Conservative rehabilitation interventions of masonry highway tunnels along the historic Genoa-Po Valley Motorway in Genoa (Italy)

Carlo Alessio[1] Roberto Pittalis[1] Giuseppe Attianese[1] Bernardino Chiaia[2] Daniele Ferretti[3] Elena Zanazzi[3] Lia Ferrari[3] Eva Coisson[3]

(*1. Tecne group Autostrade per l'Italia S.p.A., Genoa, 16149, Italy; 2. Polytechnic University of Turin, Torino, 10124, Italy; 3. University of Parma, Department of Engineering and Architecture, Parma, 43124, Italy*)

E-mail: roberto.pittalis@tecneautostrade.it

Abstract:

The present work deals with the structural safety assessment of existing tunnel masonry linings. Until the introduction of reinforced concrete, masonry linings were the common solution for railway, metro, and road tunnels. As a result, there are still many tunnels with masonry lining that have been in service for more than a century. After such a long time, masonry linings may show signs of degradation due to ageing and the long action of water infiltration may have reduced their strength. For this reason, the safety assessment of existing tunnels is becoming increasingly important, in order to timely identify the criticalities and plan the necessary rehabilitation interventions, but specific regulations are still lacking.

This paper addresses this need by proposing a methodology for the global and local static verification of masonry-tunnel-linings, describing the issues to be addressed and proposing a procedure to define the mechanical properties of the masonry, calibrate the partial safety factors, identify the local vulnerabilities and their priority order. In this process, the scientific literature and normative references developed for cultural heritage masonry structures are taken into account, considering that these tunnels have features and problems similar to old masonry constructions (bridges, porches, vaulted buildings) and that the interventions planned should also have a conservative approach, since these structures represent indeed an important element of the history of our architectural and technological evolution.

Keywords: Cultural Heritage; Masonry infrastructure; Planned conservation; Safety assessment

1 Introduction

1.1 Assessment and strengthening of masonry tunnels

This paper focuses on masonry tunnels, which were the predominant typology in Europe in the 19th and early 20th centuries, before the development of reinforced concrete. For instance, many subway tunnels in Paris and London, as well as the Simplon and Frejus railway tunnels in the Alps, are made in masonry.

Usually, the masonry is made of solid clay bricks, but stone masonry is often used, especially in the lower parts, which are potentially subject to damage by moisture. Brick or stone masonry was the material of choice for the construction of the lining for two main reasons: firstly, because the raw material was often obtained from the excavated material during tunnel construction; and secondly, because bricks have the advantage of being made up of small, easily transported and handled regular units, which were suitable for the construction of arches in confined spaces. However, in order to achieve the required lining thickness, it was usually necessary to construct several layers of brickwork in the side walls and arches with multiple rings, and to use a relatively large quantity of mortar, since the proportion of mortar in brickwork is generally much higher than in good quality ashlar masonry. The thickness of the lining was determined by simple rules of thumb, depending on the type of soil, with light soils generally considered to be self-supporting and heavy soils as requiring support (McKibbins et al., 2009). The geometric section of the tunnel and subsequent lining were usually related to the excavation and shoring techniques. The thickness and geometry of the lining, therefore, did not descend from structural mechanics but from practical guidance, often described in manuals and regulatory guidelines.

This type of construction has been widely used in Italy since the second half of the 19th century. Currently, due to its morphological conformation (the Alps in the north and the Apennines along the peninsula), Italy has the largest number of road tunnels in the Trans-European Transport Network (TEN-T). Specifically, Italy has well over 1,200 km of tunnels in the ANAS road network, 500 km in the motorway network and 1,200 km in the rail network, with 34 tunnels longer than 5 km (Tunnel, 2023). The problems associated with their preservation and safety are therefore of particular importance, considering their age, which is often a centenary or even more.

In fact, there are numerous scientific studies related to tunnel collapse cases, considering both the census of tunnel damage (Sousa, 2010; CEDD, 2015; Zhang et al., 2016) and the related statistical analysis (Špačková et al., 2013). However, these studies mainly consider two types of causes (Spyridis et al., 2021): the collapse during construction or the damage related to transport accidents followed by a fire. Instead, the present study intends to focus on the analysis of the risk of collapse or damage, both global and local, in masonry tunnels during operation. In fact, many accidents of this type have occurred recently, both nationally and internationally: e.g. Ciclopi, Tenda and Tre Madonne tunnels in northern Italy; Vierzy and Rove tunnels in France. At present, monitoring systems and preventive maintenance activities specific to these infrastructures play a very

important role in reducing this type of risk. For this reason, the safety verification of existing tunnels was recently requested in some countries. For example, in Italy, the recent "Guidelines for the classification and management of risk, safety assessment and monitoring of existing tunnels" (DM 247, 2022) require the study of existing tunnels with a multilevel approach that starts from the geometric survey and, depending on the problems found, can reach the static assessment. For the static assessment of masonry tunnel-linings, there are no specific standards, and it is necessary to refer to the code standards for new masonry buildings (DM, 2018) or those for historical buildings (D.P.C.M. 09/02/2011), which, moreover, were mainly developed for seismic problems. In the case of existing bridges, instead, there are specific guidelines for both reinforced concrete and steel (CSLLPP, 2021), or masonry bridges (CNR, 2015), which can also be a useful methodological reference for the static assessment.

