Research Article

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Structural evaluation of historical masonry walls utilizing non-destructive techniques – Comprehensive analysis

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Abstract: Assessment of structural capacity in the case of historical masonry walls is a complex task. Mathematical description is strongly hindered by the orthotropic or even anisotropic nature of masonry. Specifically, historical walls are characterized by the irregularity of texture and the variety of materials used. Furthermore, masonry is a composite consisting of two brittle materials – mortar and blocks. Phenomena like creep and deterioration impose other difficulties. Also, frequently, the central part of the walls is erected differently from the outer layers. The level of interlocking between these parts is another factor for consideration. Furthermore, over time, such walls might be modified or reshaped without any documentation. Hence, an unequivocal structural description of such walls is a challenging task, even with access to all the possible destructive tests. However, given the significant cultural value of such objects, frequently only non-destructive methods are allowed. This study provides a critical review and discussion regarding engineering applications of non-destructive methods (non-destructive testing [NDT] considering the available calculation methods and code requirements). It shows the possibilities and limitations of NDT, and the gaps and differences between the scientific, legislative, and engineering fields. Based on the gathered and processed data, proposals for the elimination of identified issues are provided.

Keywords: non-destructive testing, standards, mechanical parameters, analytical methods, numerical methods, engineering practice

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1 Introduction

Historical masonry walls are particularly challenging, and specific types of structural elements are required to analyze quantitatively [1]. In addition, their abundant variety is one of the critical factors when it comes to non-destructive testing (NDT) applications. It should also be noted that a significant amount of such structures (by default) is in the cradle of European civilization – namely, the basin of the Mediterranean Sea. This area is strongly affected by the seismic activity – Slovenia, Croatia, Portugal, Italy, Greece, and Turkey [2]. Only in the current century and in Italy alone three major earthquakes with disastrous impact on historical masonry walls can be listed: L'Aquila 2009 [3], Emilia-Romagna 2012 [4], and Central Italy 2016 [5]. Hence, in these areas, additional variable comes from different states of analyzed elements – a wall can be in its original form, in a damaged state after an earthquake, or after strengthening. Additional difficulties in terms of structural assessment are due to the fact that all these scenarios can occur within the same building.

Also, it should be noted that the assessment of historical objects requires a holistic approach, which includes a detailed and thorough investigation [6]. In many cases, significant diagnostic limitations arise from restrictions imposed on testing methods. The restrictions are related to the invasiveness of these methods and might be imposed by local or international regulations [7–9]. Specifically, Roca [7] discussed the ICOMOS/ISCARSAH guidelines, which (among other recommendations) prioritize the rule of minimum interventions; in ICOMOS [8], the safeguard of the object's integrity is pointed out, while in ICOMOS [9] it is underlined that any invasive investigation should be extensively justified. Such decisions relate to the historical and cultural value of the considered objects.

Additionally, the mathematical models for masonry walls are quite different from those for typical beams or frames analyzed in the case of structural steel or reinforced concrete [10]. In the case of numerical analysis, shell elements or solid elements are much more capable of reflecting the specificity of masonry; however, at the same time, they are significantly more difficult to handle [11,12]. Masonry is a complex material to describe mathematically; hence, in engineering practice, various mathematical models are needed for different loading scenarios – compression, in-plane shear, or out-of-plane behavior. Also, a distinction must be made between static and dynamic loading [13–15]. Specifically, Lagomarsino and Giovinazzi [13] proposed two models to deal with seismic hazard – one based on the vulnerability of the walls and the other based on their capacity curves. Penna *et al.* [14] presented a macroelement model for simulating the cyclic in-plane response of masonry walls, applicable both in nonlinear static and dynamic analysis. Ghezelbash *et al.* [15] proposed a damaging block-based model (BBM) working in quasi-static and dynamic simulations. It is a numerical approach based on 3D finite elements with a plastic-damage material formulation; the masonry units interact by means of a contact formulation (Figure 1).

Given all the enumerated factors, the practical application of NDT in the case of historical masonry walls is a challenging task. It requires not only knowledge in the field of testing methods but also strong familiarity with the specificity of historical masonry walls and existing engineering tools for structural assessment [17]. This statement also determines the setup of this article. First, the features of historical masonry walls are described, then relevant NDT methods, indications in codes and standards, and, eventually, the assessment methods. Finally, a synthesis and discussion are conducted, which confront the described components with the needs and capabilities of engineering communities. Specifically, based on the gathered and processed data/conclusions available in the literature, the knowledge gap is indicated. Also, the discrepancies, inconsistencies, and lack of communication between the scientific, legislative, and engineering communities are demonstrated. These issues might lead, in turn, to possible ineffectiveness and mistakes in the structural evaluation/

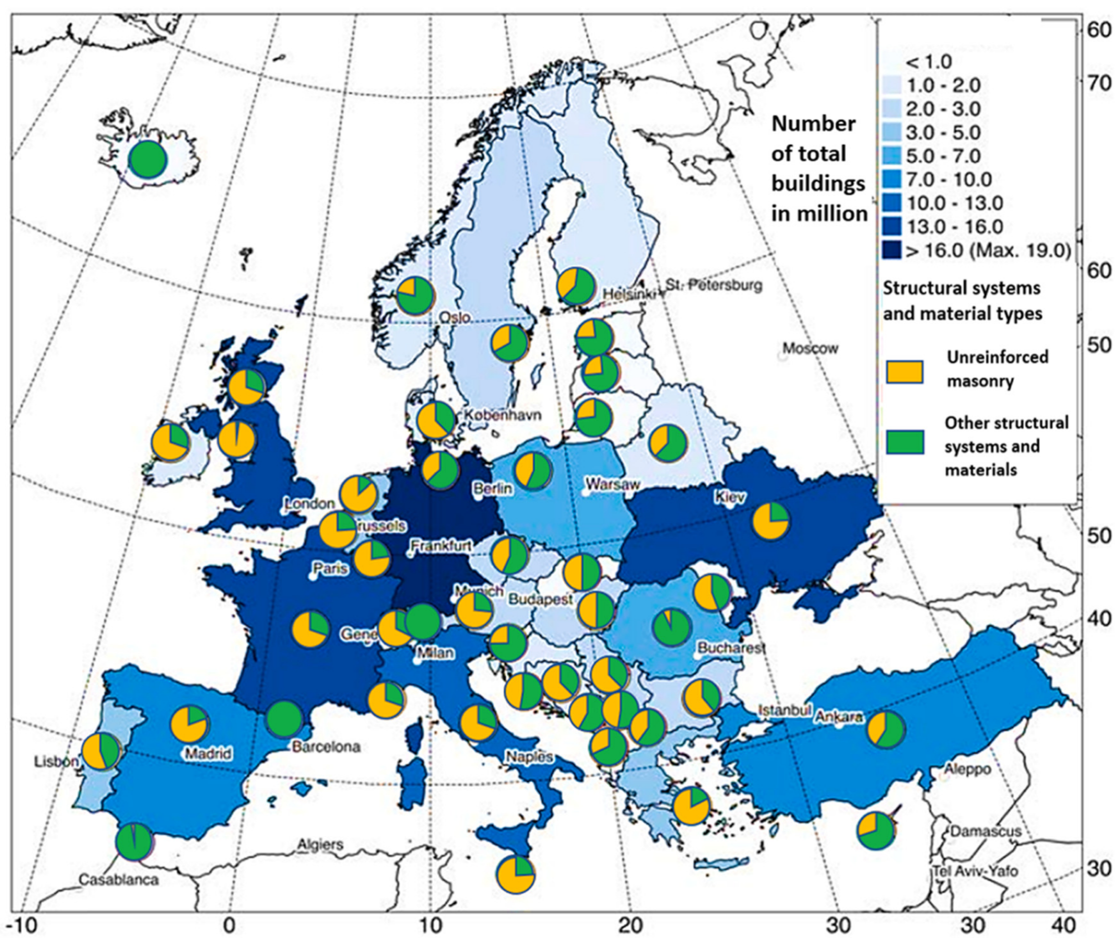

Figure 1: Distribution of unreinforced masonry buildings (in millions) across Europe; adapted from Crowley *et al.* [16].

assessment process. In conclusion, a roadmap and potential actions are provided to improve the current situation.

It should be noted that the description and specificity of the NDT methods are limited to the minimum related to the purpose of this study. For details of particular methods, the provided literature should be referred to.

2 Historical masonry walls – features

In this section, to demonstrate the specificity of the analyzed structures, some of the features are highlighted. Historical masonry walls are a broad term encompassing a variety of structures built with different materials, techniques, in different periods, and across various geographical and cultural regions [18–20].

An obvious variable is the material of blocks (units) that are inevitable components of masonry. Masonry typically is made of bricks or stones. Furthermore, historical bricks can also be divided by the type of material: burnt clay bricks, clay bricks, sand lime bricks, and soil bricks. The variety of rocks that constitute stone blocks is even greater, along with greater discrepancies in their mechanical parameters. Namely, stone blocks can be made of relatively weak sandstone (uniaxial compressive strength starting with 6 MPa [21]) or high-strength granite or basalt (uniaxial compressive strength up to 400 MPa [22]). All the discussed materials that are used as blocks possess their own physical and mechanical properties, various porosity, and chemical composition [23,24]. In the case of rocks, orthotropy or anisotropy can occur as well. As a consequence, *inter alia*, they react differently to aging [25], moisture content [26], natural chemical agents [27], freeze–thawing process [28], cyclic loading [29], or long-term phenomena like creep [30]. Moreover, a wide variety of physical and mechanical properties requires the adoption of dedicated renovation or strengthening methods and materials [31–33].

Similar considerations in terms of material can be applied to mortars. Namely, in historical masonry, walls can be found with mortars of different compositions and qualities. Their ingredients and, in turn, physical and mechanical properties are a result of local resources and tradition by the time of the structure's erection. For instance, Lezzerini *et al.* [34] demonstrated that mortar used in the bell tower of St. Nicholas Church (Pisa, Italy) was obtained from firing local carbonate rocks, cherty limestone, and secondarily *Mt. Pisano* marble. Other works dealing with the composition of historical mortars as a function of local resources are, for example, as given previously [35–37]. In the study of Yaseen *et al.* [35], Roman mortars in ancient Jerash were analyzed, and within this one city and one historical period, two different types of mortars were utilized (in terms of binders). In the study of Riccardi *et al.* [36], an eighteenth-century object in Milan and a sixteenth-century object in Pisa were analyzed. In both cases, mortars exhibited hydraulic-type reactions, and the authors underlined that due to differences in the composition of mortars, different analytical methods were required. Gleize *et al.* [37] characterized mortars from the eighteenth to the early twentieth century in the State of Santa Catarina (Brazil), and the results show that the dominant binder is hydrated lime from the burning of seashells.

