Stabilization of Masonry Arches by Hidden Prestressing Cabels with the Possibility of Clearence the Space by Removing the Forged Tie Rod

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Abstract

Stabilization of baroque masonry structures with flat arches by longitudinal prestressing can be advantageously carried out by deliberately introducing a system of prestressing forces into the structure so that the normal effects of the prestressing force exceed the radial effects. Then the arch is transformed into a prestressed tie beam with a curved centreline. Additional prestressing is possible by the method of substitute cable ducts. Then the construction of the masonry arch becomes a prestressed tie rod supporting the wall pillars and even preventing their further spreading, as happens with the original and unprestressed arch. The paper is addressed to the professional community, which, especially in the field of monumental Baroque masonry structures, often deals with failures of masonry arches and vaults. These structures are usually broken by cracks in the top. The supporting structures must resist the long term arching force, which has an oblique direction. While its vertical component creates no problems, the horizontal component of the arc force is considerable and, in addition, acts in the long term already to load the dead weight of the vaulted structure. Horizontal displacements at the base of the vault (of the supports) are the most prevalent failures, accompanied first by the formation of transverse cracks in the top section of the vault. Stabilization is a key step for their permanent rehabilitation. By the additional prestressing, the structure supported by the supports becomes a prestressed tie rod, which in turn prevents further failure development until the pressure reserve is exhausted. The method is so effective that it even allows the original forged tie rod to be removed. The removal of the forged rod of the masonry arch is an example of the high efficiency of the described method. It is a former Baroque granary adapted into a living space. Two roughly elliptical arches of brickwork of 300/600mm top section span the space with clearances of 6.0m and 6.3m. The masonry is made of solid bricks with lime mortar. The passage height under the arches was insufficient, only 1.72 m. It was raised to 2.4 m after the arch was prestressed and the forged tie rod removed. he paper contains examples of the structural design, realization and measurement of the deformation response of the structure. The method can be effectively used to stabilize masonry arches in the case of low stiffness of supports or to free space by removing a forged tie rod. Measurements of the implemented structure show its effectiveness and long-term reliability.

Keywords: *Stabilization, Masonry Arch, Prestressing, Space, Tie Rod, Substitute Cable Duct*

1. Introduction

Stabilization of baroque masonry structures with flat arches by longitudinal prestressing or even removing of the tie rod can be advantageously carried out by deliberately introducing a system of prestressing forces into the structure so that the normal effects of the prestressing force exceed the radial effects. Then the arch is transformed into the prestressed tie beam with a curved centreline. Additional prestressing is possible using the method of substitute cable ducts. The substitute cable ducts could be prepared by diamond or hammer drilling as it was for many times used by masonry bridges [2] or in case of the concrete bridges strengthening [3]. Then the construction of the masonry arch becomes a prestressed tie rod supporting the wall pillars and even preventing their further spreading, as happens with the original and unprestressed arch.

Monumental Baroque masonry structures are usually broken by cracks in the top. The supporting structures must resist the long term arching force, which has an oblique direction. While its vertical component creates no problems, the horizontal component of the arc force is considerable and, in addition, acts in the long term already to load the dead weight of the vaulted structure. Horizontal displacements at the base of the vault (of the supports) are the most prevalent failures, accompanied first by the formation of transverse cracks in the top section of the vault. Stabilization is a key step for their permanent rehabilitation.

By the additional prestressing, the structure supported by the supports becomes a prestressed tie rod, which in turn prevents further failure development until the pressure reserve is exhausted. The method is so effective that it even allows the original forged tie rod to be removed.

The removal of the forged rod of the masonry arch is an example of the high efficiency of the described method. It is a former Baroque granary adapted into a living space. Two roughly elliptical arches of brickwork of 300/600mm top section span the space with clearances of 6.0m and 6.3m. The masonry is made of solid bricks with lime mortar. The passage height under the arches was insufficient, only 1.72 m. It was raised to 2.4 m after the arch was prestressed and the forged tie rod removed. The paper contains examples of the structural design, realization and measurement of the deformation response of the structure.