In general, the guidelines aim to adopt a preventive approach, both to avoid potentially dangerous situations and to plan maintenance works without having to operate under emergency conditions with long road closures, but there are no clear indications on the quantification of the safety levels and the priority of the interventions.

1.2 Aims of the research

Starting from the instructions contained in the DM 247 (2022), written for infrastructures of all ages and types, this research aims to integrate them with approaches derived from the field of architectural conservation and existing buildings static assessment. In fact, at the theoretical level, it is now established that strengthening, when applied to an asset recognised as having historical and/or artistic value, is an essential part of the discipline of architectural conservation and not something separate and autonomous (Di Stefano; D.Lgs. 22/01/2004). For this reason, the analysis will borrow concepts developed for the approach to historical structures (D.P.C.M. 09/02/2011), both from a global point of view, intended to assess the overall structural capacity, and from a local point of view, concerning the material-pathological conditions of the surface. In the first case, the concepts of the Masonry Quality Index (Borri et al., 2019), the Confidence Factor (D.P.C.M. 09/02/2011; D.M 17/01/2018) and, more generally, the methods for defining the mechanical characteristics of an existing masonry are taken up and adapted to the specific case of tunnels, which are characterised by thick masonry built with a curved shape and with a single free face. The local vulnerability associated with surface deterioration (UNI 11182, 2006), which defines a possible risk of detachment of parts of the lining that may interact with the road network, shows similarities with the problems encountered in historic buildings. Similar safety issues were highlighted in all their importance in October 2017, with the fatal accident in the Basilica of Santa Croce in Florence, which triggered a wide-ranging campaign to check the stone facings of monuments in the Tuscan capital (Salvatici et al., 2020; Ceppetelli, 2022). Although there are obvious differences, both in terms of value and operational complexity, in the knowledge and intervention phases, this research aims to propose a possible specific protocol for the study of criticalities in historic masonry tunnels currently in use, for the assessment of their global and local stability conditions and, therefore, for the definition of targeted interventions to resolve criticalities that may pose a risk to vehicle safety, also taking into account the conservation needs of elements recognised as valuable.

The proposed protocol will be tested on two tunnels along the "Genoa-Po Valley Motorway" in Italy, which date back to the 1930s. Since their construction, the works carried out to ensure road safety have been in line with the usual maintenance operations for this type of structure, taking into account only the technical aspects, sometimes to the detriment of the conservation of the material and the perception of the asset. The recognition by the operator, Autostrade per l'Italia, of the specific nature and value of these historic tunnels is now laying the foundations for a different approach to their management.

1.3 The analysed case study

1.3.1 Historical overview of the motorway tunnels

Aware of the strategic role - both economic and social - played by road communications, the Fascist regime promoted the construction of major infrastructure projects. Among these was the “Genoa-Po Valley Motorway” (*Autocamionale*), which was intended to solve the problem of heavy traffic between the port of Genoa and the hinterland. On August 31, 1932, the preliminary project for the entire motorway between Genoa and Serravalle Scrivia was completed. The works, for a total cost of 218 million lire, were put out to tender on 6 October 1932 and took three years to complete, divided into 22 sections (Pini, 1936).

The motorway had the most modern features for a mountain road at the time and therefore represents an interesting testimony of the evolution of road and tunnel technologies.

1.3.2 Main features and constructive techniques

In the Motorway there are 11 tunnels with a total length of 3,002 m, about half of which are in the first 8 km close to Genova. The carriageway is 10 m wide, with two lanes and a platform width of 9.42m, plus margins. The tunnel profile is a horse-shoe shaped with an invert. The construction method used for the tunnels is known as "heading and bench", which involves excavation of a top pilot adit, widening to create space for the vault, excavation of the lower bench, and then construction of the invert (Fig. 1).

The thickness of the wall linings varies according to the pressure exerted by the ground, 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 themselves were constructed using brick masonry for the vaults and inverted arches, and a combination of rubble and brick for the abutments. Only in the central section of the "Littorio" tunnel was a structure of squared stone blocks used.

