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Correlation between sonic pulse velocity and flat-jack tests for the estimation of the elastic properties of unreinforced brick masonry: Case studies from Croatia

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ABSTRACT

Historic urban cores in southern Europe are characterized by a significant number of existing unreinforced masonry structures that are known for their seismic vulnerability. The first step in the preservation of such damaged buildings is condition assessment and characterization of the mechanical properties of the masonry, which can be achieved using non-destructive, semi-destructive and destructive methods. In this paper, the emphasis is on determining the modulus of elasticity of unreinforced masonry through flat-jack and sonic pulse velocity tests. Both methods are explained in detail and results from eight different case studies are presented. The results are compared and correlations among the techniques are observed, showing that both methods can be suitable for estimating the elastic properties of existing masonry. The paper provides a wide set of experimental data that has been made available. Finally, a sensitivity analysis was performed. Differences between static and dynamic modulus of elasticity and operational and practicability issues regarding on-site testing are discussed.

1. Introduction

Southern Europe was recently struck by a series of seismic events that caused severe damage to the masonry building stock in Italy [1,2], Albania [3], Greece [4], Turkey [5] and Croatia [6]. As masonry buildings are highly vulnerable to seismic excitations, the earthquakes caused great damage to historical urban cores of the affected areas. This paper focuses on the 2020 seismic events in Croatia where post-earthquake assessments and renovation of damaged buildings are currently in progress [7–9].

The first step in the preservation of damaged buildings is structural condition assessment and characterization of the mechanical properties of materials, e.g., masonry. There are numerous methods for the structural assessment of existing masonry structures, which can be roughly divided into non-destructive, semi-destructive and destructive methods based on the level of invasiveness. These methods provide information on the mechanical properties such as modulus of elasticity, shear modulus [10,11], shear and compressive strengths that are crucial for the proper modeling of existing masonry structures. Even though there are important

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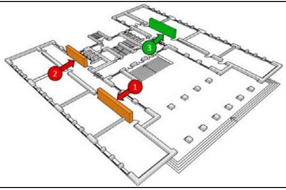
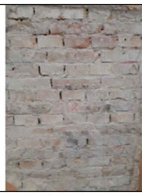
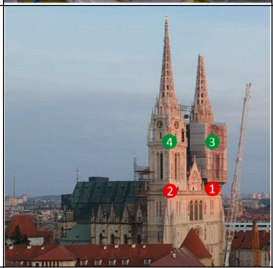
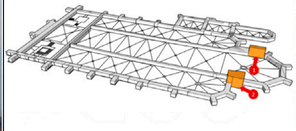
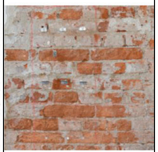
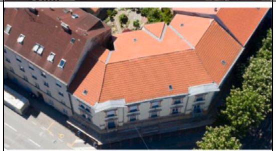
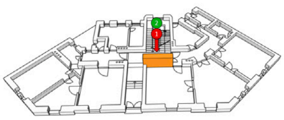
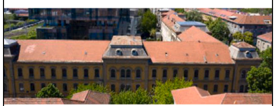
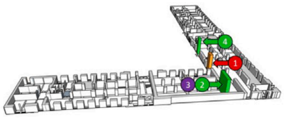
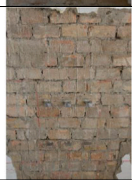
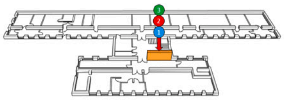
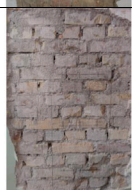
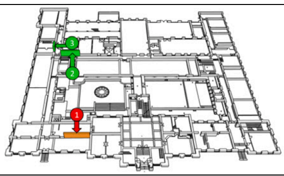
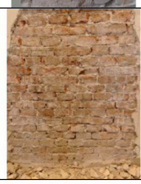
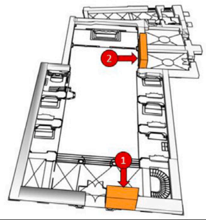
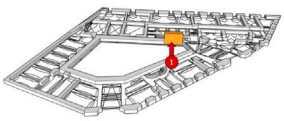
Table 1
Case studies basic information.

