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Non- and Semi-Destructive Assessment Methods Used in Croatia After Recent Earthquakes

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Abstract
In recent years, countries around the world have had devastating consequences from seismic events. This includes Croatia, which was hit by strong earthquakes in 2020. After the rapid assessments to determine if it was safe to stay in the damaged buildings, it was time for more detailed assessments. Different approaches were used depending on the level of reconstruction; from simple calculations and purely visual inspections for lower levels to more complex numerical models and design methods accompanied by in-situ testing for higher levels. The paper lists the most common non-destructive (NDT) and semi-destructive (SDT) methods used in post-earthquake assessment in Croatia. They are described and supplemented with photographs and test results from real case studies. The advantages and disadvantages of the mentioned methods are also presented. Finally, conclusions are drawn and recommendations are given for an appropriate and effective combination of different in-situ tests for post-earthquake assessment.
Keywords: Existing Structures; Croatia; Earthquake; NDT; SDT.

1. Introduction

Seismic events can have devastating consequences. In recent years, many cities and countries around the world have felt their enormous force. This includes Croatia, which was hit by two strong earthquakes. This was preceded by a long period of low seismic activity. For this reason, earthquake awareness was not at an adequate level and many were taken by surprise. The first earthquake occurred in March 2020 in the capital city of Zagreb, and the second nine months later near the town of Petrinja. The first had a magnitude of $M_L = 5.5$ ($M_w = 5.4$), and the second had a magnitude of $M_L = 6.2$ ($M_w = 6.4$) (*Croatian Seismological Survey*, n.d.). They caused significant damage to the structures and infrastructure, which are classified in detail in (Stepinac et al., 2021). Rapid assessments began the very next morning to determine if it was safe to remain in the damaged buildings (Uroš et al., 2021). After the rapid assessments, it was time to conduct more detailed assessments. Different approaches were taken depending on the chosen level of reconstruction. From simple calculations and purely visual inspections for the lower levels to more complex numerical models and design methods, accompanied by in-situ tests for the higher levels of reconstruction. Although more modern confined masonry buildings suffer almost no damage, existing unreinforced masonry (URM) buildings have been severely affected (Figure 1) by recent earthquakes (Miranda et al., 2021). Existing structures have often exceeded their design life span and have suffered some form of damage from minor earthquakes, soil settlements or various unprofessional reconstructions. Some of the buildings were constructed prior to the first seismic codes and therefore have inherent design deficiencies. In addition, the materials have deteriorated over time, especially in the parts of the building that are not protected from the elements (Amen & Nia, 2021, Aziz Amen & Nia, 2018), so their mechanical properties have been severely compromised. Also, URM buildings are known for their deficiencies such as low tensile and shear strength, inadequate wall-to-wall and wall-to-floor connections, as well as large mass and stiffness. They are also sensitive to irregularities in floor plan and elevation (Salaman et al., 2022, Aziz Amen, 2017). To determine the degree of seismic resistance of the existing structure, the structural system, dimensions and quality of materials must be determined. If the information from the existing project documentation is not sufficient for the analysis, extensive research on the mechanical parameters must be conducted. Knowledge of the mechanical properties of the load-bearing elements is important for high-quality restoration. Therefore, the in-situ testing methods used after the recent earthquakes in Croatia are presented. The paper is organized into four parts. The first chapter provides an overview of the recent events and the inherent deficiencies of the existing building stock. The second chapter presents the most common non-destructive and semi-destructive in-situ testing methods used in post-earthquake assessment in Croatia. In the third chapter, the presented in-situ testing methods are discussed based on the experience gained from recent earthquakes in Croatia and useful combinations of methods for the quality assessment process are presented. Finally, the last chapter summarizes the most important parts of the paper. Other less commonly used non-destructive and semi-destructive methods, as well as destructive in-situ methods such as the diagonal compression test (Borri et al., 2011, Amen & Kuzovic, 2018) or the in-situ removal of large samples for laboratory testing, are not discussed here. Given that timber roof structures are also an important part of existing structures, they also need to be inspected and tested. They also have some intrinsic design-specific deficiencies and vulnerabilities related to exposure to moisture and lack of maintenance over time. The NDT and SDT methods for timber floor and roof structures are not part of this paper, but a similar topic has already been discussed in detail in (Perković et al., 2021).