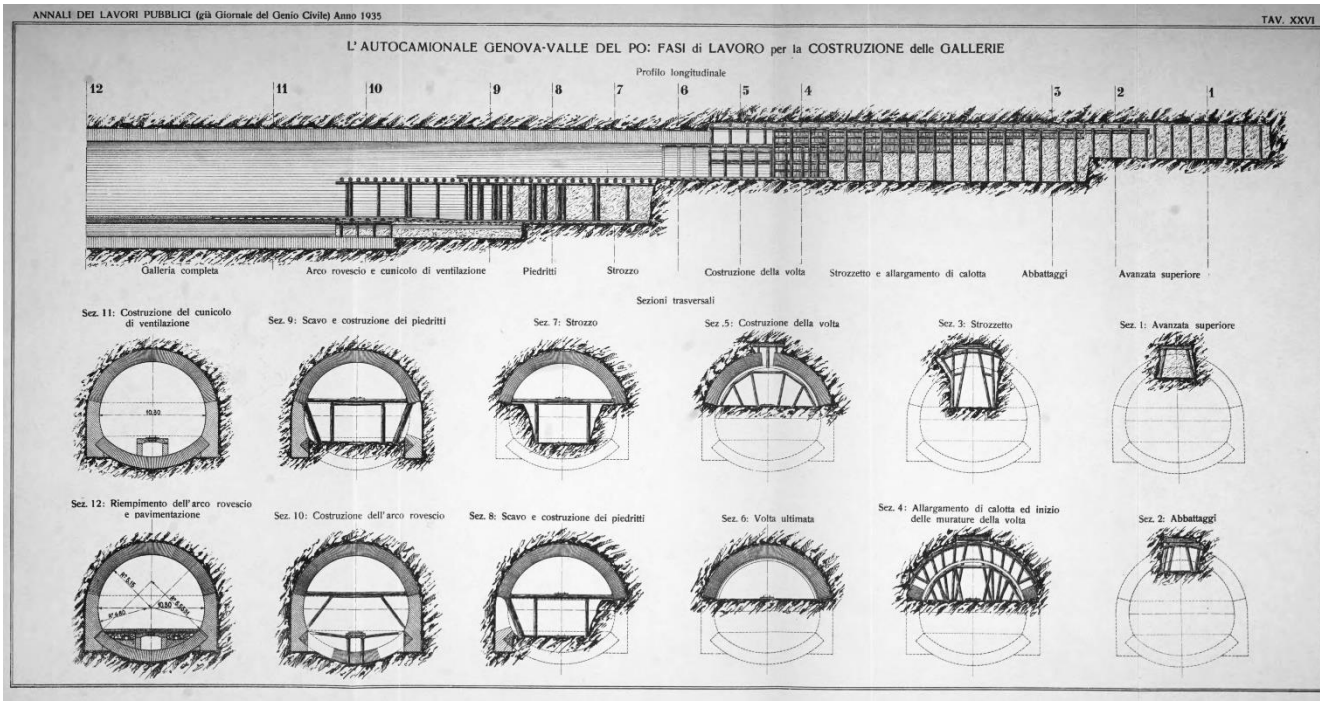

Figure 1 Construction of the masonry lining (CSLLPP, 1935).

In the areas where water infiltration occurred on the vault surfaces, waterproofing was carried out by injecting cement mortar under pressure to seal any remaining voids and to divert the water as far as possible towards the abutments. The surfaces were then coated with an external plaster of cement mixed with waterproofing agents (Pini, 1936). The façades were designed with the utmost simplicity: corniches, projections and decorative elements were eliminated, and only a variety of coloured stones were used for decorative purposes. In the "Littorio" and "28 Ottobre" tunnels, the only architectural element is a large Fascist symbol called the *Fascio Littorio* (Fig. 2).

1.3.3 The first tests on two galleries

The paper focuses on two tunnels built along the “Genoa-Po Valley Motorway”: the Campora and Giovi tunnels, 509 m and 910 m long, respectively, both opened to traffic in 1935. Unfortunately, there is no historical documentation on the design of the Campora tunnel, and for the Giovi tunnel it is incomplete, especially regarding the technical-constructive features of the masonry vaults. In fact, for the Giovi tunnel, the available historical information is derived in part from design drawings for the entrance and exit sections, ventilation shafts, fenestrations and mine work and location of the niches. Construction details are also available but are limited to the basement of the piers.

Additional data have been obtained from the documentation of surface rehabilitation works for the degraded area of both tunnels and related first aid interventions, dating back to the early 2000s (Fig. 3). In particular, it was found that the vaults are made entirely of brick masonry, plastered in some sections, while the sidewalls are composed mainly of stone masonry.

In 2023, a series of tests were carried out to provide information on the state of conservation of the coating of the two tunnels: laser scanner surveys, thermography, video-endoscopy, single and double flat jacks.

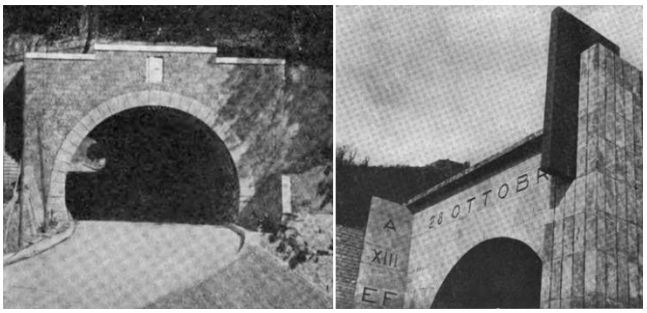

Figure 3 Portal of the Maltempo and of 28 Ottobre tunnels (CSLLPP, 1935).



