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Post-tensioning system as a strengthening solution for masonry arch bridges: numerical and experimental results

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Abstract

One of the most common bridge typologies in roadway and railway networks in Italy is the masonry arch bridge, typically built more than a hundred years ago. To keep these structures operatives with increasing traffic load, strengthening interventions are required in some cases. The solution investigated in this work is the external post-tensioning system, which consists of applying external loads to the arch by means of tensioned cables, resulting in a better configuration of internal forces. An experimental campaign was conducted on pre-damaged single span masonry arches by anchoring the cables to the intrados of the arch. The results of cyclic eccentric vertical load tests show an increase in displacement and load-carrying capacity. Numerical tests were performed to validate the experimental results using the rigid-block analysis method. The comparison between the experimental and numerical results is reported in terms of limit load capacity.

Keywords: Masonry arch bridges, Post-tension, Damaged masonry bridges, Rigid-block analysis

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1. Introduction

Several masonry arch bridges are still in service today in the Italian road and rail networks. Most of them were built between the 19th and 20th centuries, using empirical rules and considering only gravitational action and traffic loads. Due to the evolution of the Standards which define higher levels of safety, the increase in traffic loads, the lack of consideration of exceptional actions (such as earthquake) during the design stage and the deterioration of construction materials, it is necessary to provide retrofitting interventions that increase the strength of existing masonry bridges.

In addition to traditional strengthening techniques (mortar injections, steel or wood centring, etc.), new ones based on the use of composite material such as FRP (Fiber Reinforced Polymers) and FRCM (Fiber Reinforced Cementitious Matrix) have been introduced in recent years. Another strengthening technique that can be used to increase the bearing capacity of existing masonry bridges is post-tension, introduced by Jurina (2016). This technique improves the strength of the structure without substantially changing its mass and stiffness. In addition, it is economical and allows the infrastructure to remain in service without interrupting road or rail traffic.

In this work, experimental results obtained from a destructive test carried out on two post-tensioned masonry arch models with concrete haunching are presented and compared with the numerical ones, achieved using rigid-block analysis.

2. Experimental campaign

2.1. Arch specimen

Two different masonry arch models with concrete haunching were tested in the experimental campaign. They reproduced at 1:2 scale the longitudinal sections of two bridge typologies commonly found in Italian infrastructure. Specifically, the first geometry reproduced a quasi-semicircular bridge (in the follow called "semicircular" for brevity) while the second one a depressed bridge.

