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Structural safety of existing masonry-tunnel-linings: a methodology derived from existing buildings approaches

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Abstract

Masonry linings were the primary solution for tunnels before the introduction of reinforced concrete. As a result, many tunnels with masonry linings have been in operation for over a century and may exhibit damage due to ageing and prolonged water infiltration. Currently, there are no specific regulations for the static verification of masonry tunnels. These tunnels share characteristics and problems with historic masonry structures such as bridges and building facades. Therefore, the scientific literature and normative references developed for masonry heritage structures were here considered. This work focuses on estimating the masonry strength of tunnel linings. To demonstrate the proposed methodology and the addressed problems, the 'Giovi' tunnel on the historic Genoa-Valle del Po motorway in Genoa, Italy was selected as an exemplary case. The masonry's resistance is measured in situ using flat-jacks and estimated using methodologies proposed for both new and existing buildings. The comparison of these methodologies highlights the unique characteristics of tunnel linings, including thick mortar bed-joints and massive curved masonry walls, with only one free face.

Keywords: tunnel lining; masonry; existing; heritage; safety

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1. Introduction

This paper examines the issue of the conservation of masonry tunnels, which were common in Europe until the 19th and early 20th centuries before the introduction of reinforced concrete, from a point of view that integrates the usual approach to infrastructure maintenance with methodologies developed for existing masonry buildings. Since the second half of the 19th century, this type of construction has been widely used in Italy, as in other European countries.

The masonry used in tunnels is typically crafted from solid clay bricks, although stone masonry is often employed in the lower sections, which could be susceptible to moisture-related damage. Brick or stone masonry was commonly used for the lining construction for two main reasons. Firstly, the raw material could often be obtained from the material excavated during the construction of the tunnel. Secondly, bricks have the advantage of being composed of small, easily transportable, and handled regular units that are ideal for constructing arches in confined spaces. To attain the necessary lining thickness, it was essential to create multiple layers of brickwork in the side walls and arches, using multiple overlapping rings, and a significant amount of mortar. (McKibbins et al., 2009; Steiner & Einstein, 1980). After about a century of life, with the inevitable damage caused by time, these structures need to be checked and maintained.

Currently, infrastructure-specific monitoring systems and preventive maintenance activities play a crucial role in mitigating the different risks. As a result, some countries have recently requested safety verification of existing tunnels. For instance, Italy's most recent “Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Tunnels" (DM 247, 2022) defines a multilevel approach to investigate existing tunnels. However, these guidelines do not provide a specific standard for the static assessment of masonry tunnel linings. Therefore, reference must be made to the code standards applicable to new masonry buildings (DM, 2018; EC6, 2005), existing buildings (DM, 2018; CSLLPP, 2019), or historical buildings (DPCM 09/02/2011). These standards include useful references to knowledge and assessment methods for the identification of structural vulnerabilities of buildings. In addition, references can be made to the guidelines for existing masonry bridges (CNR-DT 213, 2015).

This study seeks to integrate the Guidelines for existing tunnels DM 247 (2022), conceived for infrastructures of diverse ages and types, with approaches from architectural conservation and static assessment of existing buildings. The theoretical framework recognizes the integral role of strengthening in assets with historical and/or artistic significance within the discipline of architectural conservation, as opposed to a separate and autonomous process (Di Stefano; D.Lgs. 22/01/2004). The analysis proposed is inspired by concepts developed for historical structures (DPCM 09/02/2011), applying tools such as the Masonry Quality Index (Borri et al., 2019), the Confidence Factor (DPCM 09/02/2011; DM, 2018), and, in general, methods for defining mechanical characteristics of existing masonry (CNR-DT 213, 2015) to the specific context of tunnel linings characterized by thick curved masonry with a single free face.