No.	Name	Building	Floor plan with test locations	Masonry typology	Wall thickness [cm]	Year of construction	Area [m²]
1.	Gymnasium Sisak				60	1930	3600
2.	Zagreb Cathedral				200-300	13th century – 1897	2200
3.	Deželićeva building				60	1897	1200
4.	Tobacco factory				80-100	1882	7000
5.	Hospital Sisak				45-60	1952	3100
6.	Museum of Arts and Crafts				50-60	1888	12000
7.	St. Catherine Church				105-125	1729	800
8.	The State Archives				100	1798	3200

*tested walls are shown slightly taller and colored.
**test positions are shown with an arrow and number, colour of the numbers represents the floors (basement – blue, ground floor – brown, 1st floor – green, 2nd floor – purple).

research efforts for the validation of in-situ testing for the mechanical characterization of masonry (e.g., [12–18]), there are still numerous questions regarding the applicability of non-destructive tests on different masonry typologies, the data processing techniques and the accuracy of the results.

In this paper, the emphasis is on determining the modulus of elasticity of existing brick masonry through sonic pulse velocity tests (mentioned hereafter as *sonic tests*). This is a non-destructive method that is based on the propagation of sonic waves through the tested medium. Even though sonic tests in masonry structures have been more frequently applied for qualitative purposes such as assessing the state of the material, the presence of voids or the effectiveness of an intervention [19–21], they have the potential to provide a quantitative estimation of the elastic properties [22–27]. The results of the sonic tests were compared with those of standard flat-jack tests. The investigation of possible correlations between non-destructive and semi-destructive tests is of great importance as it would encourage the use of less destructive and more reliable assessment methods for existing masonry structures. This would be particularly beneficial to cultural heritage buildings. The paper provides a large set of experimental data in the Croatian context that shows positive correlations between the two techniques.

An extensive in-situ test campaign [28] was developed to prepare the data set for the comparison between sonic and flat-jack tests. A total of 22 tests were conducted on eight case study buildings. Flat-jack tests were carried out in accordance with ASTM guidelines [29–31] and RILEM [32–34] standards. Sonic tests were subsequently performed at the same locations. The paper first introduces the case study buildings on which tests were performed and then focuses on the experimental campaign. The comparison of the two testing methods and possible correlations among the results are subsequently discussed. The paper concludes with a discussion on the advantages, applicability and practicability of the two testing methods and the limitations of the study.

2. Case studies

Croatia's traditional building stock, just like most of the European countries, has a large number of unreinforced masonry (URM) structures. Buildings with the status of cultural heritage are mostly for public use, so the assessment and conservation of such buildings are extremely important, not only due to the preservation of the cultural identity but also due to high occupancy load. The traditional building stock is primarily URM structures with wooden floors and roofs [35].

The case study buildings are situated in the Croatian cities of Zagreb and Sisak, which were affected by two earthquakes in 2020. Tests were performed on a total of eight buildings mostly on walls located at the ground and first floors. All buildings except a hospital in Sisak are under heritage protection and are a part of the Register of Cultural Heritage of the Republic of Croatia. All the buildings have an irregular floor plan and the load-bearing structural system is most often a combination of unreinforced masonry walls with masonry vaults or flexible timber floors. The roof structure is also made of timber. Apart from the hospital, which was built with solid clay bricks of the normal format 250x120x65 mm, other buildings were built with solid clay bricks of the old format 290x140x65 mm in lime mortar. Tests are performed at a height of about 0.5–1.0 m above the floor to facilitate drilling and measuring. All tested walls were plastered so environmental and time-dependent deterioration was partially reduced. Core testing and endoscopy were not part of this study, but homogeneous wall composition can be assumed (i.e., no core made of a different material). According to [36], the accuracy of the flat-jack test may be affected by the thickness of the wall. Although the flat-jack test does not perfectly represent the entire cross-section of walls with large thickness, it provides a good approximation of the mechanical properties of such masonry. Table 1 provides additional information for each of the case study buildings. The condition and quality of the masonry texture are also listed in Table 1.

3. Flat-jack and sonic investigations

3.1. Flat-jack method

A minor-destructive testing method using flat-jacks provides useful insights into the mechanical properties of existing masonry. Using single flat-jack test, the state of vertical stress in the masonry can be determined. On the other hand, the double flat-jack test allows the values of the modulus of elasticity to be determined. Furthermore, an additional third jack can be used to determine the shear strength of the masonry. In this paper, the focus is on the application of the double flat-jack test, which is a well-known testing methodology for masonry. The test principles and mechanics have already been described in detail in the relevant literature [37–39]. The method is based on the principle similar to a standard compressive test performed on an existing masonry structure. It allows the evaluation of the mechanical properties of the investigated structural element by analyzing its stress-strain behavior.