Figure 2 Detail of the masonry vault and of the first aid intervention.

Laser scanner surveys and thermographies provided preliminary and important geometric and diagnostic information about the inspected surfaces. On the vaulted surfaces, there are widespread moisture phenomena that have caused efflorescence, plaster detachment, mortar disintegration and a widespread crack pattern (Fig. 4).

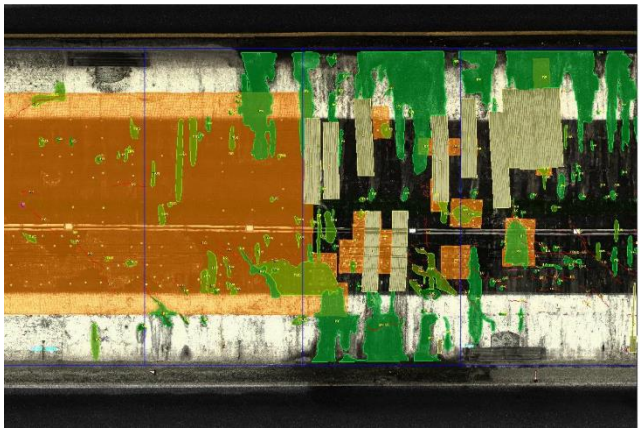

Figure 4 Survey of materials and decay of the Giovi tunnel.

In addition, a settlement in the crown of the vaults was surveyed (Fig. 5). Regarding the piers in the Campora gallery, observed degradation is limited only to the plastered surfaces, while in the Giovi gallery there is also widespread mortar deterioration and exfoliation of the stone elements.
On the basis on the above-mentioned surveys, inspection points were chosen for video-endoscopies, which showed the use of full bricks through all the cross section, with no evidence of problematic situations. On the contrary, tests with flat jacks revealed points with a stress state worthy of attention. In fact, for the Giovi tunnel, some tests showed an asymmetric stress state, with compressions on the left haunch and tension on the vault and right haunch, consistently with the asymmetrical geometric deformation surveyed with the laser scanner (orange line in Fig. 5). Regarding the Campora tunnel, high stress values are present on the left side of the tunnel and no tension on the crown in two sections (like in normal arches, gravitationally loaded).

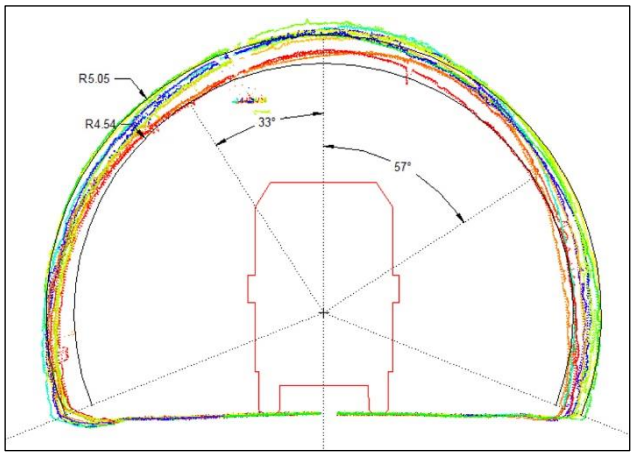

Figure 6 The laser scanner survey highlighted an asymmetrical settlement in the vault of Giovi tunnel.

The inspections described provided qualitative indications and priorities for the inspection activities to be carried out, but the present study aims to integrate these results with more quantitative data to guide the intervention choices.

2 Mechanical properties of the masonry

2.1 Double flat jack tests

Lining masonry works predominantly in compression, so its safety is determined by the compressive strength of the material. Estimating the compressive strength of existing masonry is still an open problem. Destructive methods have been proposed in the literature, such as the compression test on undisturbed walls extracted from the masonry, the compression test on cores of appropriate size, and the double flat jack (RILEM 2005, ASTM C1196 2009). In the present work, it was decided to use double flat jacks, as data were already available for the analysed tunnels. For safety reasons, the test was stopped when the measured stress-strain curve began to bend, i.e. before the masonry cracked (Fig. 6).