Although a complete understanding of the structure, mechanical properties, and deterioration level of blocks and mortar has been gathered, this knowledge is still insufficient for the structural assessment procedure. It must be noted that masonry is a composite that consists of units and joints. Hence, its overall properties are a result of the properties of these two components. It means that the structural behavior of masonry walls would also depend on the geometry of blocks (shape, size, roughness, level of processing) and mortar joints (thickness, spatial distribution). Overall, these features could be referred to as texture. The texture of masonry walls is another crucial variable in determining the wall's properties, durability, and mechanical response. The texture of masonry walls alone is a vast area of research and engineering. Level of

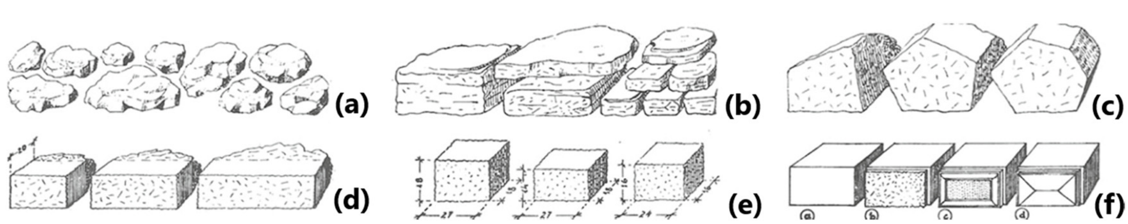

Figure 2: Classification of the units depending on the workmanship: (a) rubble stone, (b) hewn stone in the form of slate, (c) cyclopean stones, (d) squared rubble with one face not completed, (e) squared roughly tooled rubble, and (f) ashlar unit with finished edges and faces in smoothed view (after Peulić [38]).

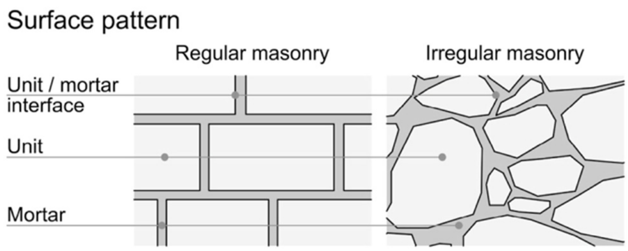

Figure 3: Distinction between regular and irregular masonry texture (after Szabó *et al.* [39]).

processing, or in other words, workmanship, has a significant impact on load transfer, both in the case of in-plane and out-of-plane loads; furthermore, it strongly affects the integrity of the wall and its cross-section. Also, the quality of surface treatment can have a significant impact on the durability of masonry. For instance, the presence of untreated surfaces promotes the spreading of internal wetting and, in turn, exposes the wall to amplified freeze–thaw processes. Exemplary classification of units regarding workmanship (after Peulić [38]) is presented in Figure 2.

The shape and level of processing applied to units determine the level of regularity in masonry walls, which in turn has a crucial role in the unit–joint interaction and stress distribution at their interface. Figure 3 demonstrates a sketch representing the distinction between regular and irregular walls.

Figure 4 shows the scale of variety in possible textures. This figure represents the typology of texture identified just in the agglomeration of the city of L'Aquila in Central Italy (after Rovero *et al.* [40]).

So far in the description, none of the mentioned features have been related to the cross-section of the historical walls. However, it is a crucial parameter, which in the case of the modern walls has minimal significance (modern walls usually consist of one layer, and if there are more than one layer, they are always properly interlocked). Hence, another aspect specific to historic masonry walls is the presence of two or three layers in the cross-section (Figure 5). Such layers are often called leaves or wythes. Walls with two or three layers are called multi-layered or multi-leaf walls. In the case of three layers, the central one is called the core or nucleus, whereas the outer layers are called the cladding. This central layer has a significant impact on the overall behavior of the masonry wall, which stems from the specific structure of the core. Cores are often made of material of lower quality – cobbles, pebbles, irregular stones, crushed bricks, debris, and various types of "on-site rubbish." Mortar is often of lower parameters as well – for example, with less binder and laid chaotically. Therefore, a significant percentage of voids and cavities are present in the cores. This inconsistency and discontinuities within a cross-section create an ambiguous state of stress, which hinders the structural understanding of such structures.

The variety of possible core-cladding configurations is also significant. Figure 8 depicts three examples of different three-layered masonry walls.

Figure 4: Example of masonry types in L'Aquila (Central Italy) (after Rovero *et al.* [40]).

Figure 5: Exemplary three-layered masonry walls. Left: example from Palermo (Italy) – irregular stone cladding and very thin core consisting of small cobbles and pebbles (own source). In the center: brick masonry with regular cladding and core with high mortar ratio – Meldert-Lummen (Belgium). Right: uncoursed random rubble stone wall, stone cladding, and core made of cobbles in a matrix of mud mortar (Maharashtra, India) (source: own and previous studies [41,42]).

Another factor related to multilayered walls (both two-layered and three-layered) is the presence and quality of interlocking between the neighboring layers. Unlike modern multilayered brick walls, which feature a clear and repetitive pattern of headers, historical walls are characterized by interlocking elements (called through-stones or keystones) in a less organized manner. The question of layers' interlocking is vital in the context of out-of-plane behavior during earthquakes and in the context of long-term behavior. In both these cases, the monolithic behavior of the entire cross-section is crucial for correct load transfer and, in turn, the safety of the walls.

There are numerous articles and reports demonstrating failure schemes in multilayered walls triggered by insufficient cross-sectional interlocking [43–46]. Most of the failures are related to seismic actions. However, deterioration of connections over time, along with geometric eccentricity, also may be destructive. Such a case is shown in Figure 6, a two-layered irregular stone wall.

The issues of weak core and interaction of layers have been investigated intensely over the last three decades – see, for example, previous studies [47–51]. Precisely, in the study of Binda *et al.* [47], using the laboratory shear test (similar to the one shown in Figure 7), the difference in quantitative and qualitative behaviors of masonry without and with keystones is depicted. Laboratory testing of three-layered masonry specimens was also done in the study of Valluzzi *et al.* [48]. In this case, three types of strengthening were tested – injections,

Figure 6: Free-standing two-layered wall in rural Poland, damaged through the separation of layers (source: own).

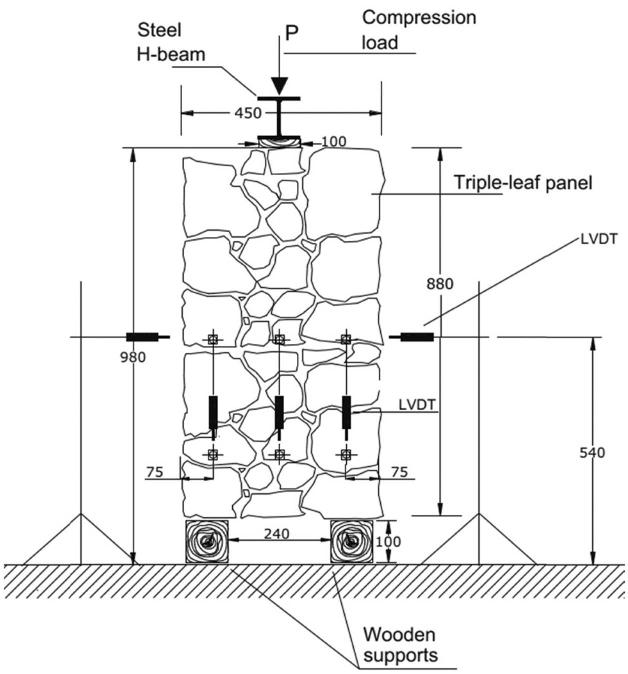

Figure 7: Shear test arrangement for multilayered wall (source: Corradi *et al.* [52]).

bed joints repointing, and transverse tying. The injections turned out to be the most effective; however, the authors underlined that each case (each specific wall) might yield a different response. Ferreira *et al.* [49] considered out-of-plane laboratory testing with varying levels of axial precompression. In conclusion, the importance of the presence and spacing of keystones in mobilizing the monolithic behavior of specimens was strongly underlined. Three-leaf wallettes constructed with mud mortar were tested in compression in the study of Meimaroglou and Mouzakis [50]. The obtained global failure mechanisms were in line with air lime mortars. In contrast, the compressive strength and the modulus of elasticity were, respectively, higher and lower than the results for air lime mortars. Numerical parametric analysis (based on experimental data) was conducted by Boscato *et al.* [51]. As variables were treated, the mechanical parameters of core and cladding, the proportions of specimens, and the strength of core–cladding connections were considered. The most important finding revealed that core–cladding interactions govern load transfer and capacity.

However, further research is still needed, as quantifying these phenomena is a challenging task that requires

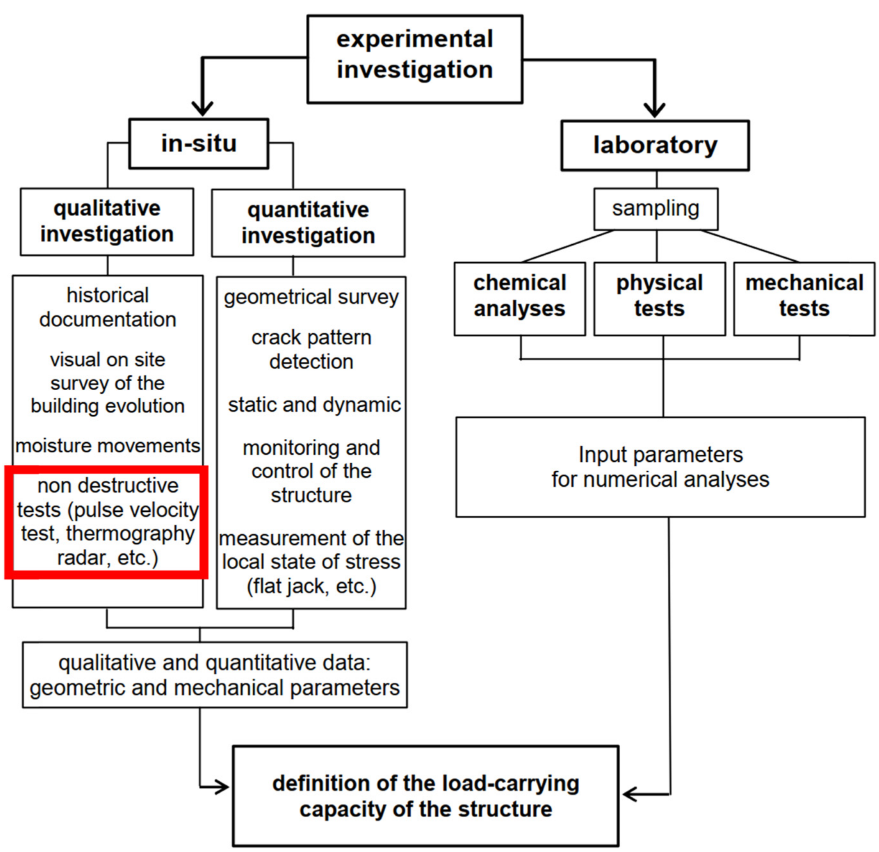

Figure 8: Possible role of NDT in assessment procedure of historical masonry walls (after Binda *et al.* [53]).

numerous specimens, real-scale testing (mostly on recreated models in laboratories – Figure 7), and considering several variables.