The method can be effectively used to stabilize masonry arches in the case of low stiffness of supports or to free space by removing a forged tie rod. Measurements of the implemented structure show its effectiveness and long-term reliability.

2. Stabilization of Arches and Vaults by Longitudinal Prestressing

Arches and vaults can be freestanding or repeated, supported by walls or pillars or decorative columns. The supporting structures must resist the long term arc force, which has an oblique direction. While its vertical component is no problem, the horizontal component of the arc force is considerable and, in addition, acts in the long term already to load the self-weight of the arched structure. Horizontal displacements at the footing of the vault (displacement of the supports) are the most prevalent failures, which are accompanied first by transverse cracks in the top section of the vault, and as the failure develops further, the vaults also crack at the footing and often throughout the vaulted structure. The basic assumption of the structural behaviour of vaults as an arched structure supported by supports is challenged.

Longitudinal prestressing of arches and vaults is the application of a prestressing force to the arch structure or to the vaulted structure including supporting elements in the direction of the span. Depending on the size of the central angle of the vault, it is sufficient to prestress the vault alone (approximately for $\alpha \leq 120°$), or it is appropriate to complete this prestressing with vertical prestressing of supporting walls, pillars (for $\alpha \geq 120°$). By the additional prestressing, the structure supported by the supports becomes a prestressed tie rod, which in turn prevents further failure development until the pressure reserve is exploited.

3. Description of Dominant Faults

Many masonry structures of historic and socially significant buildings use masonry arches, vaults and vaulted bands as the basic load-bearing element of vaulted ceilings. This corresponds to the period of construction of these structures, tentatively between 1600 and 1800 (Baroque). They are already used directly as load-bearing structures (cylindrical vaults) or support infill vaults. These are often vaulted structures in historic cellars, stables, but also in historic halls, castles and churches. In some cases, the vaulted bands are made in the form of flat (bold) arches with a constant or, more often, stepped cross-section, increasing towards the foot of the arch.

These flat arches exert significant horizontal components of the arch forces on the supporting structures (masonry walls, inter-window pillars) in the footings over a long period of time. These are deformed over time (shifting in the direction of the applied forces). The displacement of the base of the arches then causes the tops of the arches to fall. This basic deformation mechanism is accompanied by the typical formation of cracks at the lower edge of the arches at the top, and often also by cracks in the footings and in the surface of the arches. Such a disrupted flat masonry strip (arch) and flat vault structure is shown in Figure 1 . Linear analysis of the structure is difficult because such a severely disturbed structure does not conform to the assumptions made using conventional computational models. Also, capturing the time-dependent displacement of the supporting wall piers is problematic.

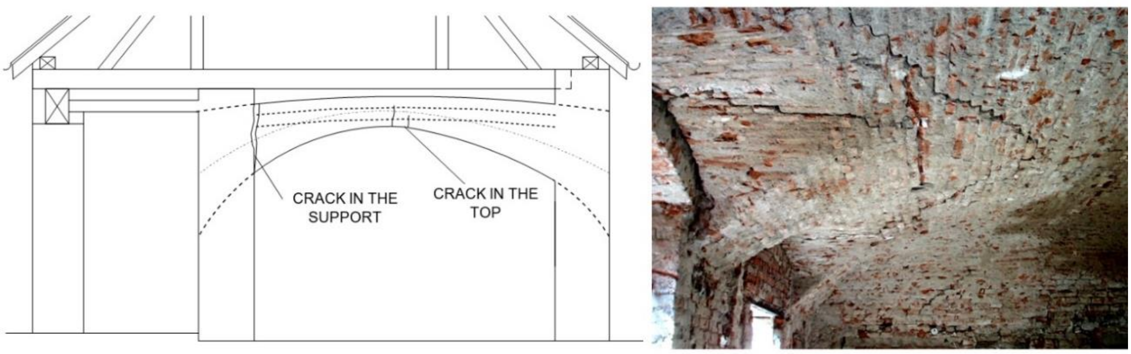

Fig. 1. Examples of the cracking of masonry arches and vaults

4. Arch and vault like a tensioned rod

The strengthening of structures with these flat arches by longitudinal prestressing consists in the effective introduction of a system of prestressing forces into the structure so that the normal effects of the prestressing force prevail over the radial effects. Then the arch is transformed into a prestressed beam with a curved centreline. The additional prestressing can be achieved by the method of substitute cable ducts. A typical cable arrangement is then shown in Figure 2.