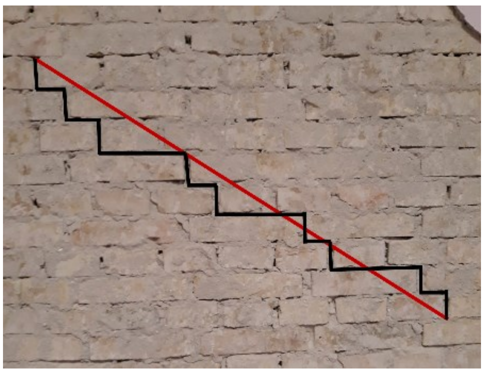
Figure 1. Sacral structure after earthquakes in Croatia

2. In-situ test methods

In-situ test methods are used to evaluate the mechanical properties of load-bearing elements, which allows better assessment of the seismic behaviour of existing structures. Each method has its own characteristics, advantages and disadvantages, and it is important to know how and when to use the appropriate methods depending on the requirements, which vary from structure to structure. There are non-destructive, semi-destructive and destructive testing methods. Destructive testing is often avoided because it is more costly in terms of money and time and leaves significant damage to the structure. Such tests are not suitable for smaller houses and especially for heritage buildings. Therefore, non-destructive and semi-destructive methods are most commonly used to better understand the current condition and typology of the structure. Different methods are used for structures built of different materials. However, here the focus is on the structure's characteristic of the continental part of Croatia. These structures are mostly URM or confined masonry with flexible timber floors or reinforced concrete (RC) floors. Next, non-destructive and semi-destructive methods of different destructive power and complexity are presented, which are most commonly used in post-earthquake reconstruction in Croatia. They are intertwined and combined depending on the damage level, the type of structure and the required level of assessment.

2.1. Visual inspection (MQI)

The masonry quality index (MQI) method is used to estimate the mechanical properties of URM walls such as compressive strength, modulus of elasticity and initial shear strength. In addition, the method is calibrated using large-scale tests (Borri et al., 2018) and has been further developed to account for the disaggregation of irregular or rubble stone masonry (Borri et al., 2020). The initial estimate is fast and useful for a first assessment, but the reported range of mechanical properties is significant and more extensive tests are often required. The obtained results can also be used for comparison with the results of more destructive and precise testing methods. Seven parameters are used in the method, including the state of preservation and mechanical properties of stone/brick (SM), the dimensions of stone/brick (SD), the shape of stone/brick (SS), the connection of wall leaves (WC), the characteristics of the horizontal bed joint (HJ), the characteristics of the vertical joint (VJ) shown in Figure 2a and the mechanical properties of the mortar (MC). The final MQI index is obtained by adding the last six parameters and multiplying by the first parameter (SM). According to the result of the MQI index which can range from 0.5 to 10, the mechanical properties can be read from the table shown in Figure 2b. The method is described in more detail in (Borri et al., 2015).



MQI(V)	$f_{m,min}$	$f_{m,max}$	E_{min}	E_{max}	**MQI**(I)	$\tau_{0,min}$	$\tau_{0,max}$
0,5	1,05	1,86	598	891	0,5	0,021	0,033
1	1,17	2,06	652	967	1	0,024	0,037
1,5	1,31	2,27	712	1049	1,5	0,027	0,041
2	1,46	2,51	776	1139	2	0,030	0,046
2,5	1,64	2,78	847	1236	2,5	0,033	0,050
3	1,83	3,07	924	1341	3	0,037	0,056
3,5	2,05	3,39	1007	1455	3,5	0,040	0,061
4	2,29	3,74	1099	1579	4	0,045	0,067

a) b)

Figure 2. MQI method: a) determination of the VJ parameter, b) table with the mechanical parameters

