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Rigid-block analysis of archeological elements retrofitted with external post-tensioning system

Paolo Zampieri[a*], Cyrille Denis Tetougueni[a] and Carlo Pellegrino[a]

[a]*Department of Civil, Environmental and Architectural Engineering, University of Padua, Via Marzolo 9, 35131 Padua, Italy*

Abstract

In Europe, many archeological sites require continuous maintenance interventions capable of preserving the cultural value of this type of heritage. To this end, particular attention must be paid to ruins, the remains of larger portions and archeological artifacts. These elements, generally made of ancient stone masonry materials are vulnerable to external action such as are earthquakes, differential settlements, degradation, etc.. In order to reduce their structural vulnerability, repair interventions are usually required using repair techniques that preserve the artistic and aesthetical values of the archeological element. One of these techniques is the use of external post-tensioning system through pre-stressed cables.
In this contribution, some examples of the application of post-tensioning to an archeological element are presented. The application of rigid-block analysis to archeological elements (retrofitted with external post-tensioning system) is developed and discussed.

Keywords: Rigid block analysis, limit analysis, archeological sites, post-tensioning system, ancient masonry structures.

1. Introduction

In Europe, many archeological sites require continuous maintenance interventions able to preserve the cultural value of this type of heritage. With this aim, particular attention to ruins, the remains of larger portions and archeological artifacts should be done [1-3]. These elements, generally made of old stone masonry materials are vulnerable to external action such as earthquake, differential settlements, degradation etc... In order to increase their

* Corresponding author. Tel.: +39-049-827-5570; fax: +39-049-827-5570.
E-mail address: paolo.zampieri@dicea.unipd.it

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structural vulnerability, repair interventions are generally required using repair techniques that preserve the artistic value of the archeological component. One of these techniques is the use of external post-tensioning system through pre-stressed cables.

In this contribution, some typological models of the application of post-tensioning system applied to archeological elements are presented. In addition, the application of rigid-block analysis [1-10] to archeological elements (retrofitted with external post-tensioning system) is developed and discussed. Ancient masonry structures are generally made of dry joint and the mechanical behavior of these type of structures depends on the equilibrium conditions of each block and the deformability of the masonry material (in this case) could be approximately negligible. With these assumptions, the generic ultimate external load (seismic action, settlement of the support, dead load, etc...) applied to the old existing structure could be defined by looking for the value of the maximum load with which the structure is still in equilibrium. Also, in these conditions, it is easy to evaluate the contribution of post-tensioning techniques to the ultimate stability of the structure because it could be represented as an additional force system.

As is well known, in masonry structures, if compressive stresses between the joints increase, there will be also an increase in the structural capacity of the construction, since shear and flexural strength of the block interfaces depend on the value of the compressive stress between blocks. With external post-tensioning a cable system is designed to increase the state of compressive stress between blocks by ensuring that the compressive stresses are less than the compressive strength of the old masonry material. For this latter reason, the cable anchorage system is the most critical element of the strengthening system and must be studied in detail because, in the area nearby the anchorage, the masonry could subject to high compressive stresses which, if not well defined, could generated local crushing of the material. For this reason, the use of additional foundations in order to anchor the post-tensioning system may be the best solution to avoid stress concentration in the masonry material.

Another important issue, which must be taken into account during the design phases of interventions to strengthen the archeological site structures, regarding the aesthetic aspect of the ancient element, which must not be altered by the introduction of new resisting elements and/or with the covering of the construction surfaces.

Moreover, the strengthening system applied to old or ancient masonry could be reversible. This is another important aspect to reduce the impact of the reinforcement on the existing old structure and, with this property, the retrofitting system can be replaced by a new one in any instant.

All these aspects will be discussed in depth in the document and some practical examples of elements of archeological site reinforced with external post-tensioning will be presented as typological models of the application of this strengthening technique.