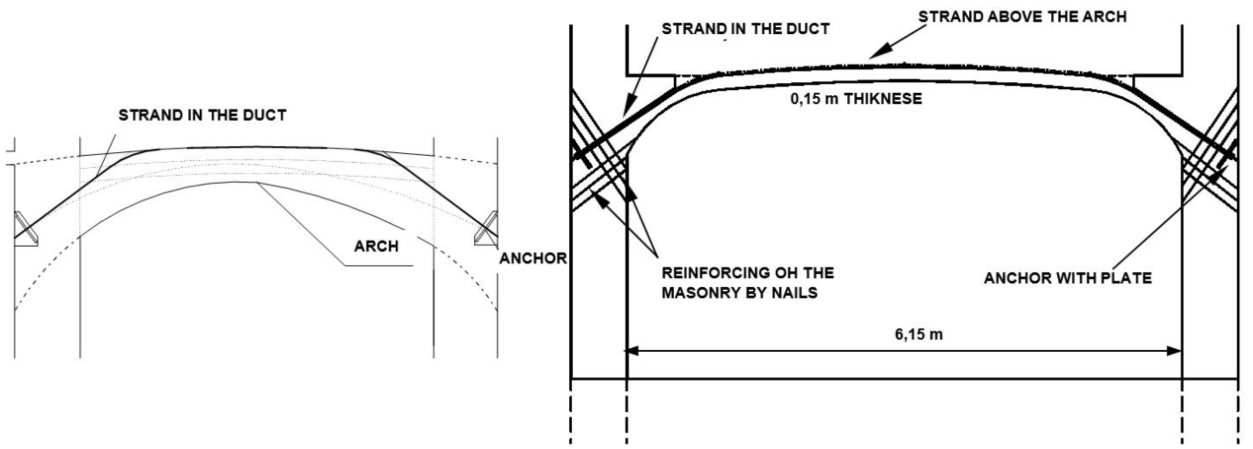

Fig. 2. Examples of the cable or strand arrangement

The prestressing of vaults breached by displacement of supports is based on the idea of ideal prestressing by reinforcement placed at the centre of gravity of the arch or vault. The prestressing force can then be used to eliminate any tension that occurs and to recreate the compressive stress in the masonry, analogous to the gravitational prestress in the vault that was present before the failure occurred. The restoration of the prestress can be suitably controlled (and even reserve) in the design by selecting the magnitude of this ideal prestressing force. The vault structure then becomes a prestressed tie rod supporting the wall piers and even preventing their further spreading as occurred in the original and unstressed vault. The arrangement of the tensioning cables as shown in Fig. 3 is based on the ideal cable arrangement described above and makes additional tensioning possible. Substitute cable ducts drilled in the masonry of the vault extend the tensioning system to the upper surface of the vault at the cost of additional stresses from local forces in the saddles. Computational models and subsequent experience from prestressing show that the additional (parasitic) stresses are not critical and can also be eliminated by a suitably large prestressing force.

Substitute cable ducts made in the masonry come from the centre of gravity of the base section of the arch to its upper surface. The theoretical point on the top surface can be located in terms of the span of the arch to l/5 to l/6. In most cases, the location of the first cross-sectional change of the vault is used. The breaking of the cable is mediated by the saddle reinforcement, which distributes the linear load to the masonry of the vault. The cable can then be conveniently routed on top of the arch along the surface of the vault, which forms another natural deviator. The radii of curvature of the vaults are relatively large, so it is possible to support the cables and cables directly against the vault masonry without exceeding the allowable radial pressure of the monostrand. Its protection is usually provided by an additional concrete shell on the reverse side, which is sometimes added to the vault reinforcement for other reasons.