Given both the described specificity of the discussed structural elements and the strict requirements related to heritage preservation, the role of NDT in diagnostics and structural assessment of historical masonry walls is crucial. We next discuss the relevant NDT methods.

3 Testing

Given all the specific features described above, it is clear that structural assessment (both in terms of statics and dynamics) of historical masonry walls is a complex, demanding, and multidisciplinary task. One of the steps is to acquire the parameters of the structure, not only in terms of quality but also in terms of quantity. The possible place and role of NDT in the entire process are demonstrated in Figure 8.

Regarding NDT methods for historical masonry walls, they can be analyzed within different frameworks. Namely, the tests could be considered in terms of the blocks, mortar, or the compound block–mortar. Furthermore, the variety of textures and the number of layers (wythes) in the cross-section might be investigated. Information can also be categorized based on static or dynamic analysis, or the long-term behavior of the structure.

The division below is purposely structured in terms of specific masonry parameters and features. However, it should be noted that, in the case of historical masonry walls, besides the methods listed below, two universal methods should always be considered in the first step. The first one is visual inspection, and the second is the study of available archive documentation and historical resources [54].

3.1 Materials

3.1.1 Mortar – strength

The most challenging aspect of NDT *in situ* testing of mortar (namely, without extraction) is its small size and parameters varying across joint depths. This variability primarily relates to weathering processes and undocumented renovative actions over the centuries. Given these stipulations, choices are limited.

The use of a penetrometer (even though it could be classified as a slightly destructive method) seems to be the most suitable tool for quantitative outcomes. It produces results that can lead to an estimation of mortar's compressive strength, obviously, along with the correlation curves. In favor of the method is its applicability to low-strength mortar, which, in the case of historic objects, is critical. Colla [55] demonstrated the application of the penetrometer to a real historic structure with practical outcomes for both engineers and architects. However, significant comparative campaigns – namely, projects that include both destructive testing and penetrometric systems are required to obtain more reliable data. To date, empirical correlations for historic mortars are still limited [56]. Schmidt Hammer type could provide similar data with a comparable level of confidence with a penetrometer; however, given its high energy impact, the application for weaker mortars (the case of historical ones) is strongly limited [57]. Besides, while a penetrometer reaches up to several centimeters in depth, a Schmidt or pendulum rebound hammer can give information only about the superficial part of the material, around 3 cm [58]. The latter method, although simple in application and non-invasive, is very highly susceptible to surface morphology variations and yields significant inconsistencies [57]. The last method with potential applications in determining compressive strength of mortars is the scratch test; however, the attempts described in the literature show that results considering only the extremely superficial layers of the joint are challenging to interpret and unsuitable for irregular masonry [59].

Nevertheless, it should always be noted that this kind of method, based on energetic/dynamic approaches, is highly influenced by the boundary conditions – for example, the stiffness of the units in masonry. Hence, mortar testing in walls composed of soft rocks might render different values, which in turn require abundant data and an experienced user. For example, Žalský *et al.* [60] demonstrated such an effect in the case of the penetrometer using steel and brick molds (Figure 9).

Active thermography might be used for determining the thickness or delamination of pointing mortar [61]. However, such information is only presumptive, and additional techniques or intrusive actions might be required.

Some promising results have been obtained in the field of crack detection in the propagation of mortar joints with the joint application of digital image correlation (DIC), acoustic emission (AE), and ultrasonic pulse velocity (UPV) [62]. The results of the experimental campaign regarding the so-called brick masonry triplets are shown in Figure 10. Among the most critical findings crucial for potential engineering applications was the fact that AE and DIC indicated the failure mode and damaged zone before visible cracking was present. However, it must be pointed

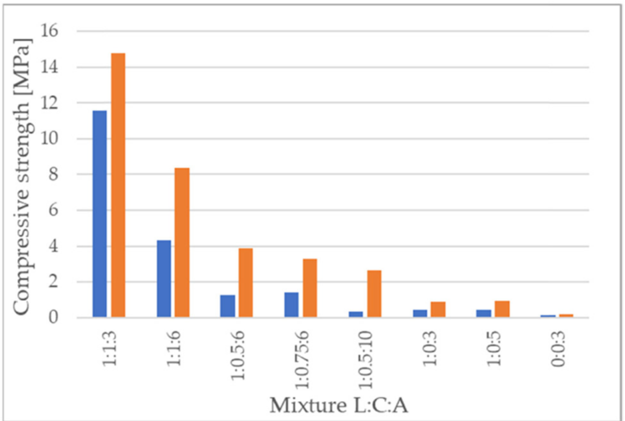

Figure 9: Compressive strength values influenced by the mold material – steel (blue) and bricks (orange) (after Žalský *et al.* [60]).

out that it was a laboratory campaign, and the transition of this approach on-site would require overcoming several challenges, for example, noise from other parts of the wall.

3.1.2 Blocks – strength

One of the most common NDT methods for blocks is the use of the rebound hammer (both Leeb/Equotip and Schmidt hardness tests). The use of these tools for blocks in masonry is an extrapolation based on the experience with concrete [63]. Hence, similar limitations could apply: size of the specimen, moisture content, smoothness of the surface, and calibration effect. Especially the last factor is significant as an extensive range of material can be tested – several types of bricks (of various ingredients and workmanship) and numerous types of rocks (as already indicated in the study of Kržan *et al.* [64]). Some of the issues with this method are statistically analyzed in the case of the vintage clay bricks in the study of Borosnyoi-Crawley [65]. When considering this group of methods, it is essential to note that, in both mortar and block cases, the absence of extensive calibration means the results should be regarded as qualitative or semi-quantitative at best.

Given the uncertainties of hardness tests, the so-called SonReb method was devised – first for concrete – Cristofaro *et al.* [66] described its evolution. This method combines the results obtained from the Schmidt test and ultrasonic pulse velocity test (UPVT). Such an approach enables the reduction of the uncertainties and limitations related to the separate methods. The SonReb application for masonry blocks is currently minimal. An experimental campaign (along with destructive testing) was conducted by Cabané *et al.* [67], where they tested 20 types of bricks. Although the combined approach yields better correlation with destructive tests, a calibration or reliable database is still required.

In the study of Gomez-Heras *et al.* [68], a combination of UPVT with the Equotip test (instead of the Schmidt test) was investigated experimentally. The study is especially valuable as it dealt with 29 different types of rocks. The combined approach was confronted with available data from destructive tests. One of the main findings is a significant improvement in accuracy in the case of non-porous polymineral rocks.

The combination of Equotip and Schmidt tests was investigated for 11 rock materials typical for masonry walls [69]. However, for selected materials, this approach provided a modest improvement in terms of prediction accuracy.

All these methods require the user's focus and experience, as they are highly susceptible to numerous factors.

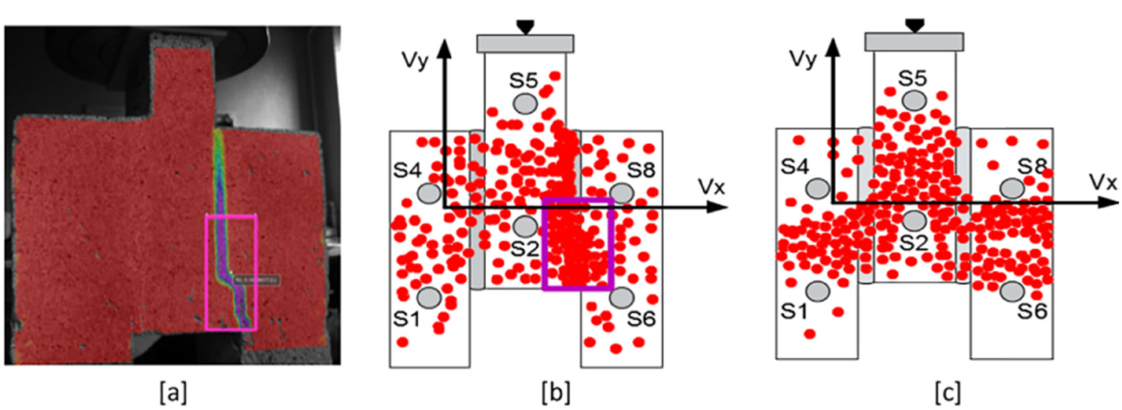

Figure 10: Crack evolution on a triplet, various representations. (a) DIC strain; (b) AE events – planar orthotropic; and (c) AE events – planar isotropic localization (after Livitsanos *et al.* [62]).

3.2 Compound

Given that masonry is a composite of blocks and joints, a reasonable approach is to test the entire wall (compound) instead of describing the ingredients separately. Besides, having independent results both for the components and the compounds provides databases for double-checking and building correlation curves/equations. Hence, significant attention in both academic and engineering communities is paid to methods that give the resultant parameters of the masonry wall.

In the case of NDT methods, the compressive strength of the entire element is derived mainly through its correlation with its stiffness [70]. Hence, for this approach, the database of destructive data is inevitable.

Investigation of stiffness promotes different kinds of acoustic wave methods. These methods are constituted by a broad group of techniques relying on the relationship between the sound energy traveling in the material and various mechanical properties of this material. In general, this is achieved through the transmission and reception of mechanical (acoustic) waves of different frequencies. The waves are applied to a given medium – for instance, masonry. In case of any discontinuities (such as a crack) encountered by the wave, some fraction of the energy is reflected from the flaw surface. The reflected signal is processed into an electrical signal and represented on a screen. With knowledge of the wave velocity, the location can be inferred. Also, information like size, orientation, and location of the object/flaw, in some cases, can be acquired. Depending on the needs and goals in each situation, the type of wave might be chosen – longitudinal, transverse, or surface acoustic waves. In estimating stiffness and density, a correlation between these parameters and the wave velocity is utilized. Materials of higher rigidity and density allow sound to travel faster. A comprehensive description of these methods can be found in numerous textbooks [71–73].