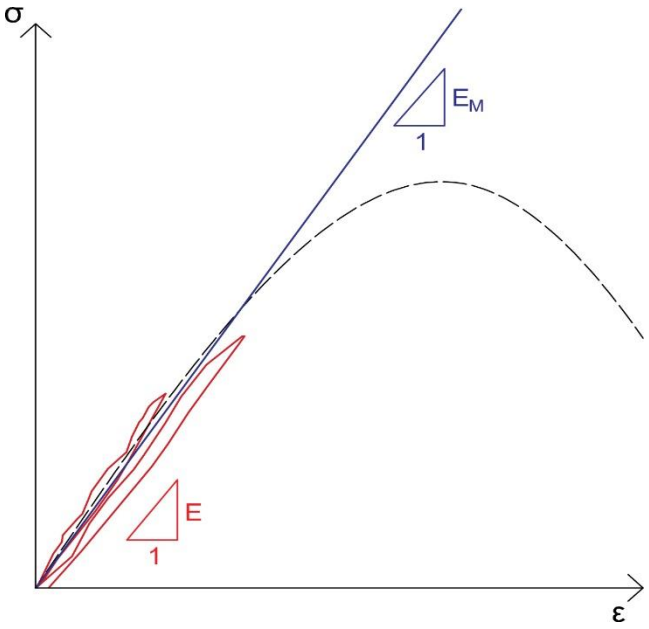

Figure 5 Double flat jack stress-strain curve: for safety reasons, the test was stopped when the measured curve began to bend.

In this case, the test provides a conservative estimate of the compressive strength and the value of the elastic modulus of the masonry E_M. From the latter, the masonry strength f can be estimated using formulae of the type $f = E_M / c$. Using the relationship suggested by EC6 (EC6, 2005), c =1000, and considering a coefficient 0.85 to transform mean strengths into characteristic strengths, gives $f = E_M / 850$. It should be noted that the flat jack used in this campaign had a thickness of 200 mm and acted on the intrados of the lining, which has a global thickness of 1200 mm. For this reason, the masonry behind the flat jack constrains the loaded masonry and causes the modulus of elasticity E_M to be overestimated. For this reason, Alecci et al. (2021) proposed a correction factor K for the modulus of elasticity that depends on the ratio

between the thickness of the jack and that of the wall. The resistance obtained in this way is still subject to several uncertainties. Firstly, some authors suggest values of c between 250 and 1200 for a solid brick wall, indicating that the correlation between the modulus of elasticity and the strength is not so certain (Costigan et al., 2015). Furthermore, EC6 refers to a secant modulus, whereas flat jacks measure an unloading and reloading modulus, which is generally higher. For this reason, it was decided to estimate masonry strength using also other approaches and to compare and validate the results.

2.2 Tests on bricks and mortar

Masonry cores with a diameter of 150 mm were taken from the masonry to characterise the constituents, mortar and bricks. Bricks or parts of bricks were taken from the cores, stoned from both sides and then cut into cubes of 50 mm side. In this way a larger number of samples were obtained, all of the same size, to avoid size-effects (Cabané et al., 2022). The cubes were tested in compression according to EN 772-1 (2011). The normalised strength $f_{b,N} = \delta f_b$ was calculated using the shape factor δ given in EN 772-1 (2011). The mortar bed joints are approximately 20 mm thick. XRD analysis has shown that the mortar is composed of lime and cement. The mortar was characterised on site using a Gucci penetrometer (Gucci, Barsotti, 1995). Mortar samples of approximately 50 mm x 50 mm x 20 mm were taken from the cores to measure the compressive strength using the UIC double punch test (UIC 778-3R, 2011).

The average strengths of mortar f_m and bricks $f_{b,N}$ can be used to estimate the characteristic strength f_k of masonry using tables or equations. As this is industrial masonry, the power equation proposed by EC6 (2005) for solid bricks and cement mortar $f_k = 0.55\, f_{bN}{}^{0.7}\, f_m{}^{0.3}$ has been used: several authors (e.g., Ferretti, 2020) have shown that this equation also gives reliable results for masonry built with mixed lime-cement mortar, such as the one in question.

Again, the factor of 0.85 proposed by EC6 (2005) was used to divide the characteristic strength f_k to obtain the average strength f. To take into account the fact that masonry consists of several layers, EC6 multiplies the strength by a coefficient 0.8. This coefficient was proposed by EC6 (2005) for buildings and is not necessarily good for the very thick walls of tunnel linings, but cathedrals and towers may also have the same problem.

2.3 Masonry Quality Index for tunnels masonries

The structural behaviour of masonry is influenced not only by the strength of its components, but also by the construction technique of the masonry within its thickness, the texture of the brick (or stone) work and by deterioration: more generally, by compliance with the so-called "rules of the art". In this study, the empirical approach defined by Borri et al (2015) for calculating the Masonry Quality Index (MQI) is used to rapidly assess the quality of masonry tunnel linings. This is achieved by measuring parameters that indicate whether certain conditions related to the correct and effective construction of the masonry have been met.

The seven parameters to be examined, which can be identified by visual and/or manual inspection, are: (a) the shape of the load-bearing elements, (b) the presence of cross-bonding elements, (c) the horizontal alignment of the layers, (d) the strength of the elements, (e) the size of the elements in relation to the wall thickness, (f) the offset of the vertical joints and (g) the quality of the mortar. The application of this method to the specific case studies makes it possible to calibrate these parameters in order to take into account the differences in behaviour between vertical thin masonry walls, for which the MQI method was defined, and the curved thick structures of masonry tunnels. In the latter case, the influence of the vault texture (Boni et al., 2022) and the different importance of some parameters under different loading conditions must be taken into account.