The reinforcement design is based on a detailed structural and static survey of the structure. In it, it is necessary to record the decisive defects, the dimensions of the structure, the strength of the construction material and the mortar used. It is sufficient to determine the size of the prestressing and the arrangement of the prestressing reinforcement using a strut model of the structure. The use of this model is made possible by the additional prestressing after the cracks have been filled. The crack filling ensures the continuity and integrity of the structure and the prestressing then provides a slight pressure reserve in the cross-sections, which then justifies the use of conventional linear models. The model must represent the arch and the supporting and loading structures. The base and top cross-sections are then decisive and must be designed for off-centre pressure according to the calculation rules for masonry structures.

Cable ducts, saddles and boxes for anchors are being made as part of the construction work. The cable ducts are defined in the project documentation by the vertical and horizontal angles and the point of penetration into the structure. Their trajectory can only be designed after prior measurement of the actual shape of the structure, usually by CAD means. After the ducts are made, the saddles and anchor boxes are prepared according to their actual alignment. The reinforcement of the saddles and the spreader plates under the anchor rings must also be included in the design. The following is the placement of the prestressing reinforcement - monostrands. In the next step, all cracks and cable ducts must be grouted. A side effect of the grouting of cable ducts is the desired grouting of any caverns in the masonry that become accessible thanks to the duct. The prestressing is done in steps, best in increments of 20 kN. The structure according to Figure 2 left) was prestressed with a force of 100 kN. Figure 3 left shows the leading of the prestressing cable on the reverse of the arch band and its penetration into the brick arch. Figure 3 right shows an example of the anchor box of the arch prestressing cable with spreader plate and covered anchor on the perimeter wall of the structure.

Fig. 3. Leading of the strand above the arch (left) and anchor with the spreading plate (right)

5. Prestressing vaults with tie rod - removing the tie rod

Some very flat arch bands are made with a tie rod. This is a structural arch with a tie rod, most often fixed into the neighbouring masonry at the foot. The tie rod, by its axial stiffness, prevents the supporting walls from being crushed by the horizontal component of the arch force. It must therefore be massive - for example, forged webs with transverse dimensions of 10 x 100 mm were used. This is how various Baroque and Renaissance farm buildings, former granaries, etc. are constructed. When these spaces are renovated for residential purposes, the owners often request the removal of the beam due to the low clearance height. At first sight, this requirement is completely nonsensical - after all, it prevents the proper operation of the arch with the rod in the very essence of this structural design.

Longitudinal prestressing of vaults according to Figure 2 allows to solve even these demanding requirements. This is the longitudinal prestressing of a masonry arch such that the original force in the arch disappears completely. In simplified terms, the arch with the beam is a statically determined structure in terms of the external connections. Theoretically, it induces only vertical reactions in the supports (the elastic elongation of the tie rod was either neglected or the tie rods were fitted with a wedge lock which allowed rectification, i.e. shortening of the tie rod by driving a pair of wedges against each other). The supporting walls could therefore be designed relatively thin as they did not have to resist the arching force. In this way, it was possible to design arched bands and vaults even on higher floors where only beam ceilings were normally designed, mainly because of the low wall stiffness in the horizontal direction.