One of the acoustic wave methods is the so-called indirect sonic impact method (ISIM). For the first time, this approach was adopted for stone masonry walls by Miranda *et al.* [74]. In this test, the wave velocities were measured along the direct and indirect travel paths of walls. Importantly, a reasonable correlation was obtained between stiffness from ISIM and stiffness from destructive tests. In the same campaign, the direct method and ultrasonic tests were applied as well. The first option also yielded a relatively good correlation, however, with a significantly higher number of tests compared to ISIM. The ultrasonic tests were found to be less reliable, mainly due to susceptibility to surface conditions (smoothness, roughness). The same authors carried out a similar campaign focusing only on ISIM [75]. The results were compared with the modulus from direct compression tests of 12 one-layered masonry panels, both with regular and irregular joints. ISIM correctly showed sensitivity to different wall types and good quantitative correlation with compression tests. However, it was still concluded that the method requires some cross-checking and should preferably be applied with other testing tools.

Spectral analysis of surface waves (SASW) was employed to diagnose stone masonry walls of Saint Justo and Pastor Church in Granada (Spain) [76]. Besides the elastic modulus, Poisson's ratio was obtained. The agreement of both values was very good with the parameters obtained from destructive tests. However, for obvious reasons, the destructive tests were run on similar stones from the region instead of utilizing the structure itself.

There was one attempt at utilizing the UPVT method alone [77]. However, it was based on an extensive cross-validation procedure, which consisted of comparison with a laboratory compressive test. Hence, it has substantial limitations.

It is worth noting that all of the above methods are limited to homogeneous walls, optimally with only one layer of cross-section. Hence, their reliability decreases in the case of multi-layered walls. For example, in the study of Van Eldere *et al.* [78], sonic testing overestimated the stiffness of double-leaf masonry walls (Figure 11) by 23 times. The authors indicated that supplementary methods, like IE (Impact Echo), could provide information about the interlocking of layers and their thicknesses, for rectification of the results.

Another branch of methods is based on different types of dynamic analyses. The vibration tests can be either forced or natural. In the first case, the so-called experimental modal analysis (EMA) is carried out, while in the second case, operational modal analysis (OMA) is carried out. The advantage of OMA over EMA stems from the fact that forcing oscillation of large structures is much more difficult than utilizing natural vibrations, such as those caused by wind actions. Both methods provide natural frequencies, damping ratios, and mode shapes of the structures. Having such an output, numerical models can be calibrated. Part of the process is the adjustment of dynamic modulus (which can be converted to the static modulus). In this sense, vibration tests show potential for the indirect assessment of mechanical properties. A similar strategy was adopted by Tomaszewska *et al.* [79] for a historic bell tower and by Tomaszewska *et al.* [80] for a historic lighthouse.

3.3 Cross-section

As already demonstrated, the properties of cross-section and inner parts of historic masonry walls are significant in terms of their mechanical behavior.

Figure 11: Specimens tested by direct and indirect sonic methods (Source: Van Eldere *et al.* [78]).

In the case of cross-sectional diagnostics, the previously mentioned vibration tests are primarily used to detect local damage and cracks. For example, such an approach was applied to crack detection in the multi-layered masonry wall of the bell tower (Figure 12 [81]).

Previously introduced wave acoustic methods are also used for cross-sectional investigation. Given their specificity, they are much more helpful for this task than for the assessment of mechanical parameters. Numerous experimental campaigns were conducted in this field. Sonic direct tests, sonic tomography (multiple pathways approach), and MASW (Multichannel Analysis of Surface Waves) were adopted by Valluzzi *et al.* [82]. The combination of methods allowed them to detect voids, cavities, different materials, and the effectiveness of grout injections executed on tested masonry panels. Qualitative information regarding the heterogeneity of masonry cross-sections was obtained through sonic methods in the case of the Cathedral of Noto. The research had a practical aspect, as it served to verify the state of damage and to indicate the possible renovation techniques in the reconstruction project (Figure 13) [83,84].

Impact-echo can also be used for the assessment of the cross-section. In the study of Sadri *et al.* [85], this technique was applied to study multilayered stone walls. The method was able to detect voids, cavities, the thickness of stones, and zones of high- and low-quality bonding between the units.

Ground penetrating method (ground penetrating radar [GPR]) – a geophysical technique based on the reflection of electromagnetic waves, is also utilized for diagnostics. A thorough review of existing experimental campaigns utilizing GPR was conducted by Binda *et al.* [83]. They concluded that this method has high efficiency for determining thickness, detecting

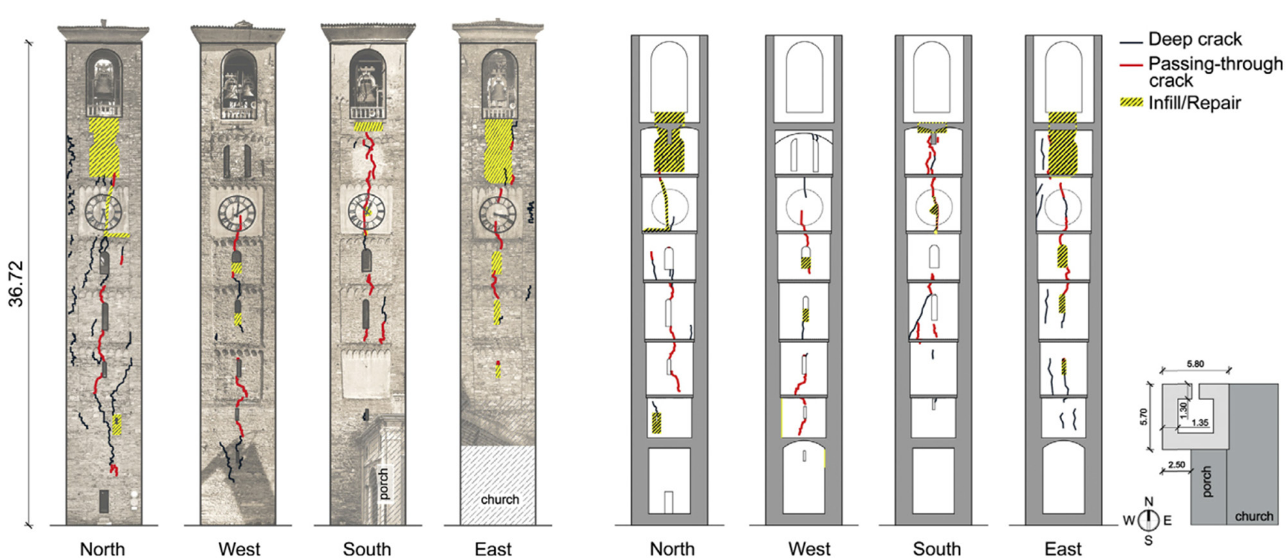

Figure 12: OMA results, crack patterns: fronts (on the left), vertical cross-sections (on the right) (Source: Gentile *et al.* [81]).

metal intrusions, and identifying air voids. To some extent, it can be utilized for the study of historical redevelopment, delamination of facing layers, and moisture mapping of structures. Frąckiewicz *et al.* [87] presented a case study that employs this method for some of the listed purposes. However, it was indicated that some initial excavations were needed to calibrate the results; hence, this method also needs auxiliary semi-destructive actions. Similar conclusions were drawn by Palierak *et al.* [88], who found that GPR needed the support of boroscopy to be reliable.

A combined approach was adopted by Grzyb *et al.* [89] during the preliminary assessment of masonry walls in Malbork Castle. Specifically, they utilized both ultrasonic tomography and portable penetrating radar tests. Thus, they were able to identify voids inside the cracked wall, indicating, however, that the results were rather qualitative than quantitative. Furthermore, the capabilities of GPR as a function of different antennas were demonstrated and, if possible, confirmed with layer removal and drilling.

There is also a constant search for other methods, such as electrical resistivity tomography [86], which was used by Abu Zeid *et al.* [90] to assess the volume of grout injections into the core of the wall. Qualitatively, the results were promising; however, quantitatively, the method required significant calibration, which also excludes it as a standalone general diagnostic tool.

3.4 Degradation and aging

In the case of historical structures, the impact of time is a significant factor. Hence, consideration of effects caused by different detrimental factors should never be excluded beforehand. Uranjek and Bokan-Bosiljkov [91] investigated the deterioration induced by freeze–thaw cycles. NDT methods were applied for assessment – thermography was able to capture delamination of bricks, and ultrasonic velocities were able to differentiate responses of various mortars. At the same time, utilization of a 3D scanner before and after loading with freeze–thaw cycles enabled a detailed assessment of the damaged brick surface. The tests were executed on specimens in the laboratory; however, there is potential for application of the described methods *in situ*.

In the study of Chen *et al.* [92], the deterioration of ancient stone walls was analyzed with ultrasound computed tomography (applied *in situ*). In that case, the deterioration induced by weathering and local stress state was investigated. However, also in this case, to extract not only qualitative but also quantitative information, a destructive support (in this case, compressive tests in a laboratory) was needed. Both GPR survey and thermography were adopted by Biscarini *et al.* [93]. These methods were used in that case to examine the deterioration of masonry caused by moisture and water.