Further calibration will be carried out by comparison with the described in-situ tests, in order to refine the formulae proposed by Borri (2015) and to guide the determination of the mechanical parameters of the tunnel masonry, whose parameters can be very variable depending on the technical details analysed in the MQI. The implementation of this method is proposed as a tool to support both the assessment of the safety level of existing tunnels, the definition of the possible inspections needed, and the indications of the necessary reinforcement interventions, also allowing a rapid evaluation of their effectiveness.

2.4 Decay phenomena

2.4.1 Decay phenomena involved in structural weakness

The alteration of the physical and chemical properties of the materials, such as the disintegration of mortar and the spalling of bricks, is a risk factor for the safety of the tunnel (increasing the possibility of detachment of individual elements) and can have a negative effect on the mechanical behaviour of the masonry, reducing its strength. According to the illustrated glossary of the ICOMOS-ISCS International Scientific Committee for Stone (2008) and Cultural Heritage - Natural and artificial stone Description of the alteration - Terminology and definition (UNI 11182, 2006), the main types of deterioration that affect the properties of the masonry and the risk of detachment of bricks from the tunnel lining can be identified as follows: (a) biological colonization (algae, lichens, moss, mould, plants); (b) deposit (crust, efflorescence, encrustation); (c) material loss (alveolization, erosion); (d) detachment (blistering, bursting, disintegration); (e) cracks (fractures, hair cracks) and (f) deformations.

2.4.2 Decay survey and in situ analysis

In the specific case of tunnels, the presence of such deterioration is detected by the evaluation procedure outlined for Level 1 of the 2022 Guidelines (D.M. 247:2022): the catalogue of defects (Annex B) includes the defects associated with the identified deterioration, evaluated in terms of extent (k1), intensity (k2) and severity (G), in order to determine the attention class of the tunnel under investigation.

After an initial qualitative assessment of the existing pathologies, further checks can be carried out using

specialised instruments and chemical analyses. In particular, the assessment of the state of deterioration of the masonry, in terms of the reduction of its mechanical properties and consistency, can be carried out by means of rapid investigations such as visual inspections to locate areas of deterioration and define their characteristics; acoustic inspections using mechanical tapping of the surface to detect hidden defects such as detachments, cavities or fractures; and manual inspections to define the surface consistency (i.e. mortar disaggregation). These can be complemented by more detailed investigations such as laboratory chemical analysis to identify materials and degradation agents, georadar and/or thermographic inspections to locate hidden defects, photogrammetric and dynamic laser scanning surveys to check deformations, and pathological material surveys.

One of the objectives of this research is to define an operational protocol for assessing the safety of masonry tunnels through the implementation of a rapid method. Following the approach proposed by CNR-DT 213/2015, the aim is to establish a coefficient for the reduction of the strengths associated with the presence of deterioration and to define the degree of urgency for strengthening interventions in the different areas. This coefficient will be calibrated by comparing the results of in-situ masonry strength tests (single and double flat jacks, drilling energy tests on mortar, and brick sampling for compression test) with expert judgement on the level of deterioration present in the study areas. This makes it possible to estimate the effect of material deterioration on the strength of the masonry and on the risk of detachment.

3. Safety assessment

3.1 Global safety

The original design reports of the lining could not be found. In those days, empirical methods such as Ritter's method and Kommerell's method were used to calculate thrusts (Steiner, Einstein, 1980). Given the actions, the masonry lining was verified using graphical statics methods derived from Mery's method. Today, verification can be conducted by means of non-linear finite element analysis or limit analysis (Tralli et al, 2014). In the latter case, a portion of the lining is studied as if it were a masonry arch. Unlike masonry arches, however, the possible interaction between the lining and the overlying rock can change the collapse mechanism and the position of the plastic hinges, like shown by the laser scanning surveys, in some cases with a possible beneficial effect on the load-bearing capacity. The stresses calculated in this way can be compared with in-situ stress measurements performed with a single flat jack in order to validate the modelling.

For the ultimate limit state assessment, appropriate partial coefficients on actions and material strengths γ_M must be considered. For compressive strength, the Italian National Annex of EC6 (2005) prescribes a γ_M coefficient between 2 and 3. The value $\gamma_M = 3$ is often too restrictive for existing masonry tunnels. However, this coefficient was defined for the design of walls of new buildings and has no clear probabilistic basis (Lulić et al., 2023). For a sound assessment of tunnel masonry linings, the partial safety factor should be defined taking into account material variability, model uncertainty, and geometric uncertainties. Model uncertainties should include not only the uncertainty arising from the EC6 (2005) equation used to estimate the compressive strength of the masonry, but also the uncertainty of the model used for the global analysis of the arch.