2.2. Flat-jack method

The method has its roots in geomechanical engineering, but has been modified since the 1980s and is widely used in the assessment of masonry structures. The method has three different setups that determine the vertical stress state (Figure 3a), modulus of elasticity (Figure 3b) and shear strength of the masonry (Figure 3c) (Lulić et al., 2022). Since these are valuable parameters for the calibration of the numerical model and the design, this method is beneficial for the assessment of URM buildings (Gregorczyk & Lourenco, 2000). The method is based on the principle of stress transfer from the flat-jack to the masonry. As a result, the masonry is deformed and the displacements are measured. The analysis of the measured data provides us with the mentioned parameters. Before the actual test, the flat-jacks must be calibrated to determine the pressure loss due to their deformation. The tests can be performed according to the American (ASTM, 2003) or international guidelines (RILEM, 2004). The flat-jack method is described in more detail in (Lulić, Stepinac, Bartolac, et al., 2023) and the results of an extensive post-earthquake test campaign are presented in (Stepinac et al., 2023).

a) b) c)

Figure 3. Flat-jack test setup for: a) vertical stress state, b) modulus of elasticity, c) shear strength

2.3. Shear test

Shear characterization of masonry is undoubtedly one of the most important procedures. Since masonry most often fails in shear, determining shear strength with a high degree of reliability is of great importance. Although the shear test does not reflect the actual shear strength of the entire masonry panel, due to the size effect, it is a good assumption considering that the wall is only slightly damaged in this type of test. Of course, further testing is needed to confirm the claim, but previous tests have shown that the local shear test gives a higher value for shear strength than the value obtained from testing the entire masonry panel (ASTM, 2003). An undamaged brick is selected for the test, and its longer side must be parallel to the wall. For this reason, the test cannot be performed on a wall with a header bond or on an irregular wall. Then openings are made in front of the brick for a small hydraulic jack and behind the brick to have room for movement. The resulting shear strength is the force in the hydraulic jack at the time of brick failure divided by the corresponding areas $A_1 + A_2$. The advantage of this test is that little damage is done to the walls, it is a relatively quick test, and a larger number of tests can be performed on the structure. This gives a good representation of the quality of the masonry throughout the structure (Krolo et al., 2021). On the other hand, the disadvantage is that we do not have information about the vertical stress state at the test location. This is very important considering that shear strength depends on vertical stress. Vertical stresses can later be determined analytically by a load analysis or extracted from a numerical model.

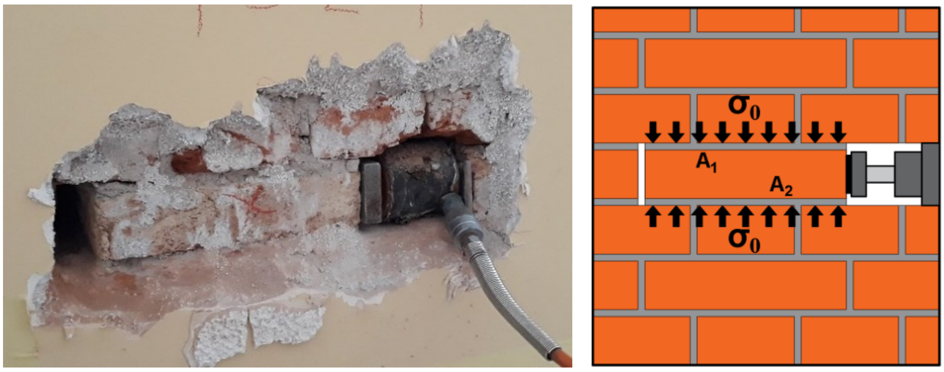
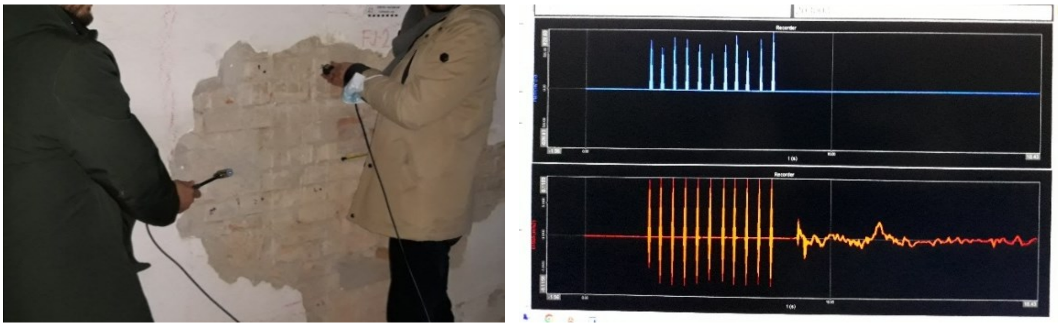