3.5 Long-term effects

Long-term effects in the case of masonry are mostly related to the creep phenomenon. Early identification of creep indicators is crucial, as damage due to this event is abrupt and signaled in a non-obvious manner. Especially

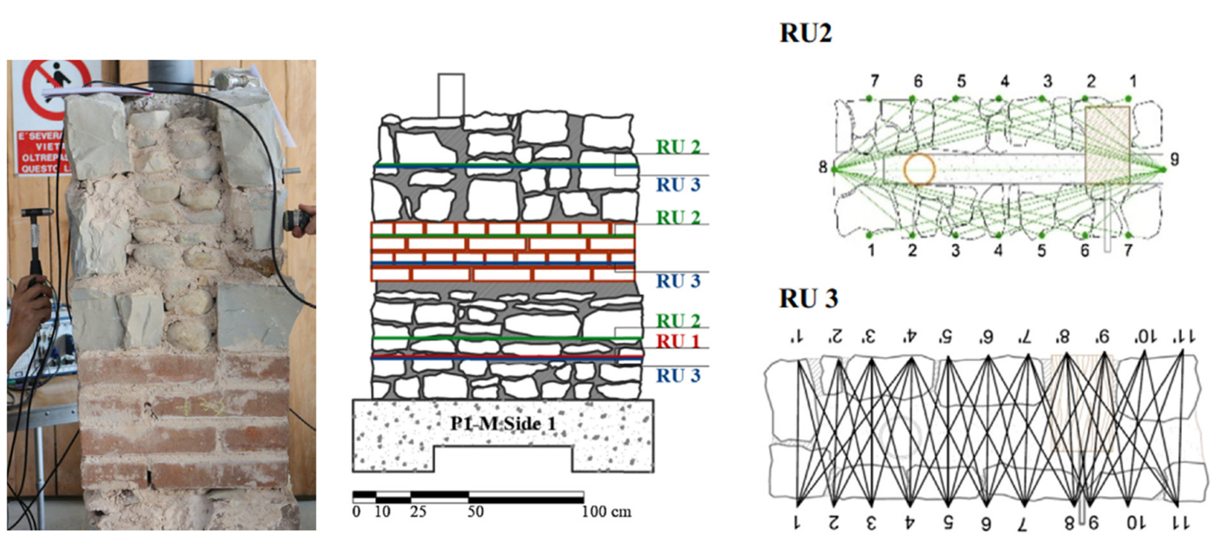

Figure 13: Exemplary specimen, tested cross-sections, and horizontal sonic tomography (Source: Valluzzi *et al.* [82]).

considering that creep-triggered structural disasters of historical masonry structures occurred in the past. For instance, the cathedral tower of Pavia [94] or the bell tower of St. Marco in Venice [95]. In the seminal work [30], it was indicated that the crucial step is the identification of local stress states and crack patterns (some of them hidden). Such zones might be associated with unstable damage accumulation in masonry. Hence, as mentioned before, EMA and OMA are valuable tools; however, they have not been pursued in that direction yet. Given its specificity, the AE method was applied to assess ongoing masonry damage accumulation by Verstrynge *et al.* [96]. In the dedicated laboratory, a series of creep tests on masonry panels was executed, and AE was utilized for quantitative analysis. However, the authors pointed out that further research and data gathering are needed to provide more reliable damage curves. Importantly, the described procedure could also be applied *in situ*.

4 Standards and codes

Testing and obtaining mechanical parameters are only a part of the structural assessment process. In general, both designing and assessing procedures are described in standards and codes. Even though engineers are not always strictly bound to obey these documents, it is a common requirement of the investors to follow standardized procedures. However, in the case of historical masonry walls, the level of precision and detail provided in standards is much lower than in the case of new structures. Furthermore, given the fact that the current approach in dimensioning is to calculate as many features as possible, the lack of accurate guidance for historical masonry is frequently a source of confusion amongst the engineering community. A review of several standards and codes is given next.

In New Zealand, given that this country is strongly affected by earthquakes, historical masonry is analyzed mainly in terms of seismic actions. In 2017, a series of codes and standards were released to deal with this disaster [97]. For existing unreinforced masonry buildings, a volume was also issued [98]. In this document, a procedure for the assessment of entire unreinforced masonry buildings is provided (including interaction between walls and walls–floors or walls–roof interaction) (Figure 14). Some indications are also given for the quantitative description of masonry properties. However, most of them are based on destructive and semi-destructive techniques. The only non-destructive method (besides study of archives and visual observations) is GPR, which is advised for the

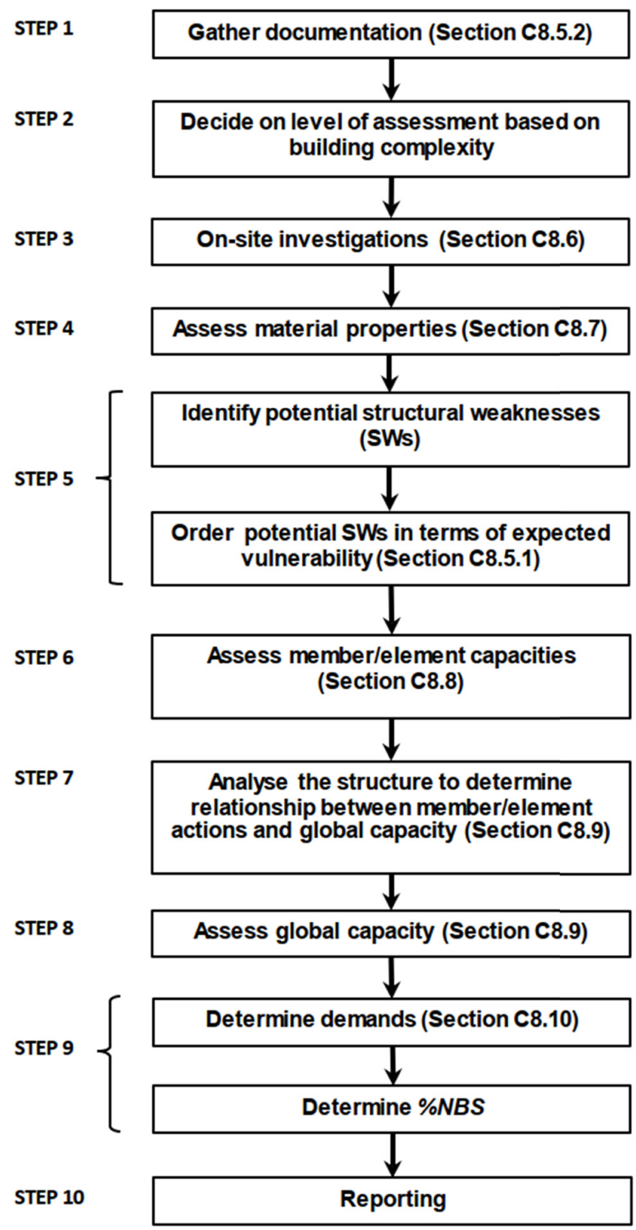

Figure 14: Assessment process of an unreinforced masonry building (Source: NZEE [98]).

determination of “the member thickness, metallic objects, voids, and other information.”

The document also underlines the importance of the wall cross-section, indicating to identify any connections between wythes, determine the material of the core, and locate voids and cavities. It is stated that all these features contribute to determining the wall’s structural properties. However, no indications are given on how to quantify the contribution of these parameters (Figure 15).

American Standard ASCE/SEI 41-13 [99], dedicated to existing structures, also provides some guidance for

Figure 15: Stone masonry cross sections in New Zealand. From left to right: dressed stone in outer leaves and rubble fill, stone facing and brickwork backing, stone facing and concrete core (Source: NZSEE [98]).

existing masonry. The document indicates that condition assessment shall include evaluation of the degradation level, deterioration of unit surface or mortar joint due to weathering induced by freeze–thaw cycles or frequent moisture saturation. Besides, the standard recognizes the importance of interlocking between wythes. The standard enlists the following non-destructive methods: UPV, mechanical pulse velocity, impact echo, radiography, and infrared tomography. A short description of each method is provided, along with its drawbacks and limitations, references to scientific articles are included. There are no indications regarding the quantitative interpretation of these tests and their integration into structural calculations. The Standard refers to other documents: FEMA 306 [100], FEMA 307 [101], and FEMA 308 [102]. First, besides the methods mentioned in ASCE, it also includes rebound hammer, SASW, and GPR. For each technique, a dedicated technical card is prepared containing the following: description, equipment, execution, personnel qualifications, reporting requirements, limitations, and references.

Canadian Standards CSA-S304.1-14 [103] does not refer to existing masonry structures; however, it gives some indications regarding the monolithic behavior of multi-wythe walls, which could be applied to historical masonry (after proper diagnostics).

Australian Standard AS 3700:2018 [104] also focuses on new structures; however, similarly to the Canadian code, some indications regarding interlocking between wythes are included.

European Standards, Eurocode 6 Design of Masonry Structures [105] does not contain information about existing masonry structures. Some indications regarding historical masonry walls might be found in part 3 of Eurocode 8 (Design of Structures for Earthquake Resistance) [106]. Appendix C of this part recommends the identification of the presence/quality of mortar, the presence of voids, and, in the case of multilayered walls, the identification of the presence, length, and spacing of through-stones. The code does not provide, however, any information about non-destructive methods or how to transfer obtained information into quantitative values for purposes of structural analysis.

Building Italian Code [107] and its accompanying Commentary [108] provide a set of mechanical values for various types of masonry in Italy. For each typology, compressive strength, shear strength, elastic modulus, shear modulus, and specific weight are provided. Besides, for all parameters, minimum and maximum values are provided (excluding specific weight). Furthermore, the code provides corrective factors for some specific features, like good-quality mortar or the presence of through-stones. This standard introduces three levels of knowledge that reflect the degree of diagnostics applied to the structure. The non-destructive tests (GPR, sonic tests, rebound hammer, thermography) are listed as allowable for the second level; however, no specific quantitative information is provided. The levels of knowledge also indicate the value of mechanical parameters – minimal, average, or probabilistic – to be adopted and the safety factors to be utilized.

In Italy, besides the approach given in the national standard, the so-called Masonry Quality Index (MQI) also functions – the first concept of this method was provided in the design code of the Umbria Region in central Italy [109]. Afterward, the approach was refined by Borri *et al.* [110]. This method might be based solely on visual inspections. The outcome is a set of mechanical parameters that is based on the total score of the masonry. Score in turn depends on the evaluation of the presence, partial presence, or absence of specific parameters that define the “rule of the art” in masonry construction. The reliability of the method was experimentally tested and calibrated on various existing wall panels by means of *in situ* destructive tests.

5 Structural assessment methods

After obtaining mechanical parameters, structural analysis can be conducted. At this point, several approaches can be adopted. Significant factors in this case are the loading scenario – static or dynamic (seismic actions) and the type of mechanical performance (in-plane or out-of-plane). Most analytical or semi-analytical methods consider the behavior of macro-panels. Geometry and mechanical properties of each panel are utilized to calculate values such as capacity, elastic, and plastic deformations. The state of stress, proportions, and boundary conditions of masonry panels determine the failure scheme [6,13,14]. In most cases, for the multilayered historical walls, some simplifications are adopted. For example, homogenized properties for the entire cross-section are assumed, or the strength of the weak core is neglected. Furthermore, if there is no reassurance about the effectiveness of connections between wythes, a separated mechanical performance is assumed [4]. However, features like voids, cavities, local degradation, and deterioration are difficult to include quantitatively.

A totally different set of tools is the numerical methods – finite element method, discrete method, distinct method, and mixed methods. A thorough review of each of these methods in the context of structural analysis of historical masonry is undertaken by Ghiassi *et al.* [111]. A different concept of classification was proposed by Daltri *et al.* [112]. Instead of differentiating by numerical methods, the classification was based on strategies in representing the masonry, specifically the interaction of joints and units. Four categories were proposed: BBM, continuum models, macro-element models (MM), and geometry-based models.