The overall research aims to propose a specific protocol for studying criticalities in actively used historic masonry tunnels. The protocol encompasses the assessment of global and local stability conditions, with a focus on defining targeted interventions to mitigate risks to vehicle safety, while considering the conservation needs of valuable elements. Over the years, road safety measures for these tunnels have primarily aligned with routine maintenance operations, emphasizing technical aspects sometimes at the expense of material conservation and the asset’s overall perception. Acknowledging the unique nature and value of these historic tunnels, Autostrade per l’Italia is now aiming at adopting a more tailored approach to their management (Alessio et al., 2024).

To develop and validate this protocol, its application to the “Giovi” tunnel, one of the tunnels along the “Genoa-Po Valley Motorway” in Italy, dating back to the 1930s, is here proposed.

2. The case study: “Galleria dei Giovi”

The so-called “Galleria dei Giovi” (historically identified as “Littorio” tunnel) is the longest of the 11 tunnels of the “Genoa-Po Valley Motorway” (“Autocamionale”). The preliminary project for the motorway, spanning from Genoa to Serravalle Scrivia, reached completion in 1932. The construction works were concluded over three years (CSLLPP, 1935; Pini, 1936), allowing a considerable degree of homogeneity in the adopted materials and techniques. The tunnel exhibits a horse-shoe-shaped profile with an invert. The construction technique employed is the “heading and bench" method, involving the excavation of an initial pilot adit at the top, widening to accommodate the vault, subsequent excavation of the lower bench, and concluding with the construction of the invert (Fig. 1a).

The thickness of the wall linings varies in response to the ground pressure, ranging from 0.94 m to 1.60 m for the shell and abutments, and from 0.67 m to 1.07 m for the inverted arch. The linings were crafted using brick masonry for the vaults and inverted arches, employing a combination of stones and bricks for the abutments. Noteworthy is the adoption of a structure comprised of squared stone blocks exclusively in the central section of the Giovi tunnel. In regions where water infiltration occurred on vault surfaces, waterproofing was made through the injection of pressurized cement mortar between lining and rock (Pini, 1936). The design of the portals prioritized the simplicity typical of Italian Rationalism: in the Giovi tunnel, the sole architectural feature present is a prominent Fascist symbol known as the "Fascio Littorio" (Fig. 1b). In the early 2000s, a surface restoration intervention was carried out on the deteriorated sections, involving the installation of welded wire mesh to prevent brick fragments from falling, drainage channels, and the demolition of the shotcrete lining, accounting for 10% of the tunnel's surface area. In 2023, a series of nondestructive and semi-destructive tests were carried out to verify the conditions of the lining. Important geometric and diagnostic data on the surfaces were obtained by laser scanning, thermography, and crack pattern survey. They have shown that moisture phenomena, widespread across the vaulted surfaces, have led to efflorescence, detachment of the plaster, mortar disintegration, and the development of a pervasive crack pattern.

(a) (b)

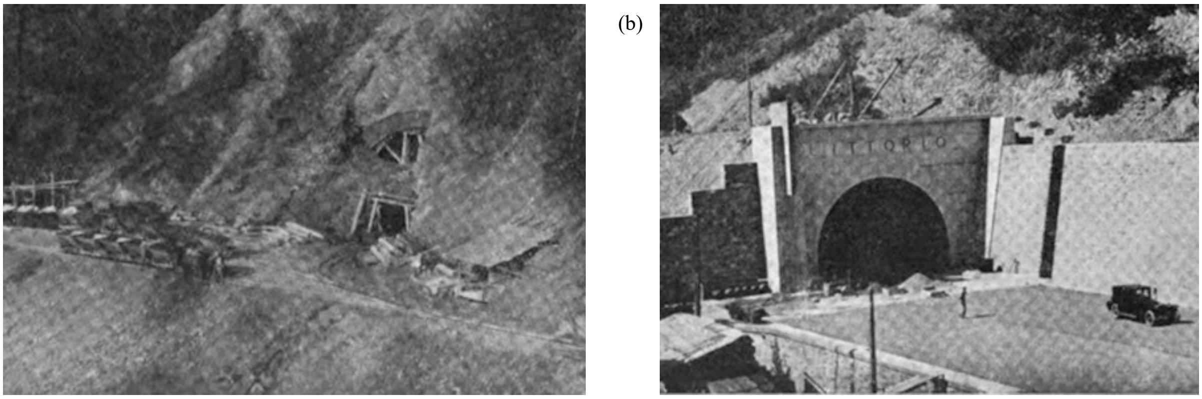

Fig. 1 Photographies of the Giovi tunnel: (a) Constructions works; (b) Portal.