Figure 4. Shear test setup

2.4. Sonic and ultrasonic methods

Sonic and ultrasonic tests can be used to evaluate the elastic properties of existing masonry structures. Their main advantage is that they are non-destructive and the test is performed relatively quickly compared to other methods. This makes them particularly valuable in the investigation of heritage buildings, since the goal is to disturb the original structure as little as possible. The difference between the sonic and ultrasonic methods lies in the excitation frequency. High-frequency ultrasonic waves are more suitable for homogeneous materials such as stone or concrete, because in masonry such waves are quickly attenuated due to the presence of discontinuities. Low-frequency sonic waves, on the other hand, easily penetrate through heterogeneous material, even old or damaged masonry. For this reason, the sonic method is more suitable for the mechanical characterization of existing masonry (Lulić, Stepinac, Ožić, et al., 2023). Figure 5a shows the sonic test. It is performed with a hammer, an accelerometer and a data acquisition system. The hammer has the function of an emitter and is used to initiate a low-frequency signal by lightly hitting the masonry. At a certain distance, the accelerometer acts as a reciever and records the initiated signal. Figure 5b shows the collected raw data, i.e., the moments of signal initiation and detection, from which the time taken for the signal to travel from the emitter to the receiver is obtained. From the distance between the emitter and the receiver and the signal travel time, the signal propagation speed is obtained. Furthermore, we can correlate the obtained velocity with the dynamic modulus of elasticity of the masonry, a valuable dynamic parameter of the structure that is important for further seismic analysis. The methodology of the sonic pulse velocity test is explained in more detail in (Ortega et al., 2022) and is complemented by the results, which are also compared with the results of the flat-jack test.



a) b)

Figure 5. Sonic test: a) measurement, b) recorded data

2.5. Ground penetrating radar and profometer

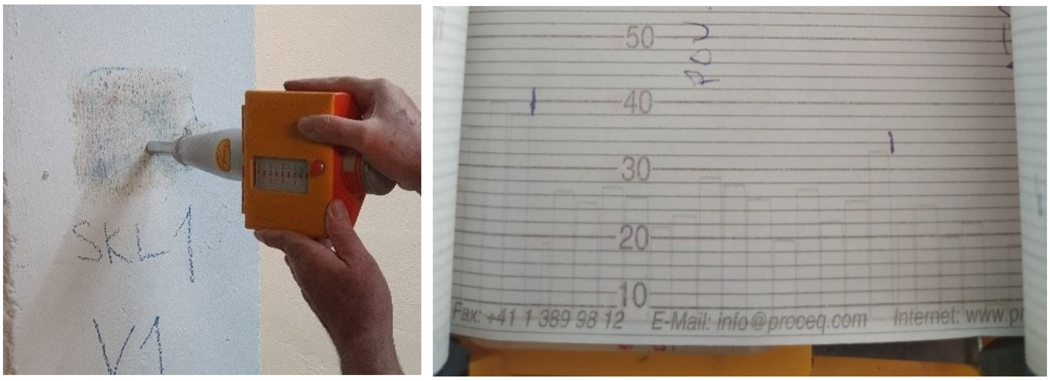
The ground penetrating radar (GPR) and profometer shown in Figure 6 are NDT methods. They are used to determine the thickness of the concrete cover layer, the distribution and amount of reinforcement, and to detect the geometry and position of other structural elements that are not visible, such as layers of vaults and other floor structures and voids in walls. The principle of the tests is based on the emission of electromagnetic waves, which are reflected by the structure and detected again by the integrated antenna. The profometer has a range of about 10 cm, while the GPR can reach up to 60-80 cm in depth, depending on the model. The test is performed by moving the instruments along a predefined line along or across the observed element. In this way, it is possible to examine large areas quickly and easily. The test results are presented in the form of a black and white radargram (Figure 6c), which is a two-dimensional reconstruction of the reflected waves along the line of motion of the instrument. The peaks of the curves represent the arrangement of the reinforcement, while their intervals represent the spacing of the reinforcement (Tešić et al., 2021a). In addition, the GPR can also evaluate the probability of reinforcement corrosion in a concrete element (Tešić et al., 2021b).