2. Rigid-block analysis

Considering a structure composed of n rigid blocks, [F] is the (3×n) vector containing the loads applied to the centroid of each block:

$$[f]^T = \left[F_{x,1}, F_{y,1}, m_{z,1}, \ldots\ldots, F_{x,n}, F_{y,n}, m_{z,n}\right]^T = [f]^T + \lambda [f_v]^T \quad (1)$$

The three internal resultants (i.e., Axial force N_i, shear force Si and bending moment M_i) acting at each i-th interface can be arranged in a (3×m) vector:

$$[q]^T = [N_1, S_1, M_1, \ldots\ldots, N_m, S_m, M_m]^T \quad (2)$$

The compact equilibrium equation can then be expressed as follows:

$$[A] \cdot [q] - \lambda \cdot [f_v] = [f] \tag{3}$$

Where [A] is the $[n \times m]$ equilibrium matrix. In order to find the solution of the lower bound limit analysis, the following yield constraints must be imposed at each interface:

$$N_i \cdot e_{LIM}^{-} \leq M_i \leq N_i \cdot e_{LIM}^{+} \tag{4}$$

$$|S_i| \leq N_{c,i} \cdot \mu \tag{5}$$

$N_{c,i}$ is the integral of compressive stresses in the masonry at interface i and μ is the friction coefficient. By using linear Programming [11-18] it is possible to define the maximum collapse multiplier that satisfies the yield constrains.

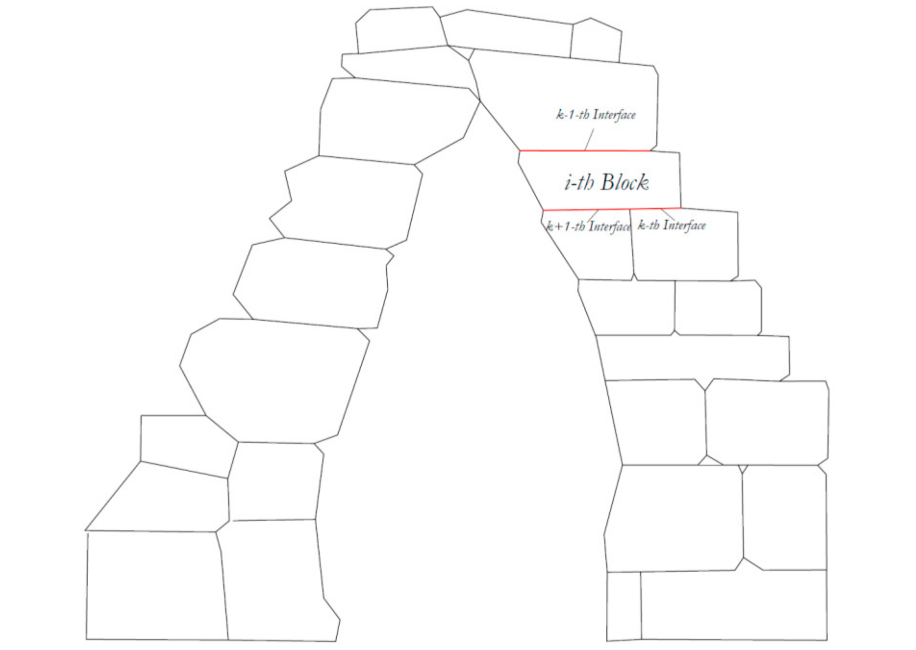

Fig. 1. Example of rigid blocks discretization of an archeological artifact

3. External post tensioning

This method of strengthening old masonry structures was presented in some Jurina's works [19-21]. The method consists of applying some external forces to the structure, which contrasts the effect of accidental actions. This is achieved by means of a post-tensioned cable anchored in the masonry.

In the case of a masonry block in Figure 2, a post-tensioning system is configured to increase the lateral capacity of the block. If W is the block weight, F and Q are the two concentrated forced transferred for the post-tensioning system to the masonry block. It is quite clear that the seismic collapse multiplier λ in the strengthened condition is greater than in the unstrengthened one. For the same purpose, a post-tensioning system could be designed for a single and multi-span masonry arch structure, as shown in Figure 3 and Figure 4.

The main issue in the application of post-tensioning in archeological elements is the design of the anchorage systems and the reversibility of the strengthening intervention. For this reason, the anchors (End anchor and Stressing-anchor) must be external to masonry structure. For example, with reinforced concrete elements.