Additionally, a local asymmetrical settlement at the top of the arches was revealed by laser scanning. Regarding the abutments, a widespread mortar deterioration and exfoliation of the stone elements was observed. Based on these surveys, inspection points were selected for video-endoscopies, which seem to confirm the brick texture of the lining, drawn in the historical design plans (Fig. 2). The results indicated the use of complete bricks throughout the cross-section. The analysed masonry (Fig. 2a) is made of solid clay bricks, all placed as headers, with mortar bed joints of thickness between 15 mm and 20 mm. Tests with single flat-jacks in the areas of asymmetric geometric deformation identified by laser scanning, showed an asymmetric stress state, with compression on the left haunch and no stress on the vault and right haunch, where the line of thrust passes behind the tested lining surface. It was thus decided to conduct structural analyses to study this behaviour. The initial step involved the mechanical characterisation of the masonry. This paper describes the methods used to estimate the strength of solid clay brick masonry, specifically made with bricks of size 12 × 5.1 × 25 cm^3.

3. Mechanical properties of the masonry

3.1. Masonry strength from double flat jack tests

Masonry linings operate mostly under compression, so their safety depends mainly on the compressive strength of the material. Assessing this strength in existing masonry is still a challenge. Among the destructive or partially destructive methods proposed in the literature, the present study used double flat jacks (RILEM, 2005). Three tests were performed on this type of masonry. For safety reasons, tests were terminated when the stress-strain curve started to bend, before compression failure of the masonry was reached. The maximum stresses attained (3.60 MPa, 6.22 MPa, 6.34 MPa) therefore underestimate the strength of the material.

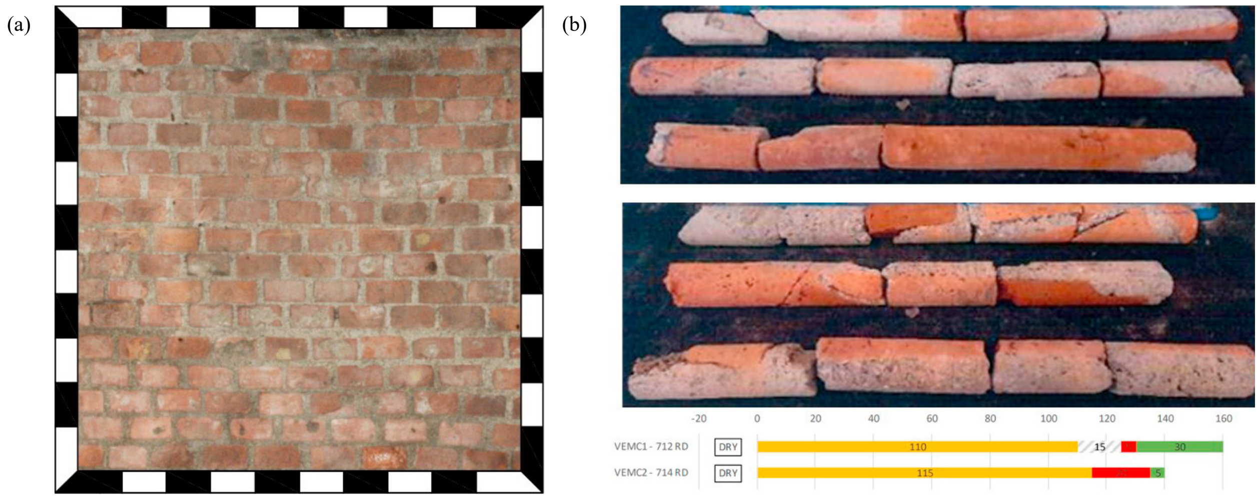

Fig. 2 (a) the masonry surface (1mx1m); (b) the stratigraphy throughout masonry cores and video-endoscopies carried out in two points of the surface. The bricks and cementitious mortar are represented in orange; voids in red; rocks in green and deteriorated cement in white-grey lines.