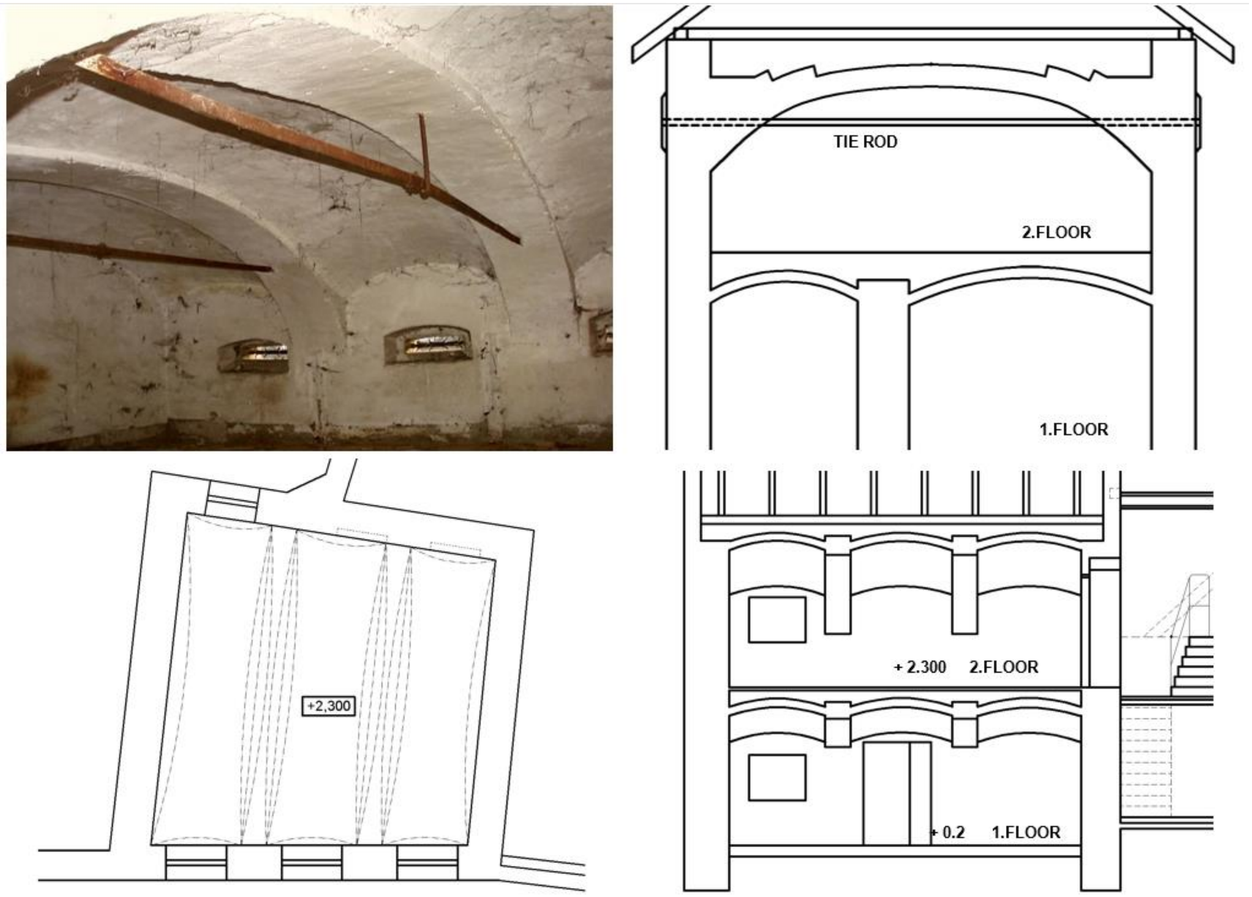

Fig. 4. Baroque vaulted granary; the ceiling structure is formed by an arch with a tie rod;
above - situation of arches and tie rods before modification and longitudinal section through the arch
bottom - plan of the granary and cross-section of the arches andinfill vaults

The tie rods are usually made across the vaulted space; they are placed in the plane of the arch and connect the two supporting walls. They are usually placed slightly higher than the theoretical footings of the arches, probably in an attempt to affect the vaulted space as little as possible. They are supported on the outer surface of the masonry by means of clamps. The construction of the supporting walls and the arches with the tie rods is relatively soft in the horizontal direction, both for the above-mentioned structural reasons and because of the thermal expansion that takes place by stretching and shortening the tie rods while the supporting walls are leaning out. These periodic expansion movements are made possible by the well-known high deformation capacity of masonry, but at the cost of cracks, especially in the mortar joints of the masonry, and at the cost of a large reduction in the stiffness of the supporting walls in the horizontal direction. Often we also find the masonry of brick arches with a beam loosened at the lower edge of the cross-section at the top of the arch (mid-span), where after many tens (sometimes hundreds) of years the drop in the top caused by mortar creep becomes visible. The deflection of the arch decreases as the mortar is deformated due to creep and, if the length of the beam is unchanged, the lower part of the top section falls into the tension zone, which is reflected in the aforementioned loosening (cracks in the joints between the bricks) of the masonry.