a) b) c)

Figure 6. NDT for reinforcement detection: a) GPR, b) profometer, c) radargram

2.6. Rebound hammer

The rebound hammer, also known as Schmidt's hammer, is a widely used non-destructive method for determining the compressive strength of RC elements. The strength is determined indirectly by the hardness of the concrete surface by striking it with a spring-loaded device. Therefore, it is necessary to first remove the finish layers of plaster and smooth the surface of the concrete before the actual test can be performed. The test is based on the elastic rebound of a metal ball. The greater the rebound, the greater the hardness of the concrete and thus the compressive strength of the concrete. The value of the compressive strength is determined from the calibration curves given in the standards using the results obtained for the rebound (Ivanchev, 2022). The method is subject to certain uncertainties, such as the lack of experience and skill of the operator, the small test area, the presence of moisture and the sensitivity to local imperfections of the concrete surface. Due to the aforementioned potential shortcomings, there is a possibility that the surface will not provide representative results for the entire cross-section of the element. On the other hand, the speed, simplicity and non-destructive nature of the test make the method very useful for assessing the current condition of RC elements (Brencich et al., 2020). Overall, the rebound hammer can be a useful method, but it is necessary to try to reduce the uncertainties as much as possible and to combine it with the other methods mentioned.



a) b)

Figure 7. Rebound hammer test: a) application, b) recorded data

2.7. Concrete samples

Concrete core samples can be taken from all concrete elements. Figures 8a and b show core removal from an RC beam and column, and figure 8c testing of the sample. In addition to this test, a rebound hammer test can be performed to compare the results obtained to increase precision. This is a more destructive test than the rebound hammer test, but it is useful to perform it because the compressive strength is determined directly by a destructive test in the laboratory, whereas the strength in the rebound hammer is determined indirectly by the hardness of the surface, which may not be representative of the deeper parts of the cross section. The cores have a cylindrical shape and may have different dimensions depending on the standard. The test requires a special diamond drill bit with water cooling and the ability to attach it to a wall/beam. The sample must be cut to a predefined length, weighed and prepared for a laboratory test. The location of the hole should be in a part of the cross section where high compressive stresses are not expected and where there is no reinforcement. Certain test conditions, such as damage caused by drilling and the size of the core sample itself, can significantly affect the results. These differences can be as high as 20% (Brencich et al., 2021).

a) b) c)

Figure 8. Concrete specimen: a) drilling, b) residual hole, c) cylindrical specimen

2.8. Inspection of the reinforcement

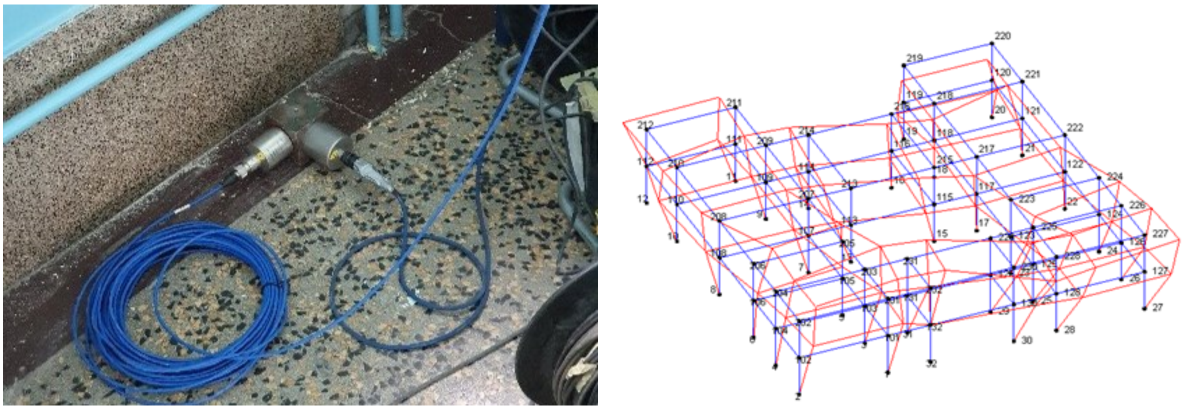
Verification of the quality, type, integrity and quantity of existing steel reinforcement is of great importance in determining the load-bearing capacity of the RC element if there is no associated project documentation. Reinforcement can be traced using the GPR method mentioned above, but such equipment is often unavailable or financially unviable for a small number of tests. Reinforcement inspection involves the destroying and removing a section of concrete to expose the reinforcement. To determine the reinforcement, it is not necessary to demolish the entire section, but it is sufficient to remove the concrete cover layer on a part of the element with a power tool. As a result, we get the diameter and spacing of the longitudinal and transverse reinforcement and see whether the reinforcement is smooth or ribbed. For the other side, symmetrical reinforcement is assumed.