Instead, the test allows the modulus of elasticity E_M to be correctly assessed. The mean compressive strength f can be more effectively estimated from the elastic modulus E_M. For instance, EC6 (EC6, 2005) suggests $E_M = c\, f_k$, with c = 1000 and $f = 1.2\, f_k$, resulting in $f = E_M / 833$. Since the tests were carried out on the intrados of the lining, which has a total thickness of 1200 mm, using a flat jack 200 mm thick, the masonry behind the flat jack constrains the loaded masonry and causes an overestimation of the modulus of elasticity E_M. To solve this problem, Alecci et al. (2021) proposed a correction factor K = 0.72 for the modulus of elasticity, which depends on the ratio between the thickness of the jack and that of the wall. Applying this formulation to the analysed experimental measurements yields an E_M modulus value between 3879 MPa and 6003 MPa while the corresponding compressive strength is 4.66-7.21 MPa, slightly greater than the stresses attained with the tests. Minimum and maximum values have been given and no statistical calculations have been made, as these would require at least 5 samples to be statistically significant. The resistance obtained by this method remains uncertain due to several factors. Firstly, the correlation between modulus of elasticity and wall strength is not clear, with some authors suggesting c values between 250 and 1200 for solid brick walls (Costigan et al., 2015). In fact, the elastic modulus should depend on the size of the bricks and thickness of mortar bed-joints. In addition, EC6 (2005) refers to a secant modulus, whereas flat jacks measure an unloading and reloading modulus, which is typically higher. Therefore, this method should only be used as a first approach in combination with other methods.

3.2. Masonry strength from Eurocode 6

Cores of diameter of 150 mm were drilled from the masonry to assess the mortar and bricks characteristics. The bricks were acquired from the cores, smoothed on both sides, and cut into 50 mm cubes: this resulted in n = 22 uniformly sized samples, eliminating size effects (Cabané et al., 2022). The cubes were subsequently subjected to compression tests according to EN 772-1 (2011) to measure their strength f_b. The normalized strength $f_{b,N} = \delta\, f_b$ was then calculated using the shape factor δ = 0.85 giving an average strength $f_{b,N}$ = 24.39 MPa and a coefficient of variation CV = 0.27, which is high. The thickness of the mortar bed joints is roughly 20 mm and composed of mixed lime and cement (as confirmed by XRD analysis). On-site evaluation of the mortar strength was conducted with a

Gucci penetrometer (Gucci & Barsotti, 1995) on 24 points. The average compressive strength of mortar was f_m = 4.16 MPa with CV = 0.13. The average strengths of mortar f_m and bricks $f_{b,N}$ can be used to estimate the characteristic strength f_k of new masonry using equations or tables. Since the masonry under investigation was made from industrially produced bricks, in principle this approach can be applied also for existing masonries. The equation for solid bricks and cement mortar recommended by EC6 (2005), $f_k = 0.55 f_{b,N}^{\ 0.7} f_m^{\ 0.3}$, was used because various authors, including Ferretti (2020), have demonstrated the reliability of this equation also for masonry assembled with mixed lime-cement mortar. Again, the EC6 (2005) proposed $f = 1.2 f_k$ to obtain the average strength f. EC6 (2005) considers that when masonry consists of several layers, the strength should be multiplied by a coefficient of 0.8. According to this formulation, the average compressive strength of the masonry is equal to 7.89 MPa. This method also has some uncertainties. According to EC6 (2005), it can be applied if $f_{b,N}$ has CV<0.25. Moreover, the coefficient 0.8 may not be suitable for very thick walls of tunnel linings, as well as cathedrals and towers facing a similar problem. Finally, EC6 (2005) proposes this formulation when bed joints thickness ranges from 6 mm to 15 mm, while Giovi tunnel has joints that are approximately 20 mm thick.