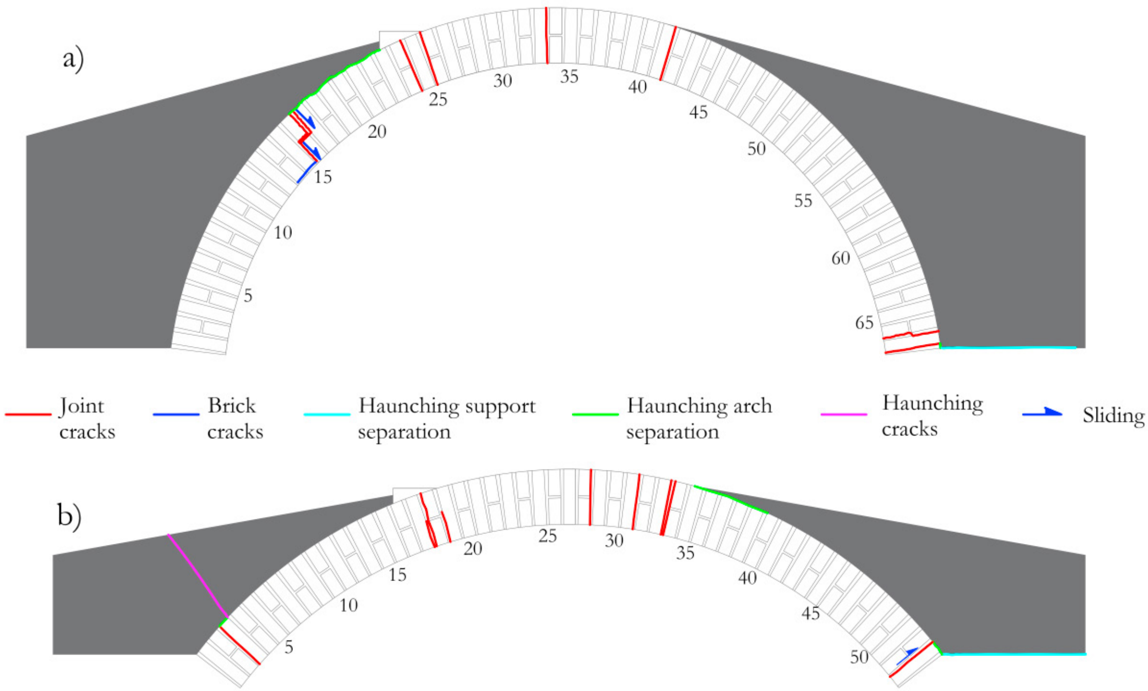


Figure 1 - Damaged configuration of the arch models before strengthening application.

The two arch models were composed of fired-clay solid bricks of size 25x12x55 cm^3, hydraulic lime-based mortar joints and haunching made of hydraulic lime mortar-based conglomerate. Both models were characterized by a span of about 3 m, an arch thickness of 0.25 m and a depth of 0.51 m while the arch rise was equal to about 1.30 m and 0.75 m for the semicircular and depressed arch, respectively.

The two virgin arch models were initially damaged before being strengthened. To do so, they were tested under displacement control by imposing a nonsymmetrical vertical displacement, as reported in Zampieri et al. (2022). The damage configurations obtained for the two models are shown in Figure 1. Specifically, radial cracks were identified at the block-joint interface (where the hinges opened) and there were a partial arch-haunching separation and a separation between the right haunching and the support.

2.2. Application of post-tension

Before being strengthened, the semicircular arch was mechanically repositioned to the initial configuration, eliminating the residual displacements that occurred during the preliminary test. This operation, however, was not performed for the depressed arch because the residual sliding was not relevant in this case.

A post-tensioning system was then applied to the intrados of the arches, consisting of two 6 mm diameter steel cables and two 10 kN load cells, used to monitor the tensile force on the cables (Figure 2).

Subsequently, destructive tests were performed on the two damaged and strengthened arch models. A series of quasi-static load-unload cycles of increasing amplitude of vertical load was applied to the arches eccentrically by means of a servohydraulic jack.