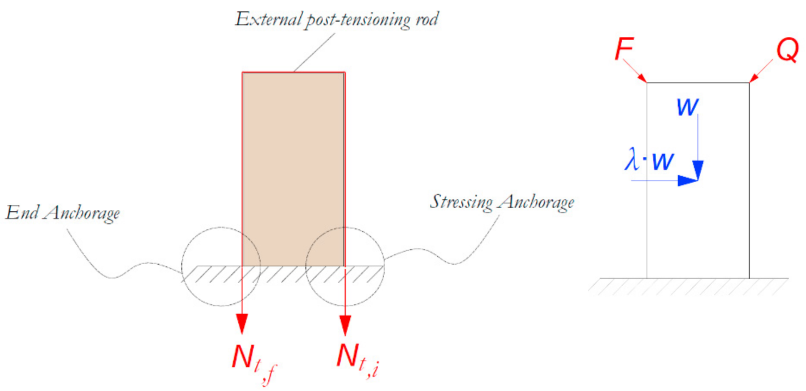

Fig. 2. Example of a masonry block strengthened with an external post-tensioning system

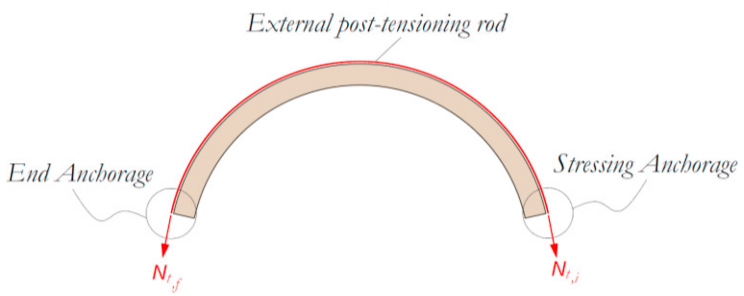

Fig. 3. Example of a masonry arch strengthened with an external post-tensioning system

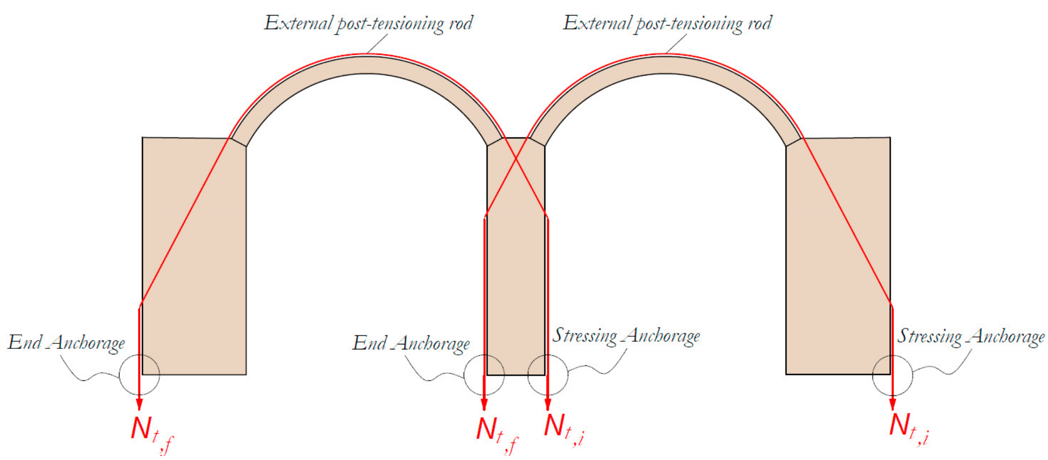

Fig. 4. Example of a multi-span masonry arch structure strengthened with an external post-tensioning system

4. Conclusion

Rigid-block analysis is a fast numerical tool for define the effectiveness of the post-tensioning system applied to archeological elements, taking into account some important aspects and simplifications:

The tensile force in spost-tensioned cables decreases from the stressing anchor ($N_{t,i}$) to the end anchor ($N_{t,f}$) due to the friction between cable and masonry surface as shown in Figure 5a and others;

For a quick evaluation of the horizontal collapse multiplier λ, the defomability of the cable is neglected due to an external force system applied to the structures (Figure 5b);

The deformation of the masonry is neglected.