The calculation should be performed for an assigned probability of failure evaluated for an assigned reference period T_R using the reliability index β. This obviously is different for tunnels than for new buildings. By reducing the reference period T_R, for example by prescribing periodic inspections and safety assessments, the β coefficient and consequently the coefficient γ_M can be reduced as already proposed for existing reinforced concrete bridges (CSLLPP, 2021).

3.2 Local safety

While ensuring the overall safety of the tunnel, it's important not to overlook the local risk, which corresponds, for example, to conditions of detachment of materials that may interact with the carriageway but do not pose a global instability risk to the structure. The Guidelines (D.M. 247, 2022) provide a procedure for evaluating the level 2 local attention class of structures on portions of tunnels which are 10 m long.

In addition to this procedure, this research aims to define a specific investigative method for assessing in a more detailed way the type and level of risk of detachment of individual elements in masonry tunnels, in order to plan focused rehabilitation interventions to prevent blocks from falling. This proposal draws on the methodologies suggested by Salvatici et al. (2020), Ceppetelli (2022), and Mariotti et al. (2023) for stone masonry facades in monumental buildings: through the visual analysis of the stone surface, the detachment hazard index is determined, allowing for a rapid assessment comparable to that obtained through in-situ investigations. In the case of tunnels, the parameters contributing to the definition of the detachment hazard index should be tailored to the specific case, with primary consideration given to the effects of water, the main cause of deterioration in these structures.

4. Conclusions and future developments

The present paper presents a new approach to the local and global safety assessment of historical masonry tunnels, starting from the analysis process proposed in the Italian guidelines for tunnels and integrating some aspects derived from the Italian guidelines for bridges, the Italian guidelines for cultural heritage in seismic areas, and data from the scientific literature in the field of historical masonries mechanical properties, and of monumental façades conservation.

The aim is the quantification of the urgency of the interventions, both from a global structural point of view,

and also considering the impact of local degradation and material deterioration. The assessment of the masonry strength has been defined adopting equations and coefficients proposed in EC6 for industrial masonry, considering the presence of large thicknesses and multiple brick layers, applied to the strength of bricks (or stones) and mortars obtained through in situ tests. A possible calibration of the Masonry Quality Index specific for the tunnels conditions was also proposed, to take into consideration not only the blocks and mortars properties but also the effects of the texture and other qualitative parameters that were proved for old buildings to have a high impact on the mechanical behaviour of ancient masonries.

A discussion about the material partial safety factor γ_M to be adopted was also made, considering the possibility of reducing it by prescribing periodic inspections and safety assessments, in line with the prescriptions for Italian RC bridges.

Finally, a proposal was made for the assessment of the level of risk of local detachments, starting from the survey of the materials decays and integrating the data with some on site tests, following a method already used for historical buildings subjected to similar risks of local material detachments.

The results obtained with the proposed method will define a priority list for the interventions and possibly a link between the type and level of risk with the type and urgency of the re-habilitation required, also considering the nominal life of the construction.

Considering these tunnels not only as an important operating infrastructure, but also as a specific typology of historical construction, has made it possible to merge different approaches into a single procedure with one aim: plan the conservation activities on these artefacts in order to preserve them in the best possible conditions, for their future use and for the testimony they represent.

Author Contribution

Conceptualizaton and methodolology: D.F.; E.C.; R.P.; C.A. Investigation: D.F.; Draft writing of the paragraph 1.1; 1.3.3: E.Z.; Draft writing of the paragraph 1.2, 4: C.E.; Draft writing of the paragraph 1.3; 2.3; 2.4; 3.2: 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.

REFERENCES

Alecci, V., Ayala, A. G., De Stefano, M., Marra, A. M., Nudo, R., Stipo, G., 2021. Influence of the masonry wall thickness on the outcomes of double flat-jack test: Experimental and numerical investigation. In: Construction and Building Materials, 285, 122912.

ASTM C1196 (2009), 09: Standard Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flatjack Measurements.

Boni, C., Ferretti, D., Lenticchia, E., 2022. Effects of brick pattern on the static behavior of masonry vaults. In: International Journal of Architectural Heritage, 16(8), 1199-1219.

Borri, A., Corradi, M., Castori, G., De Maria, A., 2015. A method for the analysis and classification of historic masonry. In: Bulletin of Earthquake Engineering, 13:2647–2665. (DOI 10.1007/s10518-015-9731-4).

Borri, A., De Maria, A. 2019. Il metodo IQM per la stima delle caratteristiche meccaniche delle murature: allineamento alla circolare n.7/2019. In: Proceedings of the 18th Italian National Association of Earthquake Engineering (ANIDIS), pp. 2-21 (in Italian).

Cabané, A., Pelà, L., Roca, P., 2022. Anisotropy and compressive strength evaluation of solid fired clay bricks by testing small specimens. In: Construction and Building Materials, 344, 128195.

CEDD, 2015. Catalogue of no table tunnel failure case histories (up to April 2015). Hong Kong: CEDD.