Removal of the rod can be achieved by strengthening the arch itself by longitudinal prestressing. The prestressing cable or strand is routed along the upper outer surface of the arch. At the points of cross-sectional change, a substitute cable duct specially constructed by drilling shall enter the masonry of the arch. The duct leaves the outer surface of the supporting walls at the base of the arch. The projection of the arch footing onto the outer surface in the direction tangential to the axis of the arch at its theoretical support must be investigated by graphical methods based on a detailed structural survey of the arch shape, preferably using CAD tools (AutoCad, etc.). Finding the centre of gravity of the arch footing cross-sections is crucial. Masonry arches are generally very sensitive to the eccentricity of the prestressing force in the anchor zone. An incorrectly found centre of gravity of the footing sections leads to additional moment stresses near the footing and to the unwanted development of tension cracks during prestressing. Another cable arrangement according the Czech patent [4] allows the prestressing even in that situation when there is the the wall above the arch not free space.

The prestressing force is applied by the steel spreader plates, which are supported by the masonry perpendicular to the axis of the arch. The anchor plates are usually placed in the anchor chambers in such a way that they remain hidden in the masonry after embedding. A saddle (deviator) is made at the transition point of the channel to the upper surface of the arch, which converts the point force in the theoretical bending into a partial uniform linear load by means of a circular saddle arch. Radii of 1,2 to 1,5 m are sufficient, where the circularity of the cable used is not lost and the magnitude of the radial thrust does not exceed the permissible value. Depending on the properties (design and strength) of the masonry, the cable on the upper surface of the arch is supported only by the masonry of the arch, or the length of the contact may also be reinforced with steel strips. Coated stabilized low relaxation prestressing strands(monostrands) are used for prestressing. They are placed in a PP sheath and protected by a passivation lubricant. The low friction values allow the prestressing to be achieved without significant losses, even though the strand frictions against the surface of the arc and saddles during tensioning. After the structure has been prestressed, the original tension rods can be removed by cutting them close to the masonry; the parts passing through the masonry are left. To protect against mechanical damage, it is recommended to cover the cable in the section above the arch with a reinforced and anchored concrete cover.

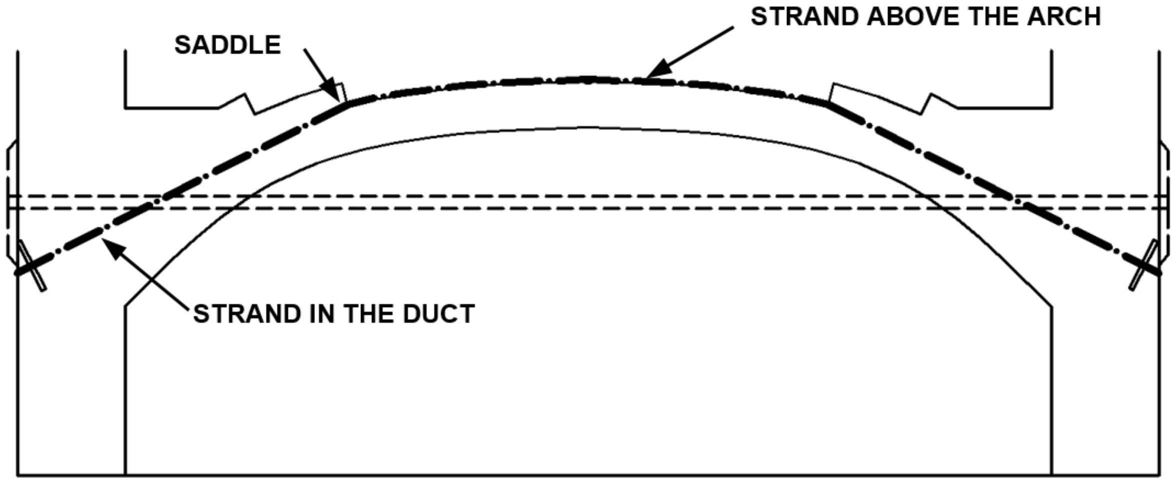

Fig. 5. Prestressing of masonry arch with tie rod

The design is best carried out using wall models with FEM using the same principles and procedures as in prestressed concrete are used. Prestressing allows the use of conventional linear calculations, since the required state of the masonry is a fully compressed top and footing section, which is then free of tensile cracks.