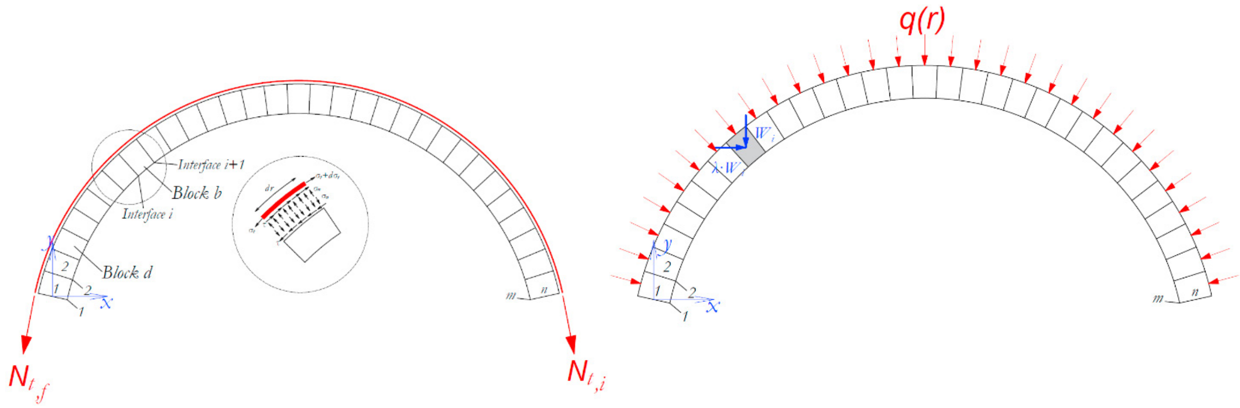

Fig. 5. Example of rigid blocks discretization of a post-tensioned masonry arch

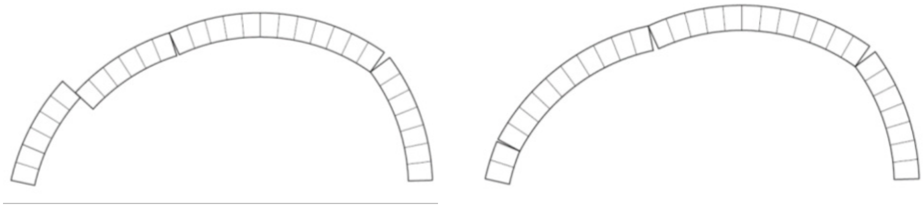

Fig. 6. Possible collapse mechanisms of masonry arches subjected to lateral actions.

Under these hypotheses the horizontal collapse multiplier λ can be easily evaluated and a parametric analysis shows that the sliding resistance between masonry blocks increases with the value of the tensile force in the cables (N_t); the collapse mechanism then involves only plastic hinges (Figure 6). Moreover, the horizontal collapse multiplier increases linearly with N_t (Figure 7). The Rigid-block analysis is first of all a simplified numerical analysis able to define the ultimate load multiplier. Different analysis approaches [22-25] are able to perform the stress and strain of the material at each load step until the collapse.

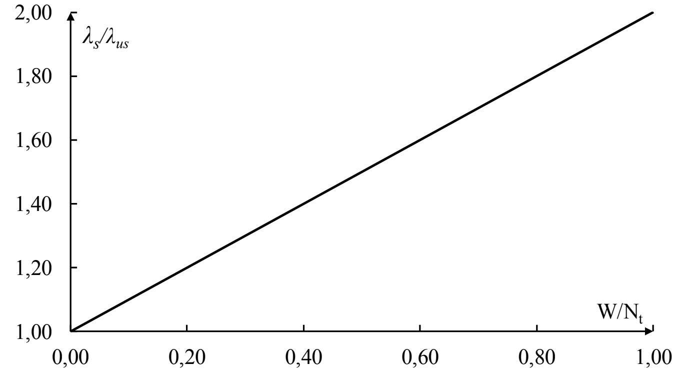

Fig. 7. Ratio between collapse multiplier in both strengthened and the unstrengthened conditions Vs dimensionless cables tensile force.

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