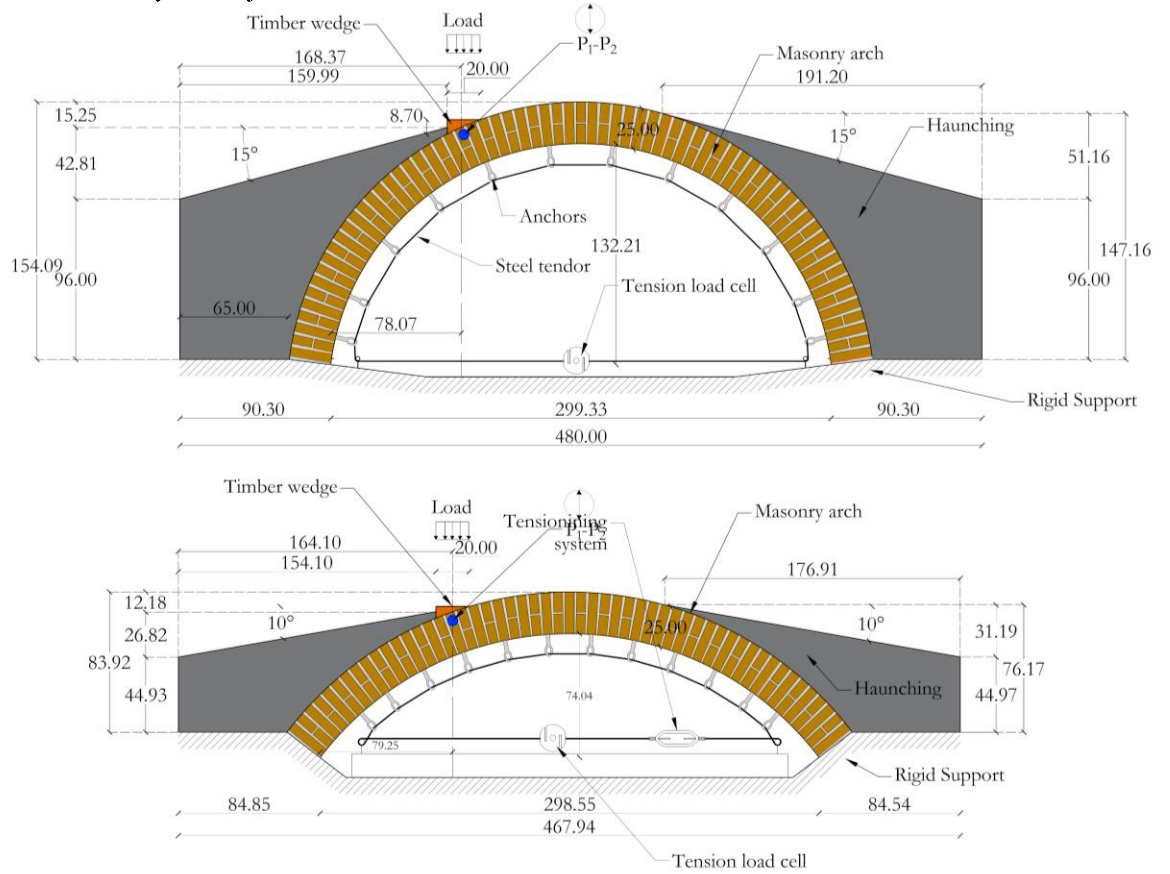


Figure 2 – Graphical representation of the post-tensioning system applied to the arch intrados.

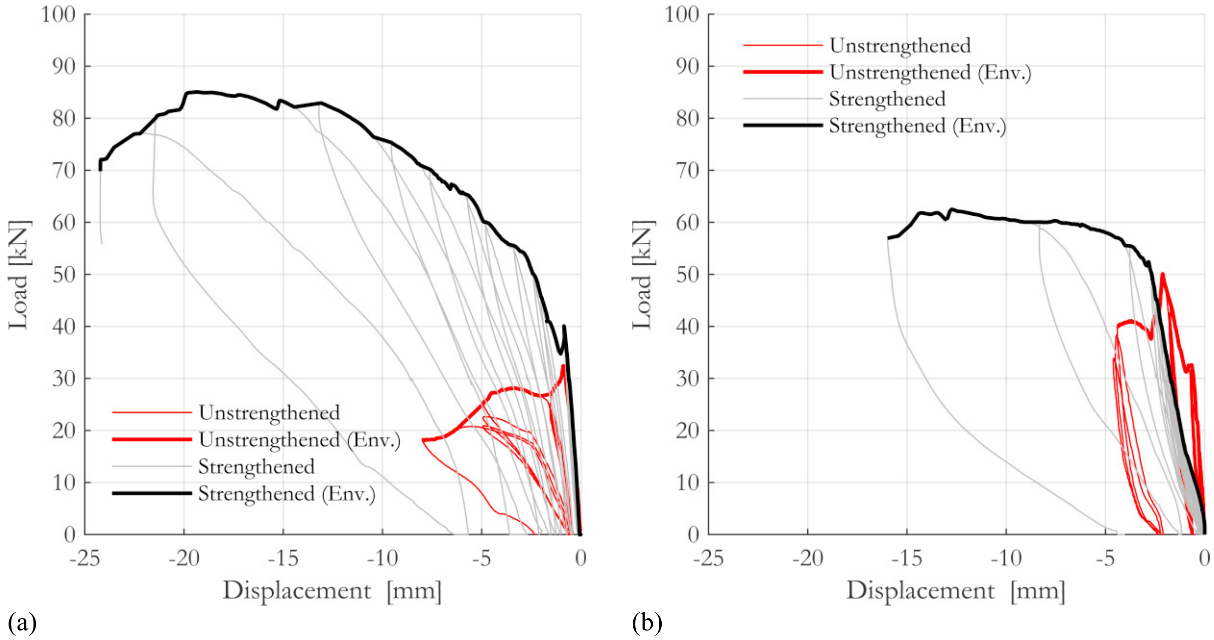


Figure 3 – Comparison of load-displacement curves obtained in undamaged and unstrengthened configuration and in damaged and strengthened condition for the semicircular (a) and depressed (b) arches.