In general, with numerical methods and dedicated commercial software, many more features of historical masonry walls can be described mathematically. Namely, crushing in compression and cracking in tension, nonlinear stiffness, hardening, and softening. Furthermore, using contact elements, the limited strength of throughstones can be captured; with adequate modeling techniques, voids and cavities might be represented. A masonry can be described as a whole – macro-modeling or with separated joints and units – meso- or micro-modeling [113]. In the case of macro-modeling, the mechanical parameters are derived either directly from testing [114] or by using homogenization [115]. Homogenization could be subsequently divided into three groups: (a) *a priori* approach [116], (b) step-by-step multiscale approach [117], and (c) adaptive multiscale approach [118]. Frequently, the level of anisotropy and irregularity of historical masonry walls is so high that a direct continuum isotropic approach is the most effective and reasonable approach (Figure 16). Proper constitutive models enable modeling of creep [119]. Capture of various uncertainties and scatter of data is possible by using adequate probabilistic tools and procedures [120]. Hence, numerical models provide significantly more opportunities to utilize data obtained from NDT. The drawbacks of numerical methods include the high skills required from users (mostly professional engineers), the

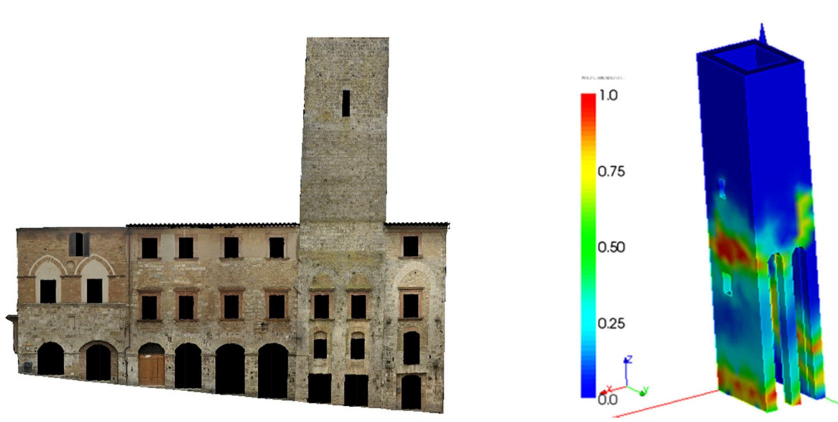

Figure 16: Irregular and various textures of masonry (on the left), results representing the level of damage on a continuum isotropic numerical model (Source: Bartoli *et al.* [121]).

time-consuming preparation of models, limited access to specialized software, and possible convergence issues related to a high level of nonlinearity. Furthermore, even though undeniable progress has been made in terms of numerical modeling strategies for masonry structures, each computational approach exhibits distinctive shortcomings and can be reliably applied to a particular problem (for example, in-plane or out-of-plane loading).

6 Overall discussion

This study covers and analyzes a specific area of structural engineering – precisely, structural evaluation/assessment of historical masonry walls with application of non-destructive methods. Such a defined problem is significant, particularly in the case of historical objects, where interactions with their tissue are restricted, and non-invasive tools are frequently the unique source of data gathering. The layout of the article is deliberately unorthodox. Particularly, four aspects are discussed: features of historical masonry walls, NDT, different building standards, and, finally, assessment methods. While discussing the specificity of historical masonry walls, it was underlined that, besides typical mechanical parameters – compressive strength and elastic modulus, historical walls are characterized by the presence of two or three layers (wythes). Frequently, the core of the wall is of a different structure than the cladding; the core may possess voids and cavities. The high variety in materials and texture was emphasized as well; high heterogeneity and possible weak interlocking between wythes were also indicated. Since the concept of practical outcomes drives the article, the NDT methods were associated with subsequent features of historical masonry walls. In other words, the discussion regarding NDT methods was governed by previously enlisted parameters of masonry. Hence, some of the methods could be recalled a few times. Given the fact that the literature describing the theory and procedures of NDT testing is relatively abundant, for the sake of brevity, these methods are usually not described. As the NDT methods are intended to serve common engineers in everyday practice, an overview of several standards and codes was provided. Particularly, it was analyzed whether the NDT methods are included in standards for the structural assessment of historical masonry walls. Then, the form, detail, and practicality of such inclusion were investigated. Special attention was paid to any quantitative indications, as assessments ultimately rely on numerical outcomes. Finally, the structural assessment methods were presented, both analytical and semi-analytical and numerical. Primarily, numerical methods were investigated as their role in engineering steadily grows; these methods are under constant development, and they also have higher potential to utilize data obtained from various non-destructive tests.

7 Conclusions

The comprehensive analysis of the stated problem led to the following conclusions and remarks.

- Choice and applicability of given NDT methods depend not only on the material considered but also on the type of structural elements and on the type of structural analysis that needs to be conducted. As a matter of fact, it is a general rule concerning any structure that was confirmed within this research.
- The driving factor of structural assessment in the case of historical masonry walls is their peculiar set of features. Namely, in addition to typical parameters regarding modern masonry walls, like compressive strength or stiffness of units and joints, a significant role is played by the geometry, texture, size, and shape of units; the number of wythes, the interlocking between them, and the quality of the central wythe (materials, voids, cavities). Based on this factor, NDT methods should be accordingly adopted. However, beforehand, some of the wall's parameters are unknown. Hence, the choice of testing methods itself might be an iterative process.
- The choice of NDT methods is also strongly dependent on the purpose of the assessment. Namely, different parameters and consequently different testing methods would be needed in the case of in-plane loading schemes, out-of-plane loading schemes, or the evaluation of creep effects. There is always a possibility that all the purposes would have to be considered in parallel.
- The development of codes and standards should take into consideration the current state-of-the-art in the fields of numerical tools and NDT methods. The research demonstrated that even if standards list NDT methods (along with their description and purpose), there is no information regarding the quantitative application of the results and their incorporation into the structural assessment process.
- Besides, many codes, including Eurocode, do not directly address the assessment of existing structures. Also, many of them do not consider the application of NDT methods in the process of data acquisition.
- The already mentioned lack of quantitative indications for NDT in standards and codes comes from the fact that

for these methods, such indications in general rarely exist. In most cases, to correctly interpret NDT output in terms of quantity, some minor-destructive or destructive method would be needed. For instance, sonic wave and GPR methods can identify voids, cavities, or loose materials; however, to convert these data into quantitative results, initial boroscopy or wall opening is necessary for verification and calibration.

- The closest to a stand-alone technique is the utilization of different types of energetic methods (hammer, pendulum, *etc.*) for the assessment of compressive strength. However, an extensive database is needed for interpretation; furthermore, results obtained for joints might depend on the stiffness of units and vice versa.
- Research indicated that one of the most suitable pathways to increase the role of NDT might be the creation of extensive databases and the elaboration of correlation equations and curves. However, to proceed with this concept along with NDT testing, destructive testing should be included (compressive tests, diagonal shear tests, creep tests, *etc.*). Obviously, given the cultural value of discussed structures, such attempts *in situ* on real structures are and would be very rare. Hence, laboratory tests on properly erected specimens (using desired historical materials and techniques) should be conducted. This strategy, on the other hand, requires thorough research programs, which in turn require ample financial resources, probably with collaboration at an international level.
- Most of the demonstrated methods require significant experience, access to correlation curves or datasets, and good judgment. As almost all cited authors indicated, the results are very sensitive and tricky to interpret. Such a situation may lead to erroneous conclusions and decisions in the case of users who are less conscious but are equipped with high-tech instrumentation. Hence, adequate legislative bodies and organizations should provide dedicated workshops, training, or guidelines.
- From the engineering perspective, it is essential to support the development and refinement of easy-to-apply tools like the MQI, which give engineers a clear path to proceed in the assessment process. Significantly, such methods might be based exclusively on archive documentation (if it exists) and visual inspections. The original MQI is developed based on Italian masonry walls; therefore, additional research is needed to tailor this method to different construction techniques in other parts of Europe and the World.
- It should be noted that the development of non-destructive tests should be carried out along with the development of calculation tools and assessment methods. Namely, large sets of specific data, even with a significant level of detail, become useless in the case of a lack of proper and reliable routines that transfer these data into practical applications.

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References

[1] Borri A, Corradi M, Castori G. A method for the analysis and classification of historic masonry. Bull Earthq Eng. 2015;2647–65.
[2] Elnnashai A, Di Sarno L. Fundamentals of earthquake engineering: from source to fragility. 2nd edn. Chichester, West Sussex, England: John Wiley & Sons, Ltd.; 2015.
[3] Scala SA, Del Gaudio C, Verderame GM. Fragility curves derivation for masonry buildings damaged after 2009 L'Aquila earthquake accounting for the effect of construction age. Int J Disaster Risk Sci. 2022;83:103428.
[4] Milani G, Valente M. Failure analysis of seven masonry churches severely damaged during the 2012 Emilia-Romagna (Italy) earthquake: Non-linear dynamic analyses vs conventional static approaches. Eng Fail Anal. 2015;54:13–56.
[5] Acito M, Magrinelli E, Milani G, Tiberti S. Seismic vulnerability of masonry buildings: Numerical insight on damage causes for residential buildings by the 2016 central Italy seismic sequence and evaluation of strengthening techniques. J Build Eng. 2020;28:101081.
[6] Vinci M. Metodi di calcolo e tecniche di consolidamento per edifici in muratura. 3rd edn. Milano, Lombardia, Italia: Dario Flaccovio Editore; 2019.
[7] Roca P. The ISCARSAH guidelines on the analysis, conservation. In 12th International Conference on Structural Analysis of Historical Constructions SAHC 2020. Barcelona: 2020. p. 1629–40.
[8] ICOMOS. The Venice Charter. In 2nd International Congress of Architects and Technicians of Historic Monuments. Venice: 1964.
[9] ICOMOS NZ. Charter for the conservation of places of cultural heritage value. Auckland: The New Zealand National Committee of the International Council on Monuments and Sites; 2010.
[10] Lopez J, Oller S, Oñate E, Lubliner J. A homogeneous constitutive model for masonry. Int J Numer Methods Eng. 1999;1651–71.
[11] Schiavoni M, Giordano E, Roscini F, Clementi F. Numerical modeling of a majestic masonry structure: A comparison of advanced techniques. Eng Fail Anal. 2023;149:107293.