3.3. Masonry strength from Italian Technical Code

The Italian Technical Code (DM, 2018) and its Commentary (CSLLPP, 2019) suggest different formulations to estimate strength values both for existing (Ch. 8) and new (Ch. 11) load-bearing masonry. Applying the regulations for new buildings, the value of the characteristic compressive strength f_k of masonry consisting of artificial solid or half-filled elements can be estimated as a function of the characteristic compressive strength of the elements f_{bk} and the class of mortar (DM, 2018). In our case, the mortar class is comprised between M2.5 and M5. The characteristic strength of bricks f_{bk} can be derived, using the formula $f_{bk} = (1\text{-}k \text{ CV}) f_b$, where f_b is the mean value of the normalized brick strength, CV is the corresponding coefficient of variation, and k = 1.64 if the number of specimens $n \geq 30$. With n = 22, PD CEN/TR 16886 (2016) instead provides k = 2.174, which corresponds to a characteristic strength f_{bk} = 9.86 MPa, which seems too conservative because of the high CV and small number of specimens. Therefore, k = 1.64 was tentatively used, resulting in a brick characteristic strength f_{bk} = 13.43 MPa. According to Tab 11.10.VI (DM, 2018), assuming $f = 1.25 f_k$, (Tab. C8.5.III in CSLLPP, 2019) the average compressive strength of the masonry is equal to 5.98 MPa for mortar M2.5 and 6.99 MPa for M5. The adoption of this table would require mortar bed-joints between 5 mm and 15 mm thick. Furthermore, no reference is made to the wall thickness.

Alternatively, the Italian Technical Code proposes a table for evaluating the strength and the elastic modulus of existing masonry according to its typology (Tab. C8.5.I in CSLLPP, 2019). For masonries made of solid bricks and lime mortar of compressive strength f_m = 2 MPa, the values are given in Table 1. A correction coefficient $c_1 = f_m^{0.35}$ = 1.625 is introduced in CSLLPP (2019) to consider the good quality of the mortar. In addition, since the masonry is made in a proper craftmanship manner with good cross connections, a correction coefficient c_2 = 1.3 can also be adopted. Finally, the standard introduces a reduction coefficient c_3 = 0.7 (0.8 for elastic modulus) to take account of mortar beds thicker than 13 mm. The minimum, maximum and mean values of the strengths calculated in this way, considering only one, two or all three parameters, are shown in Table 1, together with the values of E_M.

Table 1 The strengths of masonry defined by Chapter 8 of DM (2018) and CSLLPP(2019).

	f min (MPa)	f max (MPa)	f mean (MPa)	E_M min (MPa)	E_M max (MPa)	E_M mean (MPa)
Solid clay brick masonry	2.60	4.30	3.45	1200	1800	1500
With effect of mortar	4.22	6.99	5.61	1950	2925	2438
Mortar + texture	5.49	9.08	7.29	2535	3801	3169
Mortar + texture + joint	3.84	6.36	5.10	2028	3042	2535

3.4. Masonry strength from Masonry Quality Index MQI

The structural performance of masonry is not solely dictated by the strength of its constituent elements but is also influenced by factors such as the construction technique employed within its thickness, the texture of the brick (or stone) work (Boni et al, 2022), and deterioration, in adherence to established craftsmanship principles. In this investigation, we adopted the empirical approach proposed by Borri et al. (2015) for computing the Masonry Quality Index (MQI). This involves measuring parameters indicative of whether conditions pertinent to the correct and effective construction of the masonry have been met. Seven parameters, discernible through visual and/or manual inspection, were examined: the configuration of load-bearing elements (SS), the presence of cross-bonding elements (WC), the horizontal alignment of layers (HJ), the strength of the elements (SM), the size of the elements relatively to the wall thickness (SD), the disalignement of vertical joints (VJ), and the quality of the mortar (MM). The application of this method on a portion of masonry in the Giovi tunnel, made it possible to identify which of the parameters described above were fulfilled (F), partially fulfilled (PF) and not fulfilled (NF) (Tab. 2). A "score" was then associated with each parameter, based on the above qualitative judgment (Tab.3). Regarding the VJ and WC parameters, these can also be defined on the basis of graphical methods of Minimum Line Drawn MLD (Fig. 4b). However, in this case, since the masonry is mainly characterised by transversal header elements, it was decided not to consider the indication provided by the graphical method for the VJ parameter, as this can be directly defined as 'non-fulfilled', according to the indications of Borri et al. (2015). Based on these qualitative judgments it was possible to define the Masonry Quality Index MQI and to determine the average compressive strength f and the average value of the modulus of elasticity E_M of the considered masonry (Tab. 3), thanks to the calibrations made by Borri et al. (2015) on old masonry buildings. It would be advisable in the future a specific calibration to the case of tunnel linings to improve its reliability.