2.3. Results

Post-tensioned arch models show an increase in bearing capacity compared to undamaged and unstrengthened models: in fact, even in the post-peak phase the recorded load increases although their stiffness decreases (Figure 3). In addition, post-tension allows greater vertical displacements than those recorded in the undamaged and unstrengthened configuration.

The experimental results show also that the post-tension efficiency depends on the arch geometry. A peak load of 85.05 kN was recorded for the semicircular arch and 62.48 kN for the depressed one, which must be compared with the residual load observed in the unstrengthened models to evaluate the strengthening system. The ratio is then about 3.00 and 1.50 for the semicircular and depressed arch, respectively. Therefore, even though the same forces were applied on the cables, the semicircular arch has a smaller radius of curvature, which allows the application of higher post-tensioning forces that increase the capacity of the structure more.

3. Numerical modelling

3.1. Rigid-block analysis method

The discretization of masonry structures into rigid blocks represents an established method for analyzing the behavior of this type of construction, where damage is generally localized at the interfaces and block deformability is negligible (Baggio & Trovalusci, 1993).

Two bidimensional discrete models (Gilbert et al., 2006; Portioli et al. 2014) were developed using geometric properties obtained from experimental data. Each numerical model consists of n rigid blocks, which interact each other through concave interfaces (m points). External loads and displacement rates, applied to the barycenter of each block, are collected in vector $\boldsymbol{f} \in \mathbb{R}^{3n}$ and $\boldsymbol{u} \in \mathbb{R}^{3n}$:

$$\boldsymbol{f} = \left[f_{x1},\, f_{y1},\, m_1, \ldots, f_{xn},\, f_{yn},\, m_n\right]^T \tag{1}$$

$$\boldsymbol{u} = \left[u_{x1},\, u_{y1}, u_{\theta 1}, \ldots, u_{xn},\, u_{yn},\, u_{\theta n}\right]^T \tag{2}$$

In contrast, the internal static $\boldsymbol{x} \in \mathbb{R}^{2m}$ and kinematic $\boldsymbol{q} \in \mathbb{R}^{2m}$ parameters are located at the vertices of the interfaces and are defines as:

$$\boldsymbol{x} = [n_1,\, t_1, \ldots, n_m,\, t_m]^T \tag{3}$$

$$\boldsymbol{q} = [\varepsilon_1,\, \gamma_1, \ldots, \varepsilon_m,\, \gamma_m]^T \tag{4}$$

The equilibrium equations between internal stresses and external loads acting on the masonry arch can be written in compact form as:

$$\boldsymbol{Bx} = \boldsymbol{f} = \boldsymbol{f_D} + \alpha \boldsymbol{f_L} \tag{5}$$

where $\boldsymbol{B} \in \mathbb{R}^{3n \times 2m}$ is the equilibrium matrix and the vector $\boldsymbol{f}$ is expressed as the sum of the known dead loads $\boldsymbol{f_D}$ and live loads $\boldsymbol{f_L}$, multiplied by an unknown scalar factor α.
Masonry mechanical properties are specified at the interfaces by imposing the following yield conditions at each contact point:

$$y_{s+} = -t + \mu n \geq 0 \tag{6.a}$$

$$y_{s-} = t + \mu n \geq 0 \tag{6.b}$$

$$y_r = n \geq 0 \tag{6.c}$$

where μ is the friction coefficient. In matrix form, the yield conditions of the entire structure are defined as:

$$\boldsymbol{y} = \boldsymbol{N^T x} \leq 0 \tag{7}$$

where $\boldsymbol{y}$ is the vector of failure conditions and $\boldsymbol{N^T}$ is the matrix that collects the constraints conditions.
Both the static (8) and kinematic (9) approaches were used to find the limit condition, solving a maximum and minimum problem:

