm^2] at the intrados of the vault/wall (consolidated case with s=6m, d=5m, t=0.4m).

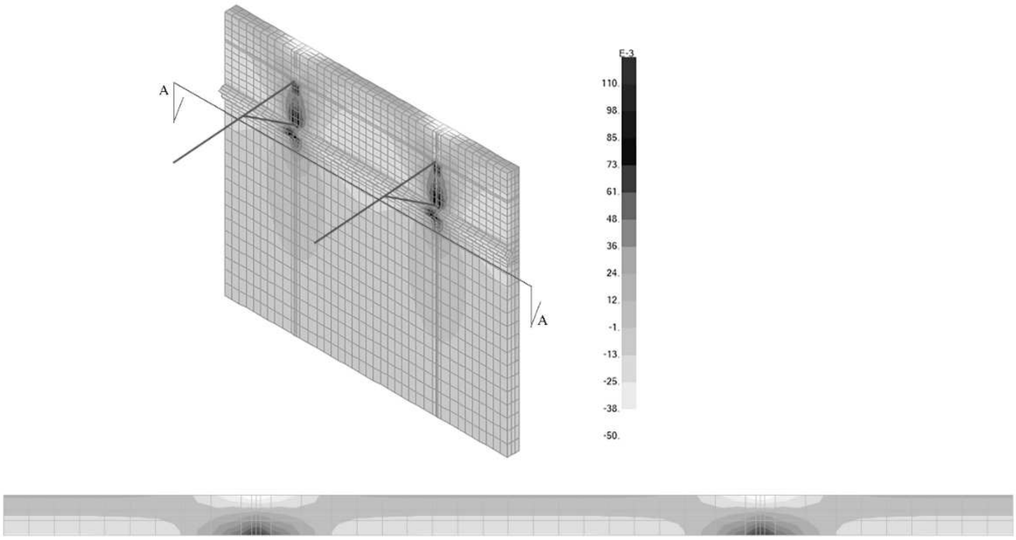

Figure 15 – Longitudinal stresses σ_y [N/mm^2] showing a relieving arch formed between clamps (consolidated case with s=6m, d=5m, t=0.4m, horizontal section at the impost of the vault).

Also, at the extrados of the vault it can be noticed that there is a concentration of compressive stress in correspondence with the clamps, caused by the highest stiffness of this consolidating system, compared with the masonry one (Figure 16). This also possibly gives rise to the unwanted effect of a non-uniform deformation of the wall in the transversal direction. Nevertheless, it must be underlined that the advantages of this strengthening technique largely overcome the disadvantages.

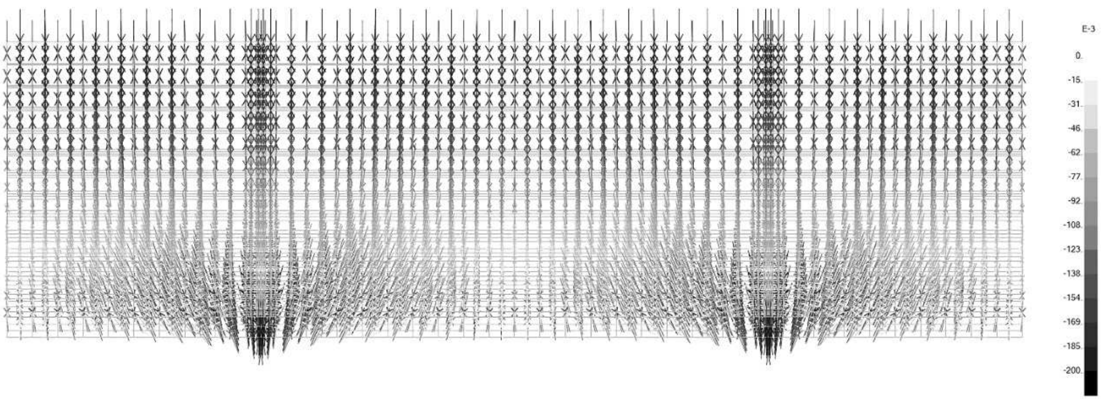

Figure 16 – Principal compressive stress arrows [N/mm^2] seen from the top of the vault. Notice the concentration in correspondence with the clamps (consolidated case with s=6m, d=5m, t=0.4m, section at the impost of the vault).

With the same procedure explained above, the amount of bar tension to be applied to obtain an uncracked stress state has been determined for each of the 24 cases considered and has been reported on the abacus shown in Table 2. With this abacus an optimal configuration of the clamp can be chosen.

Vault span s [m]	**Clamps spacing d** [m]	**Wall thickness t** [m]			
		0.3	**0.4**	**0.5**	**0.6**
4	**2**	11.3	10.5	9.8	-
	3	16.9	16.1	15.3	-
	4	22.6	21.9	20.3	-
	5	29.0	28.5	26.8	-
6	**2**	-	29.6	28.6	27.4
	3	-	45.0	42.3	41.2
	4	-	58.6	56.8	55.2
	5	-	72.7	71.2	69.7

Table 2 - Abacus of bar tension (in kN) to be imposed to diagonals to obtain an uncracked stress state inside the vault.

5. CONCLUSIONS

The clamp method, recently applied after years of oblivion, is an appropriate and structurally effective system for the consolidation of arches and vaults. Good aesthetic results are added to the structural advantages as the new elements are positioned in not visible places. Other advantages are the reduced invasiveness of the intervention, the substantial reversibility and the possibility of re-tensioning the diagonal bars, making the system effective along time.

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