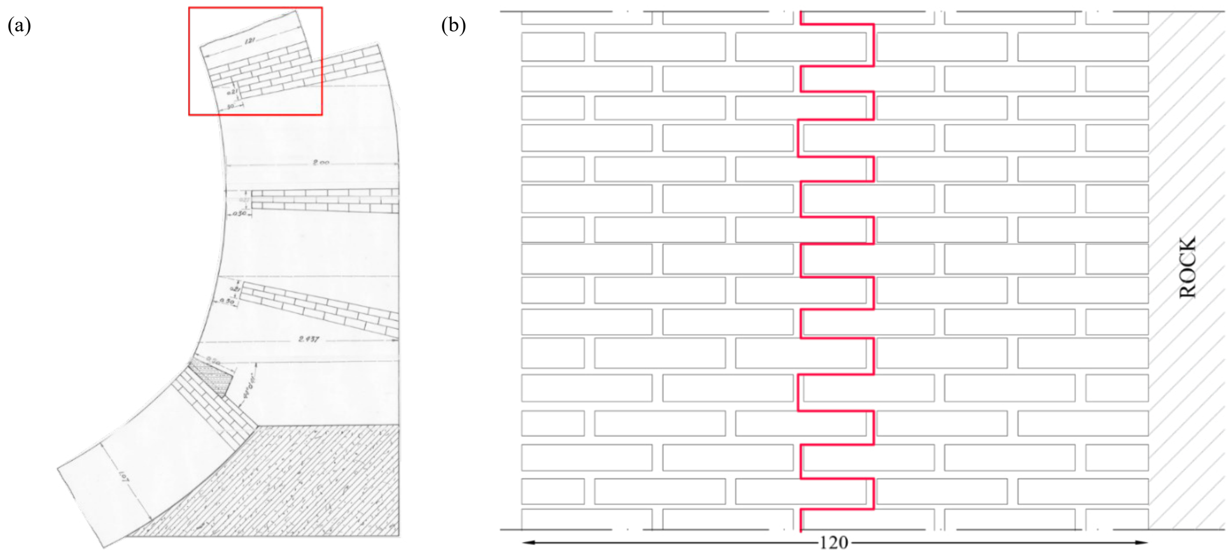

Fig. 3 (a) Historical drawing of the section of the Giovi tunnel abutment; (b) detail of the section and assessment of the presence of only headers, creating a cross-bonding effect, and quantitative analysis of the WC parameter through the graphical method of the Minimum Line Drawn.

Table 2 The seven parameters of MQI method and the relative qualitative judgments (F=Fulfilled, PF=Partially Fulfilled, NF=Not Fulfilled).

WC	MM	SS	VJ	SM	HJ	SD
F	PF	F	NF	F	F	PF

Table 3 Qualitative scores and strengths of the masonry defined through the MQI method for vertical and out of plane forces.

Category	Vertical	Out of Plane
Score method	A	a
MLD		163 cm / 100 cm
MQI	7	6.5
Mechanical parameters	f	E_M
Min-Max values (MPa)	4.47 – 6.78	1851 – 2578

4. Discussion

The mechanical properties obtained using the various methods are summarised in Table 4. In particular, the minimum, maximum, and average compressive strengths f and elastic moduli E_M are reported. For the sake of comparison, the bed joint thickness has not been taken into account for those methods that do.