a) b)

Figure 9. Removal of concrete cover in: a) beam, b) column

2.9. Operational modal analysis

Operational modal analysis (OMA) is used to characterise the dynamic parameters of a structure (Ereiz et al., 2021). These include natural frequencies, vibration modes and damping coefficients. The dynamic parameters obtained are essential for calibrating the numerical models used to perform seismic analyses (D'Ambrisi et al., 2012). Accelerometers, shown in Figure 10a, distributed throughout the structure and a data acquisition system are used for the measurement. Operational modal analysis uses excitations from the environment such as wind, seismic and traffic excitations. Such an approach is much more practical for large structures. The second type of analysis, called experimental modal analysis, would require expensive and large equipment for the purpose of controlled excitation of the structure (Damjanović et al., 2018). In OMA, the mentioned excitations are assumed to have a stochastic character with a wide frequency range. Therefore, the structure will be excited by all frequencies, and the dominant response of the structure will be at its own natural frequencies. The only thing to be careful of is that there are no harmonic excitations from sources such as various machines, generators and the like, as these can cause misinterpretation of the results. The data of the OMA test before and after the earthquake may indicate a deterioration of the global stiffness of the structure in a certain direction, which is a consequence of the damage to the load-bearing elements. Similarly, by repeating the test after the retrofit, the effectiveness of the strengthening and its influence on the global stiffness can be determined. Figure 10b shows one of the results of the operational modal analysis in terms of the obtained mode shape.



a) b)

Figure 10. OMA: a) accelerometers, b) obtained mode shape

2.10. Inspection of the floor structure

Inspection of the layers of the floor structure and its connection with the walls is useful from several aspects (Ortega et al., 2018). In addition to determining the actual thickness of the floor, it also identifies the layers that affect the load analysis. Also, an inspection of the condition of the structure is performed at the same time to determine, for example, if the timber beams are rotten due to moisture or termites. The inspection is usually performed from above for vaults or timber beams, while for ribbed RC structures, the inspection must also be performed from below. At the same time, the strength and modulus of elasticity of concrete and timber beams can be determined with a rebound hammer, ultrasound or by taking a sample and testing it in the laboratory.

a) b)

Figure 11. Inspection of floor structure: a) from above, b) from below

2.11. Other methods

Other valuable in-situ testing methods frequently used in post-earthquake assessment in Croatia include the pendulum mortar hammer, videoboroscopy, determination of the compressive strength of bricks, detailed study of existing documentation and examination of finish layers of the structure. The pendulum hammer works on the same energy principle as the rebound hammer for concrete. It is used to indirectly determine mortar quality and can be correlated to the compressive strength of the mortar through calibration with a destructive test. Its non-destructive natur, simplicity, low cost and speed of testing make it a valuable tool in the assessment of masonry structures (Stepinac et al., 2020). Videoboroscopy is a visual method that provides insight into the internal morphology of masonry that is not easily accessible. Such inspection is suitable in combination with semi-destructive tests, which include in their procedure the drilling or cutting of openings in the masonry. It can also be used to confirm the results of non-destructive methods such as sonic testing. For example, if the results of sonic test show low sonic velocities at some locations in the wall that could be due to voids, this can be confirmed with videoboroscopy (Binda et al., 2004). The determination of the compressive strength of bricks is performed in the laboratory on prepared specimens according to the guidelines of the European standard. The bricks are removed from the structure, the existing mortar is removed and a thin layer of cement mortar is applied to create a flat surface. The specimens are allowed to mature for 14 days at a controlled temperature and relative humidity. The crushing force of the brick is divided by the surface area of the brick to obtain the compressive strength (Krolo et al., 2021). Existing documentation of old buildings is often lost or non-existent. In this case, it is necessary to create new digital documentation and study in detail the connection, geometry and material properties of the structure. If the existing project documentation is available, the level of knowledge about the structure itself is higher and thus the uncertainties in all further analyses are reduced. For cultural heritage buildings, an important aspect of renovation is the restoration of the original condition. Therefore, it is necessary to examine all the final layers of the wall as they have changed over the years. This examination is not essential for the seismic safety of the structure, but it is carried out as part of the architects' investigation work. Figure 12e shows a typical result of the mentioned procedure.