[12] Giordano E, Francesco C, Nespeca A, Lenci S. Damage assessment by numerical modeling of Sant'Agostino's Sanctuary in Offida during the Central Italy 2016–2017 Seismic Sequence. Front Built Environ. 2019;4:87.

[13] Lagomarsino S, Giovinazzi S. Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bull Earthq Eng. 2006;4:415–43.

[14] Penna A, Lagomarsino S, Galasco A. A nonlinear macroelement model for the seismic analysis of masonry buildings. Earthq Eng Struct Dyn. 2014;43:159–79.

[15] Ghezelbash A, D'Altri AM, Sharma S, Lourenço PB, Rots JG, Messali F. A block-based numerical strategy for modeling the dynamic out-of-plane behavior of unreinforced brick masonry walls. Meccanica. 2025;60:2069–105.

[16] Crowley H, Rodrigues D, Silva V, Despotaki V, Martins L, Romao X. The European seismic risk model 2020 (ESRM 2020). EUCENTRE Foundation; 2019. Report No.: EFEHR Technical Report 002.

[17] Anzani A, Cardani G, Condoleo P, Garavaglia E, Saisi A, Tedesch C, et al. Understanding of historical masonry for conservation approaches: the contribution of Prof. Luigia Binda to research advancement. Mater Struct. 2018;51(6):140.

[18] Binda L, Penazzi D, Saisi A. Historic masonry buildings: necessity of a classification of structures and masonries for the adequate choice of analytical models. In VI International symposium computer methods in structural masonry – STRUMAS. Rome; 2003. p. 168–73.

[19] Binda L, Caerdani G, Saisi A. A classification of structures and masonries for the adequate choice of repair. In Workshop Repair Mortars for Historic Masonry. RILEM; 2009. p. 20–34.

[20] de Felice G. Out-of-plane seismic capacity of masonry depending on wall section morphology. Int J Archit Herit. 2011;5:466–82.

[21] Jasieńko J, Bednarz Ł, Misztal W, Raszczuk K. Distribution of compression stress in historical three-leaf stone masonry walls after internal injection. In Proceedings of the 16th International Brick and Block Masonry Conference. Padua; 2016. p. 1653–7.

[22] Vasconcelos G, Lourenço PB. Experimental characterization of stone masonry in shear and compression. Constr Build Mater. 2009;23:3337–45.

[23] Calliari I, Canal E, Cavazzoni S, Lazzarini L. Roman bricks from the Lagoon of Venice: a chemical characterization with methods of mutlivariate analysis. J Cult Herit. 2001;2:23–9.

[24] Calabria JA, Vasconcelos WA, Boccaccini AR. Microstructure and chemical degradation of adobe and clay bricks. Ceram Int. 2009;35:665–71.

[25] Elert K, Cultrone G, Navarro CR, Pardo ES. Durability of bricks used in the conservation of historic buildings – influence of composition and microstructure. J Cult Herit. 2003;4:91–9.

[26] Franzoni E, Gentilini C, Graziani G, Bandini S. Towards the assessment of the shear behaviour of masonry in on-site condtions: a study on dry and salt/water conditioned masonry triplets. Constr Build Mater. 2014;65:405–16.

[27] Larsen PK. The salt decay of medieval bricks at a vault in Brarup Church, Denmark. Env Geol. 2007;52:375–83.

[28] Grubeša N, Teni IM, Krstić H, Vračević M. Influence of freeze/thaw cycles on mechanical and thermal properties of masonry wall and masonry wall materials. Energies. 2019;12(8):1464.

[29] Xia Q, Guo C, Li Y, Liu T, Liu J. Fatigue characteristics of ancient brick masonry under cyclic load. Constr Build Mater. 2023;400:132653.

[30] Binda L, ed. Learning from failure. Long-term behaviour of heavy Masonry Structures. Southampton: WIT PRESS; 2008.

[31] Vintzileou E, Chryssi-Elpida A. Interventions to historic masonries: Investigation of the bond mechanism between stones or bricks and grouts. Mater Struct. 2008;255–67.

[32] Corradi M, Mustafaraj E, Speranzini E. Sustainability considerations in remediation, retrofit, and seismic upgrading of historic masonry structures. Environ Sci Pollut Res. 2023;25274–86.

[33] Apostolopoulou M, Aggelakopoulou E, Siouta L, Bakolas A, Douvika M, Asteris P, et al. A methodological approach for the selection of compatible and performable restoration mortars in seismic hazard areas. Constr Build Mater. 2017;155:1–14.

[34] Lezzerini M, Legnaioli S, Lorenzetti G, Palleschi V, Tamponi M. Characterization of historical mortars from the bell tower of St. Nicholas church (Pisa, Italy). Constr Build Mater. 2014;69:203–12.

[35] Yaseen IAB, Al-Amoush H, A-Farajat M, Mayyas A. Petrography and mineralogy of Roman mortars from buildings of the ancient city of Jerash, Jordan. Constr Build Mater. 2013;38:465–71.

[36] Riccardi MP, Lezzerini M, Carò F, Franzini M, Messiga B. Microtextural and microchemical studies of hydraulic ancient mortars: Two analytical approaches to understand pre-industrial technology processes. J Cult Herit. 2007;8:350–60.

[37] Gleize PJP, Motta EV, Silva DA, Roman HR. Characterization of historical mortars from Santa Catarina (Brazil). Cem Concr Compos. 2009;31(5):342–6.

[38] Peulić D. Konstruktivni elementi zgrada Zagreb: Tehnička knjiga; 1976.

[39] Szabó S, Funri MF, Lourenço PB. Masonry patterns' influence on the damage assessment of URM walls: Current and future trends. Dev Built Env. 2023;13:100119.

[40] Rovero J, Alecci V, Mechelli J, Tonietti U, de Stefano M. Masonry walls with irregular texture of L'Aquila (Italy) seismic area: validation of a method for the evaluation of masonry quality. Mater Struct. 2016;49:2297–314.

[41] Van Gemert D, Vos P, Ignouls S. Collapse and reconstruction of the tower of the St Willibrordus Church at Meldert Lummen. Restor Build Monum. 2014;20:3–24.

[42] Bothara J, Brzev S. A tutorial: Improving the seismic performance of stone masonry buildings. 1st edn. Oakland, CA, USA: Earthquake Engineering Research Institute; 2011.

[43] Vlachakis G, Vlachaki E, Lourenço PB. Learning from failure: Damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece). Eng Fail Anal. 2020;117:104803.

[44] Van Gemert D, Ignoul S, Brosens K, Toumbakari EE. Consolidation and strengthening of historical masonry by means of mineral grouts: Grout development. Restor Build Monum. 2015;21:29–45.

[45] Sorrentino L, Cattari S, da Porto F, Magenes G, Penna A. Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. Bull Earthq Eng. 2019;17:5583–607.

[46] Thelin K, Balksten K, Host F. Collapse and rebuilding of a medieval city wall – an assessment of the structure and material. In SAHC2014 – 9th International Conference on Structural Analysis of Historical Constructions. Mexico City; 2014.

[47] Binda L, Pina-Henriques J, Anzani A, Fontana A, Lourenço PB. A contribution for the understanding of load-transfer mechanisms in multi-leaf masonry walls: Testing and modelling. Eng Struct. 2006;28:1132–48.

[48] Valluzzi MR, da Porto F, Modena C. Behaviour and modelling of strengthened three-leaf stone masonry walls. Mater Struct. 2004;37:184–92.