During prestressing, resulting forces are introduced into the foot of the arch and at the same time the arch is loaded by the radial effects of the tensioned cable. The effects of the horizontal component of the tensioning force prevail, the top of the arch rises during prestressing and the footing (supporting walls) moves towards it. The original forged tie rod is loosened while inducing a pressure reserve in the arch masonry. The prestressed arch ceases to exert horizontal pressure on the masonry, becomes a prestressed masonry tie rod with a curved centre line and in turn prevents the walls from spacing apart. The original arch tie rod is taken out of function and can be removed.

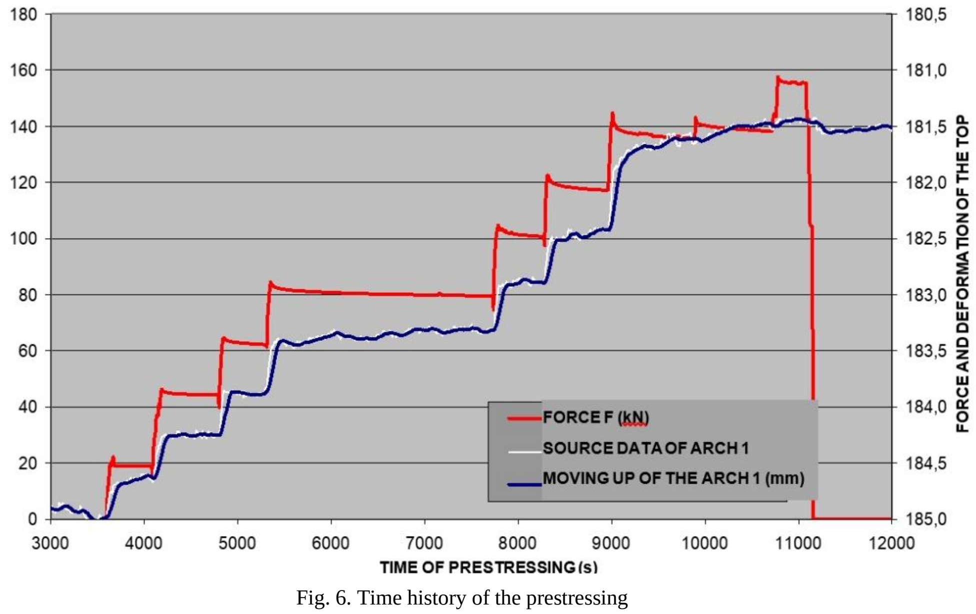

Fig. 6. Time history of the prestressing

An example of the removal of an arc rod is the design shown in Figure 4. This is the space of a former Baroque granary adapted to residential use. Two roughly elliptical arches of brickwork of 300/600mm top section span the space with clearances of 6.0m and 6.35m. The arches are supported by infill vaults with a double curvature of 150 mm. The arches are situated in the 2nd floor. The through height below the arch bar was insufficient, only 1.72 m. The longitudinal prestressing was designed according to the above principles and the static analysis, the prestressing scheme is shown in Figure 5. After the cable ducts were made using the diameter 35 mm hammer drilling technique with a length of 2.4 m, the anchor chambers and saddles were prepared, and the prestressing system (cables, spreader plate and anchor plates) was installed. After the plates had hardened sufficiently, tensioning was carried out. During the prestressing, measurements were taken of the prestressing force (with a force gauge temporarily placed behind the prestressing jack) and the deflection of the arch at the top. Figure 6 shows the time history of prestressing. Figure 7 shows the relation of the arch deflection at the peak to the prestressing force. In accordance with the calculation, the arch rose during the introduction of prestress at the peak. Prestressing was carried out in steps of 20 kN with delays to allow the effects of prestressing to be observed. The structure responded to the prestressing force elastically and from the first pre-stressing stages.