a) b) c) d) e)

Figure 12. Other methods: a) pendulum hammer, b) videoboroscopy, c) compression test, d) review of existing documentation, e) plaster composition

3. Discussion

Given that the earthquake-affected areas in Croatia are currently undergoing major renovation, there is a great need for an assessment of these buildings. In order for this process to be comprehensive, certain in-situ tests are required to determine the current, deteriorated and damaged condition of the mechanical properties of load-bearing elements. In-situ tests require certain financial resources and time, which temporarily drives up costs and slows down the reconstruction process itself. In the long run, however, they increase accuracy and safety and reduce overall costs by avoiding unnecessary excessive strengthening of the structure. The first and most important step in evaluating the current condition and performance of the existing structure is certainly to analyse the existing documentation and characterize the resulting damage. Appropriate repair and strengthening measures, regardless of the extent of in-situ testing, are difficult to determine without understanding the behavior of the structure, the initiated failure mechanisms and the resulting damage. After a detailed analysis of the behavior of the structure based on experience and the resulting damage, further investigation required for the design phase can begin in the form of in-situ testing. The mechanical properties are important input parameters that significantly influence further assessment (Hafner et al., 2022; Lulić et al., 2021) and the strengthening process (Kišiček et al., 2020; Moretić et al., 2022), and therefore must be performed in accordance with the required renovation levels. For example, for a low level of renovation, it is recommended to use non-destructive, fast and simple methods such as the rebound hammer and the MQI method. For a medium level of renovation, in addition to the methods mentioned for a low level of renovation, methods such as shear testing, sonic testing, and floor structure inspection can be used. At a high level of renovation, more complex and destructive methods are used to characterize the mechanical properties of the structure. These include flat-jack testing, operational modal analysis, reinforcement inspection (destructive or with GPR), concrete sampling, and of course all the other previously mentioned methods used for lower levels of renovation. For heritage structures, special care must be taken in the choice of in-situ testing methods because of the need to interfere as little as possible with the existing structure. For example, GPR has a great advantage in evaluating cultural heritage buildings when destructive testing is to be avoided and unseen objects are to be detected below the surface. In addition to established methods, new advanced technologies such as laser scanners, drones, BIM and new materials are constantly being developed that make the assessment and seismic strengthening of existing structures more time- and cost-efficient while achieving sufficient seismic resistance (Stepinac et al., 2022). Finally, cultural heritage preservation (Formisano & Marzo, 2017; Milić et al., 2021; Modena et al., 2011) and energy retrofitting of buildings (Milovanović et al., 2022; Requena-Garcia-Cruz et al., 2022) should be integral parts of the strengthening process as well.

4. Conclusions

This paper highlights the importance of assessment procedures with the aim of a high-quality and time-appropriate process of maintenance and strengthening of the existing building stock, whose vulnerability increases over time as their stability and resistance decrease due to various external influences, especially earthquakes. The main conclusions can be summarized as follows:

- Due to the large number of vulnerable existing masonry structures in earthquake-prone areas in Europe and the world, there is a great need for high quality and detailed assessment.
- In-situ testing methods are essential for a comprehensive characterization of the mechanical properties and for understanding the seismic behavior of a structure.

- The scope and combinations of non-destructive and semi-destructive methods should be carefully considered in advance, depending on the level of restoration required.
- In addition to the necessary structural strengthening, it is also important to simultaneously consider and implement sustainable energy renovation and heritage preservation.

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Conflict of Interests

The authors declare no conflict of interest.

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