Table 4 Comparison of the values (in MPa) of compressive strength f and elastic modulus E_M of masonry obtained through different approaches.

Parameter	Flat jack	EC6	DM2018 new	DM2018 existing	MQI
f min (MPa)	4.66			5.49	4.47
f mean (MPa)	5.53	7.58	5.98-6.99	7.29	5.63
f max (MPa)	7.21			9.08	6.78
E_M min (MPa)	3879			2535	1851
E_M mean (MPa)	4613	6314	4798-5592	3169	2215
E_M max (MPa)	6003			3801	2578

The different methods give fairly similar strengths, whereas greater differences are observed in the elastic modulus values. The proposed methods for existing buildings (DM, 2018 existing, and MQI) seem to provide lower values. This is perhaps also due to the fact that they do not explicitly consider the properties of the constituents. This aspect, however, is an advantage because it allows the initial safety assessment to be carried out before testing.

For methods based on experimental tests (such as flat-jack, EC6 and ITC18 new buildings), the number of measured values is usually small. For this reason, in Chapter 8, the CSSLLPP (2019) proposes a Bayesian update that takes a weighted average between the experimental values and typical values in Tab. C8.5.I. In the case of tunnels, it would be useful to evaluate this update by considering also previous data from similar tunnels. Among the analysed standards, only DM (2018) Chapter 8 considers the thickness of mortar joints by multiplying the strength by 0.7. This seems a strong approximation, particularly for joints which are only slightly thicker than the limit of 15 mm. It would be better to use an approach that takes into account the thickness of the joints, the dimensions of the bricks and the mechanical properties of the materials. The calculations have used the mortar resistance measured in situ, but most standards refer to the resistance measured on prisms 40x40x160 mm^3, which may be lower. For this reason, it would be prudent to reduce the value of the measured mortar strength. Finally, it would be important to consider the reduction in strength and elastic modulus caused by the infiltrations of water.

5. Conclusions

This paper is part of a wider study on the structural safety of historic masonry-lined tunnels, which is based on the investigation procedure proposed in the Italian guidelines for tunnels. Also, it incorporates some concepts from the Italian guidelines for bridges and cultural heritage, as well as studies from academic research on the mechanical properties of historic masonry and monument conservation. The paper focuses on estimating the strength of masonry linings, using the Giovi Tunnel in Italy as a paradigmatic example. The strength of the masonry for this tunnel is measured in situ using double flat jacks. Additionally, the resistance of the mortar and bricks is measured, and the resistance of the masonry is estimated using the methods proposed by EC6 (2005) and DM (2018) for new buildings.

Finally, this study applies two methods for existing buildings: the MQI (Borri et al., 2015) and the table proposed by the DM (2018). Comparison of the four approaches shows that:

- The different methods give similar ranges of compressive strengths, whereas greater differences are observed in the elastic modulus values, usually lower with the methods proposed for existing buildings.
- None of the analysed methods takes effectively into account the role of the massive walls with large mortar bed-joints, typical of masonry tunnel linings.
- Because of its ease and speed of application, the MQI method could be an effective tool to obtain a first estimate of the masonry strength, to be used in conjunction with the table for existing buildings of DM (2018).

The obtained results demonstrate the unique characteristics of tunnel linings and the necessity to modify the methods proposed in the literature for buildings to suit the specific case of tunnels.

Authors Contribution

Conceptualizaton and methodolology: D.F.; E.C.; R.P.; C.A. Investigation: D.F.; Draft writing of the paragraph 1.1; 1.3; 2.3: E.Z.; Draft writing of the paragraph 1.2, 4: C.E.; Draft writing of the paragraph 1.3; 2.3: L.F.; Draft writing of the paragraph: 2.1; 2.2; 3.1: D.F.; Writing-review: E.C.; D.F.; C.A.; Supervision: D.F.; E.C.; R.P.; C.A. Funding: D.F., C.A., B.C.

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