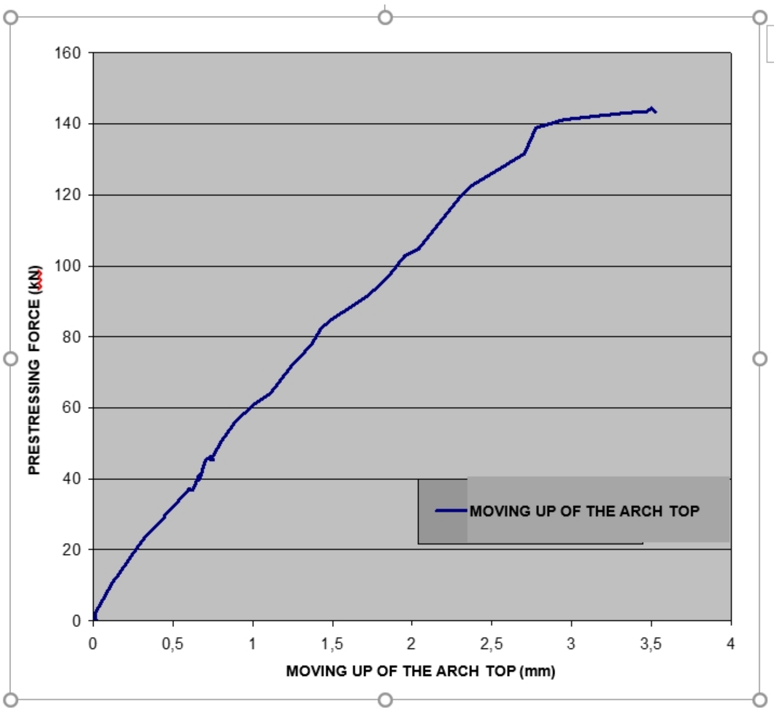

Fig. 7. L-D diagram (relation of the arch deflection at the peak to the prestressing force)


Fig. 8. Removing the tie rods by prestressing the arches
left - arches after breaking the forged tie rods
top right - wrinkling due to prestressing at the top
bottom right - anchor areas on the perimeter wall

Contrary to the assumptions, the supporting walls with a thickness of 700 mm were very soft in the horizontal direction and their bending stiffness was practically not affected at all during the introduction of prestressing. The prestressing was stopped at 140 kN in each arch, when plastic deformation started to occur (the dependence of the arch buckling on the prestressing force was no longer linear). At the same time, the compressive stresses in the masonry were manifested by the compression of the mortar and the wrinkling of the lime painting over the joints between the individual bricks of the masonry (rather, there was a compression of the micro-cracks in the joints between the bricks, later covered by repeated lime paintings). This phenomenon occurred at the apex of the arch on the inner surface of the brickwork. No tensile cracks appeared anywhere, which can be considered as evidence of a properly designed prestressing.

The total arch 1 peak rise achieved during pre-stressing was 3.55 mm. Afterwards, the rods were removed and the structure was monitored for 90 days (medium-term). Temperature effects were found to be significant, with the arch peak fluctuating by aproximatly1.6 mm over the temperature range -10°C to +10°C. After elimination of temperature effects, the arc peak decreased by 0.6 mm after 3 months. The long-term loss of prestress can therefore be estimated at 20%. This value corresponds to the strain values determined in research papers [1] and [6] for short-term [6] and long-term [1] measurements of the strain response of prestressed masonry in the direction parallel to the brick bed joint. In our case, the masonry is stressed in this way at the foot of the arches. In the arch, the prestressing is then already perpendicular to the bed joint. Therefore, the long-term strain and thus the losses can be expected to be rather less than the 20% indicated.

In Figure 8, the structure is shown after the original forged bars were broken. In Figure 9, the structure is shown after the 16 years long exploitation. The described method was signed as verified technology by Brno Univesrsity of Technology in 2012 [7].

Fig. 9. Today's view of the space under the prestressed arches

6. Conclusion

The paper shows an effective method of stabilizing masonry arches and vaults by longitudinal prestressing. By using substitute cable ducts, it is possible to stabilize these structures and make them reliable for many years of use. These structures are 200 or more years old and are often damaged by cracks in the top of the arches and vaults, usually due to horizontal displacement of the supports and, in part, by masonry creep. The effectiveness of the method even allows the original forged tie rod to be removed, freeing up the space under the arch.

Acknowledgments

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