[49] Ferreira TM, Costa AA, Arêde A. Experimental characterization of the out-of-plane performance of regular stone masonry walls, including test setups and axial load influence. Bull Earthq Eng. 2015;13:2667–92.
[50] Meimaroglou N, Mouzakis H. Mechanical properties of three-leaf masonry walls constructed with natural stones and mud mortar. Eng Struct. 2018;172:869–76.
[51] Boscato G, de Carvalho Bello CB, Cecchi A. Multi-leaf masonry walls: Load transfer mechanisms sensitivity to mechanic and geometric parameters. Structures. 2021;31:540–57.
[52] Corradi M, Borri A, Poverello E, Castori G. The use of transverse connectors as reinforcement of multi-leaf walls. Mater Struct. 2017;50:113–26.
[53] Binda L, Maierhofer C. Strategies for the assessment of historic masonry structures. In RILEM/NSF International Engineering Research and Education Workshop “In-situ Evaluation of Masonry and Wood Historic Structures: Challenges and Opportunities”. Prague: 2006. p. 37–56.
[54] Yildizlar B, Sayin B, Akcay C. A case study on the restoration of a historical masonry building based on field studies and laboratory analyses. Int J Archit Herit. 2019;14:1341–59.
[55] Colla C. In situ investigation of the mechanical strength of the mortars: the case of the vaults of the Modena Cathedral. Key Eng Mater. 2014;624:170–7.
[56] Pelà L, Roca PR, Aprile A. Combined in-situ and laboratory minor destructive testing of historical mortars. Int J Archit Herit. 2017;12:334–49.
[57] Gambilongo L, Barontini A, Silva R, Lourenco PB. Evaluation of non-destructive techniques for mechanical characterisation of earth-based mortars in masonry joints. Constr Build Mater. 2023;392:131960.
[58] Standardization ECf. BS EN 12504-2:2021 Testing concrete in structures Non-destructive testing. Brussels; 2021.
[59] Dagrain F, Descamps T, Scaillet JC. The scratching test, an alternative technique for determining strength properties of historical mortars. In HMC 08 1st Historical Mortars Conferenc. Lisbon; 2008.
[60] Žalský J, Vokác M, Hrabánek M, Hurtig K. Development of a new nondestructive method for the in-situ determination of mortar strength. Buildings. 2023;13:273–84.
[61] Bosiljkov V, Maierhofer C, Koepp C, Wöstmann J. Assessment of structure through non-destructive tests (NDT) and minor destructive tests (MDT) investigation: Case study of the church at Carthusian Monastery at Žiče (SLOVENIA). Int J Archit Herit. 2009;4:1–15.
[62] Livitsanos G, Shetty N, Verstrynge E, Wevers M, Van Hemelrijck D, Aggelis DG. Shear failure characterization in masonry components made with different mortars based on combined NDT methods. Constr Build Mater. 2019;220:690–700.
[63] Gorzelańczyk T, Schabowicz K. Use of nondestructive test methods to determine the thickness and compressive strength of unilaterally accessible concrete components of building. Open Eng. 2025;15(1):20240100.
[64] Kržan M, Gostič S, Cattari S, Bosiljkov V. Acquiring reference parameters of masonry for the structural performance analysis of historical buildings. Bull Earthq Eng. 2015;13:203–36.
[65] Borosnyoi-Crawley D. Non-destructive strength estimation of vintage clay bricks based on rebound hardness in architectural heritage buildings. J Build Eng. 2023;80:108055.
[66] Cristofaro MT, Viti S, Tanganelli M. New predictive models to evaluate concrete compressive strength using the SonReb method. J Build Eng. 2020;27:100962.
[67] Cabané A, Seneschal T, Roca P, Pelà L. Non-destructive evaluation of solid fired clay brick strength using the SonReb method. Constr Build Mater. 2025;485:141919.
[68] Gomez-Heras M, Benavente D, Pla C, Javier MM, Fort R, Brotons V. Ultrasonic pulse velocity as a way of improving uniaxial compressive strength estimations from Leeb hardness measurements. Constr Build Mater. 2020;261:119996.
[69] Gunes Yilmaz N, Goktan RM. Comparison and combination of two NDT methods with implications for compressive strength evaluation of selected masonry and building stones. Bull Eng Geol Environ. 2019;78:4493–503.
[70] Avorio A, Borri A, Corradi M. Ricerche per la ricostruzione. Iniziative di carattere tecnico e scientifico a supporto della ricostruzione Roma. DEI s.r.l.; 2002.
[71] Ida N, Meyendorf N. Handbook of advanced nondestructive evaluation. Cham, Switzerland: Springer Nature Switzerland AG; 2019.
[72] James B. Acoustics and ultrasonic waves: Fundamentals and applications. New York: Murphy & Moore Publishing; 2023.
[73] Ryan C. Industrial ultrasonic inspection: Levels 1, 2, & 3. 4th edn. Victoria, BC, Canada: Friesen Press; 2017.
[74] Miranda LF, Rio J, Miranda GJ, Costa A. Sonic impact method – A new technique for characterization of stone masonry walls. Constr Build Mater. 2012;36:27–35.
[75] Miranda L, Cantini L, Guedes J, Costa A. Assessment of mechanical properties of full-scale masonry panels through sonic methods. Comparison with mechanical destructive tests. Struct Control Health Monit. 2016;23:503–16.
[76] Martinez-Soto F, Avila F, Puertas E, Gallego R. Spectral analysis of surface waves for non-destructive evaluation of historic masonry buildings. J Cult Herit. 2021;52:31–7.
[77] Vasanelli E, Micelli F, Colangiuli D, Calia A, Aiello MA. A non destructive testing method for masonry by using UPV and cross validation procedure. Mater Struct. 2020;53(6):134.
[78] Van Eldere H, Ramos LF, Verstrynge E, Shetty N, Van Balen K, Barroso CE, et al. The application of sonic testing on double-leaf historical portuguese masonry to obtain morphology and mechanical properties. In Structural Analysis of Historical Constructions RILEM. Cham, Switzerland: Springer International Publishing AG; 2019. p. 661–8.
[79] Tomaszewska A, Drozdowska M, Szymczak C. Vibration-based investigation of a historic bell tower to understand the occurrence of damage. Int J Archit Herit. 2022;16:1063–75.
[80] Tomaszewska A, Drozdowska M, Szafrański M. Material parameters identification of historic lighthouse based on operational modal analysis. Materials. 2020;13(17):3814.
[81] Gentile C, Saisi A. Operational modal testing of historic structures at different levels of excitation. Constr Build Mater. 2013;48:1273–85.
[82] Valluzzi MR, Cescatti E, Cardani G, Cantini LZL, Colla C, Casarin F. Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls. Constr Build Mater. 2018;192:272–86.
[83] Binda L, Saisi C, Tirabosch S, Valle S, Cola C, Forde M. Application of sonic and radar tests on the piers and walls of the Cathedral of Noto. Constr Build Mater. 2003;17:613–27.
[84] Binda L, Tiraboschi C, Baronio G. On-site investigation on the remains of the Cathedral of Noto. Constr Build Mater. 2003;17:543–55.

[85] Sadri A. Application of impact-echo technique in diagnoses and repair of stone masonry structures. NDT E Int. 2003;36:195–202.
[86] Frąckiewicz P, Raszczuk K, Jasieńko J. Areas of GPR application in researches of historical masonry structures. J Herit Conserv. 2025;81:27–42.
[87] Frąckiewicz P, Raszczuk K, Jasieńko J. Identification of alternations in the structure of historical masonry walls using the GPR method accompanied with architectural survey in the former Piast Gymnasium in Brzeg. Civ Environ Eng Rep. 2024;34:32–42.
[88] Palieraki V, Vintzileou E, Miltiadou-Fezans A, Delinikolas N. The use of radar techniques and boroscopy in investigating old masonry: The case of Dafni Monastery. Int J Archit Herit. 2011;2:155–86.
[89] Grzyb K, Drobiec Ł, Zając J, Drobiec K. Preliminary assessment of structural masonry damage in Malbork Castle. Case Stud Constr Mater. 2025;22:e04166.
[90] Abu Zeid N, Balducci M, Bartocci F, Regni R, Santarato G. Indirect estimation of injected mortar volume in historical walls using the electrical resistivity tomography. J Cult Herit. 2010;11:220–7.
[91] Uranjek M, Bokan-Bosiljkov V. Influence of freeze–thaw cycles on mechanical properties of historical brick masonry. Constr Build Mater. 2015;84:416–28.
[92] Chen X, Qi XB, Zhao-Yi X. Determination of weathered degree and mechanical properties of stone relics with ultrasonic CT: A case study of an ancient stone bridge in China. J Cult Herit. 2020;42:131–8.
[93] Biscarini C, Catapano I, Cavalagli N, Ludeno G, Pepe FA, Ubertini F. UAV photogrammetry, infrared thermography and GPR for enhancing structural and material degradation evaluation of the Roman masonry bridge of Ponte Lucano in Italy. NDT E Int. 2020;115:102287.
[94] Binda L, Gatti G, Mangano G, Poggi C, Sacchi Landrini G. The collapse of the Civic Tower of Pavia: a survey of the materials and structure. Mason Int. 1992;6:11–20.
[95] Fradeletto A. Il campanile di San Marco riedificato. Studi, ricerche, relazioni, ed. Comune di Venezia Venezia: Carlo Ferrari; 1912.
[96] Verstrynge E, Schueremans L, Van Gemert D, Wevers M. Monitoring and predicting masonry's creep failure with the acoustic emission technique. NDT E Int. 2009;42:518–23.
[97] NZSEE. The seismic assessment of existing buildings: Assessment objectives and principles. Technical Guidelines for Engineering Assessments. Wellington, New Zealand; 2017.
[98] NZSEE. Section C8 – Seismic assessment of unreinforced masonry buildings, The seismic assessment of existing buildings: Technical guidelines for engineering assessment; 2017.
[99] American Society of Civil Engineers. ASCE/SEI 41-13. Reston; 2013.
[100] Applied Technology Council ATC-43. FEMA 306 Evaluation of earthquake damaged concrete and masonry wall buildings. Basic Procedures Manual. Washington, D.C.: Federal Emergency Management Agency; 1998.
[101] Applied Technology Council. Evaluation of Earthquake damaged concrete and masonry wall buildingsTechnical resources. Washington, D.C.: Federal Emergency Management Agency; 1998.
[102] Applied Technology Council. Repair of earthquake damaged concrete and masonry wall buildings. Washington, D.C.: Federal Emergency Management Agency; 1998.
[103] Canadian Standard Association. CSA-S304.1-14. Desing of Masony Structures. Mississauga; 2019.
[104] Standards Australia. AS 3700:2018. Masonry Structures. BD-004; 2018.
[105] CEN. EN 1996-1-1, Eurocode 6: Design of masonry Structures, Part 1-1. Brussels; 2005.
[106] CEN. EN 1998-3, Eurocode 8: Design of Structures for Earthquake Resistance, Part 3: Assessment. Brussels; 2005.
[107] Ministero delle Infrastrutture e dei Trasporti. NTC 2018, Norme Tecniche per le Costruzioni, D.M. 17 January 2018; 2018.
[108] Ministero delle Infrastrutture e dei Trasporti. Circolare n. 7 del 21 gennaio 2019. Roma; 2019.
[109] Regione dell'Umbria. Norme tecniche per la progettazione degli interventi e la realizzazione delle opere di cui alla L.R. 23.10.2002 no. 18 finalizzate alla riduzione della vulnerabilità sismica; 2003.
[110] Borri A, De Maria A. L'indice di Qualità Muraria (IQM): Evoluzione ed Applicazione nell'Ambito delle Norme Tecniche per le Costruzioni del 2008. In 13th Italian National Conference for Earthquake Engineering. Bologna: 2009.
[111] Ghiassi B, Milani G. Numerical modeling of Masonry and historical structures. Duxford: Woodhead Publishing. Elsevier; 2019.
[112] D'Altri AM, Sarhosis V, Milani G, Rots J, Cattari S, Lagomarsino S, et al. Modeling strategies for the computational analysis of unreinforced Masonry structures: Review and classification. Arch Comput Methods Eng. 2020;27:1153–85.
[113] Theodossopoulos D, Sinha B. A review of analytical methods in the current design processes and assessment of performance of masonry structures. Constr Build Mater. 2013;41:990–1001.
[114] Brignola A, Frumento S, Lagomarsino S, Podesta S. Identification of shear parameters of Masonry panels through the in-situ diagonal compression test. Int J Archit Herit. 2009;3:52–73.
[115] Sacco E, Addessi D, Sab K. New trends in mechanics of masonry. Meccanica. 2018;53:1565–9.
[116] Anthoine A. Derivation of the in-plane elastic characteristics of masonry through homogenization theory. Int J Solids Struct. 1995;32:137–63.
[117] Milani G, Lourenco PB. Homogenised limit analysis of masonry walls. Part II: structural examples. Comput Struct. 2006;43:166–80.
[118] Talirecio A. Closed-form expressions for the macroscopic in-plane elastic and creep coefficients of brick masonry. Int J Solids Struct. 2014;51:2949–63.
[119] Verstrynge E, Schueremans L, Van Gemert D, Hendriks MAN. Modelling and analysis of time-dependent behaviour of historical masonry under high stress levels. Eng Struct. 2011;33:210–7.
[120] Avila F, Esther P, Gallego R. Probabilistic reliability assessment of existing masonry buildings: The church of San Justo y Pastor. Eng Struct. 2020;223:111160.
[121] Bartoli G, Betti M, Vignoli A. A numerical study on seismic risk assessment of historic masonry towers: a case study in San Gimignano. Bull Earthq Eng. 2016;14:1475–518.