Ceppetelli, A., 2022. Le Facciate del cortile dell'Ammanati di Palazzo Pitti a Firenze. Master Thesis. Polytechnic University of Marche, Italy.

CNR-DT 213, 2015. Istruzioni per la Valutazione della Sicurezza Strutturale di Ponti Stradali in Muratura (in Italian).

Costigan, A., Pavía, S., Kinnane, O., 2015. An experimental evaluation of prediction models for the mechanical behavior of unreinforced, lime-mortar masonry under compression. In: Journal of Building Engineering, 4, 283-294.

CSLLPP, 1935. Annali dei lavori Pubblici, Consiglio Superiore dei Lavori Pubblici (in Italian).

CSLLPP, 2021. Guidelines for risk classification and management, safety assessment and monitoring of existing bridges, DM 17/12/2020, n. 578.

D.Lgs. 22/01/2004, n.42. Codice dei Beni Culturali e del Paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137.

D.M 17/01/2018. Aggiornamento delle Norme tecniche per le costruzioni (in Italian).

D.M. 247, 2022. Linee Guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio delle gallerie esistenti (in Italian).

D.P.C.M. 09/02/2011. Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme tecniche per le costruzioni (D.M. 14 gennaio 2008) (in Italian).

Di Stefano, R., 1981. Analisi Strutturale: Tecniche e Tecnologie, Atti del I° Congresso Nazionale "Consolidamento e Restauro Architettonico", II, Roma, Ed. Kappa, 76.

EC6 (2005), EN 1996-1-1:2005 Eurocode 6: Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures.

EN 772-1, 2011. Methods of test for masonry units - Part 1: Determination of compressive strength.

Ferretti, D., 2020. Dimensional analysis and calibration of a power model for compressive strength of solid-clay-brick masonry. In:

Engineering Structures 205: 110064.

Gucci N., Barsotti R., 1995. A non-destructive technique for the determination of mortar load capacity in situ. In: Materials and Structures, vol. 28, pp. 276-283.

ICOMOS, 2008. Illustrated Glossary on Stone Deterioration Patterns. ICOMOS, Paris, France.

Lulić, L., Lukačević, I., Skejić, D., Stepinac, M., 2023. Assessment of existing masonry resistance using partial factors approaches and field measurements. In: Buildings, 13(11), 2790.

Mariotti, C., Ruggieri, P., Pozzi, E., Salvatici, T., Centauro, I., Ceppetelli, A., Garzonio, C.A., in press. Governare l'emergenza progettando la cura, tra conservazione materiale e fruizione in sicurezza. Approcci predittivi per Palazzo Pitti a Firenze. Proceedings of the SIRA conference, Naples, 12-14 June 2023.

McKibbins, L., Elmer, R., Roberts, K., 2009. Tunnels : inspection, assessment and maintenance. CIRIA, London.

Pini, G. (Eds.), 1936. L'autocamionale Genova – Valle del Po', Roma.

RILEM (2005), RILEM Recommendation MDT. D. 5: In-situ stress - strain behaviour tests based on the flat jack. In; Mater. Struct. 37 497–501.

Salvatici, T., Garzonio, C.A., Intrieri, I., Pecchioni, E., Centauro, E., Calandra, S., 2020. Monitoring and Evaluation of Sandstone Decay Adopting Non-Destructive Techniques: On-Site Application on Building Stones. Firenze.

Sousa, R. L. 2010. Risk analysis for tunnelling projects. PhD Thesis. Czech Technical University, Prague, Czech Republic.

Špačková, O., Šejnoha, J., Straub, D., 2013. Probabilistic assessment of tunnel construction performance based on data. In: Tunnelling Underground Space Technol. 37, pp. 62–78. https://doi.org/10.1016/j.tust.2013.02.006.

Spyridis, P., Proske, D., 2021. Revised comparison of tunnel collapse frequencies and tunnel failure probabilities. In: Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 7(2), 04021004.

Steiner, W., Einstein, H. H., 1980. Improved Design of Tunnel Supports. In: Empirical Methods in Rock Tunneling--Review and Recommendations, vol. 5, United States. Urban Mass Transportation Administration.

Tralli, A., Alessandri, C., Milani, G., 2014. Computational methods for masonry vaults: a review of recent results. In: The Open Civil Engineering Journal, 8 (Special Issue 2), pp. 272-287.

Tunnel and perforation - www.tunnel-and-perforazioni.it/-news/ (last accessed 2023.02.10)

UIC 778-3R, 2011. Recommendations for the inspection, assessment and maintenance of masonry arch bridges. In: UIC International Union of Railway.

UNI 11182, 2006. Materiali lapidei naturali ed artificiali. Descrizione della forma di alterazione - Termini e definizioni (in Italian).

Zhang, G. H., Jiao, Y. Y., Chen, L. B., Wang, H., Li., S. C., 2016. Analytical model for assessing collapse risk during mountain tunnel construction. In: Can. Geotech. J. 53 (2), pp. 326–342. https://doi.org/10.1139/cgj-20150064