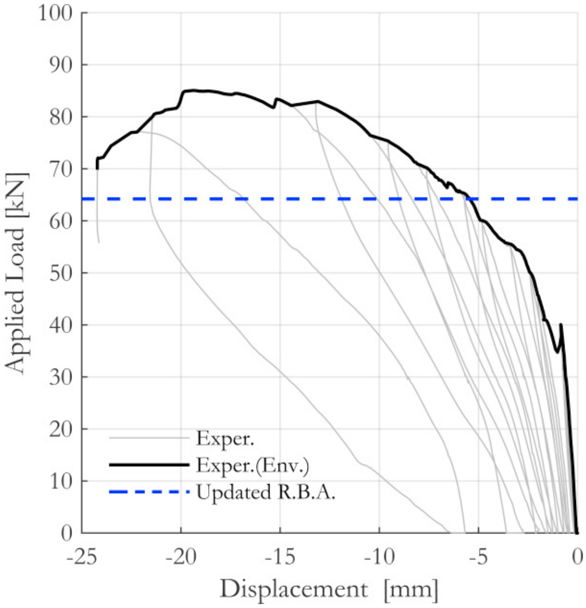
$$\begin{array}{ll} \text{maximize} & \alpha \\ \textit{subject to} & \begin{array}{l} \boldsymbol{Bx} - \alpha \boldsymbol{f_L} = \boldsymbol{f_D} \\ \boldsymbol{N^T x} \leq 0 \end{array} \end{array} \tag{8}$$

$$\begin{array}{ll} \text{minimize} & -\boldsymbol{f_D^T u} \\ \textit{subject to} & \begin{array}{l} \boldsymbol{f_L^T u} = 1 \\ -\boldsymbol{B^T u} + \boldsymbol{N\,z} = 0 \\ \boldsymbol{z} \geq 0 \end{array} \end{array} \tag{9}$$

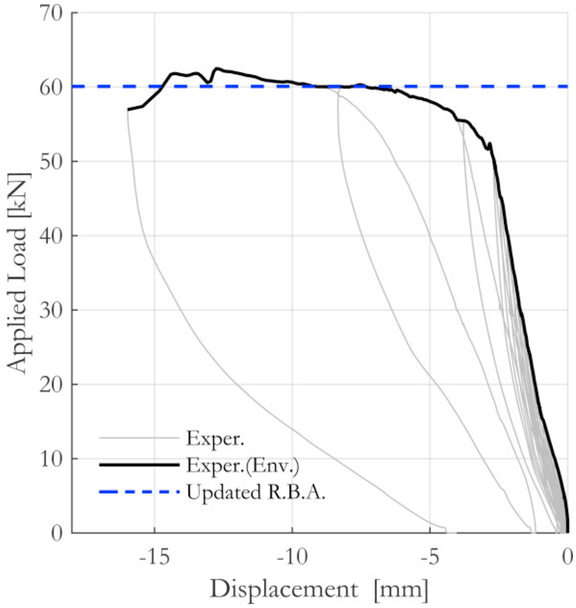
where $\boldsymbol{z}$ is the vector of resultant strain rates.

3.2. Results

The rigid-block analysis method was used to determine the limit load of both post-tensioned arch models. Both the increase in intensity and the change in cable configuration, which occurs as the mechanism develops, were considered to determine the post-tensioning forces. However, the equilibrium of the structure was always calculated in the undeformed configuration for simplicity. Looking at the comparison of results shown in Figure 4, the collapse multiplier obtained from rigid-block analysis intercepts the envelope of experimental data at a significant change in system stiffness.



(a)



(b)

Figure 4 – Comparison of numerical results and load-displacement envelope curve for the semicircular arch (a) and the depressed one (b).

4. Conclusion

In this work, a post-tensioning system was used to strengthen two masonry arch models representing bridge typologies commonly found in Italian infrastructure. Subsequently, the simplified rigid-block analysis method was used to evaluate the contribution of post-tension in a simplified and expeditious manner.

In conclusion, post-tension is a valid strengthening technology for damaged masonry bridges, which allows increasing the bearing capacity of the structure without changing its mass or stiffness. Furthermore, rigid-block analysis is a method that can be used for expeditious and preliminary evaluations of the post-tension contribution.

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