The displacement variation required for further evaluation of the deformation were measured using displacement sensors or LVDTs (linear variable differential transformers). Although RILEM [33] and ASTM [30] recommend four measuring devices, they also allow the use of three. Due to the size of the brick and the distance between the flat-jack valves, it is often difficult to implement even three devices. Also, an obstacle to the installation of additional devices is the age and degradation of the brick's properties, which make drilling and adhesion difficult. Due to all the mentioned reasons and the greater efficiency of performing a large number of tests, it was decided to use three measuring devices. The response of the three displacement sensors was generally such that the middle sensor had the highest value and the two edge sensors had a similar value but less than the middle one. Such an answer is expected considering that the flat-jack has a curved deformation line and is most deformed in the middle. However, such a response was not always recorded. In some cases, one edge sensor measured the highest displacement. This can happen due to imperfections in the masonry itself or small imperfections during the creation of openings for flat-jacks. Other researchers have also used three vertical measuring devices for flat-jack tests [40] or even two in each perpendicular direction for new experimental test configurations [41]. When aiming to determine the Poisson's ratio and shear modulus, an additional horizontal measuring device should be used during the double flat-jack test. For the same reasons mentioned earlier and since those parameters were not the focus of this research, a horizontal measuring device was not used in the present research.

Before the test itself, it is necessary to determine the geometric and stiffness properties of each flat-jack. This is done through the calibration process in an accredited laboratory following the guidelines from the ASTM standard [30]. In this way, the partial stress loss caused by the deformation of the flat-jack is taken into account. At the test site, it is necessary to determine the load-bearing wall that is suitable for testing using engineering judgement. Then the slots for flat-jacks are made in the wall. A semi-oval flat jack was used in all the tests and an eccentric circular saw was used for cutting the slots. The slot area varies slightly with each test and affects the results. Therefore, it is important to determine its dimensions precisely in order to obtain the ratio of the gross area of the flat-jack to the area of the slot. This parameter is required for the evaluation of one of the non-dimensional constants required by the standards for the calculation of the modulus of elasticity. The dimensions of the slots were measured using a laser scanner (Fig. 1), which significantly speeds up and improves the test quality itself. An alternative is to measure the depth of the slot every 10–20 mm and sum up the area of the measured strips. This method proved to be unreliable and was abandoned.

In the first part of the test, the state of vertical stress is measured using a single flat-jack. Three pairs of metal measuring points are fixed vertically above and below the mortar joint in the wall where the slot is cut. The initial distance of these points is recorded with portable extensometers. Then a slot is cut in the horizontal mortar joint, which causes the masonry to relax and deform. The distance of the measuring points is measured again to record the displacement. A flat-jack is inserted into the slot and the pressure is gradually increased. After each increase in pressure, the change in displacement is monitored. The pressure (corrected with the previously mentioned coefficients) required to return the displacement to the initial position, i.e. to zero, represents the state of vertical stress in the masonry.

Next, the deformation properties (i.e. modulus of elasticity) of the masonry are measured using the double flat-jack test. Above the previously used flat-jack, a second slot is made for another flat-jack. The section of masonry between the two flat-jacks is under uniform vertical stress, and this stress can be controlled with flat-jacks. Three LVDTs are placed between the flat-jacks. Before the test, it is necessary to first pressurize the flat-jacks in the wall to adjust them in the slot. This pressure should not exceed half the expected strength of the masonry. The pressure is then reduced to zero and then increased in small increments, while at the same time data is collected to evaluate the deformation of the masonry in accordance with the increasing load. Usually, the maximum stress level did not exceed the value of 1 MPa to avoid damaging the masonry. The way in which the level of stress and plastic deformation was monitored was the observation of the tangent modulus. A sudden change in slope indicates that the masonry is going into a plastic area where cracks can occur. The data is processed and a stress-strain diagram and modulus of elasticity are obtained. The exact geometric specifications of the test site shown in Fig. 2 are explained in detail in [30]. Finally, the shear strength is measured by adding a third horizontal jack. It must be noted that the vertical stress state test and shear strength test are not part of this paper and can be found described in more detail in [29,31,42,43].

The determination of the actual modulus of elasticity is of great importance for the estimation of the stiffness of the structure and to get a better understanding of the seismic behavior of the building. For this reason, these types of in-situ tests are important. On the

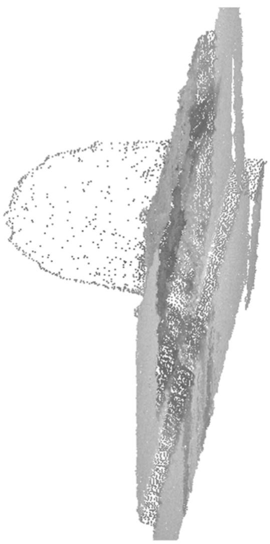


Fig. 1. Point cloud of the drilled hole in the wall.

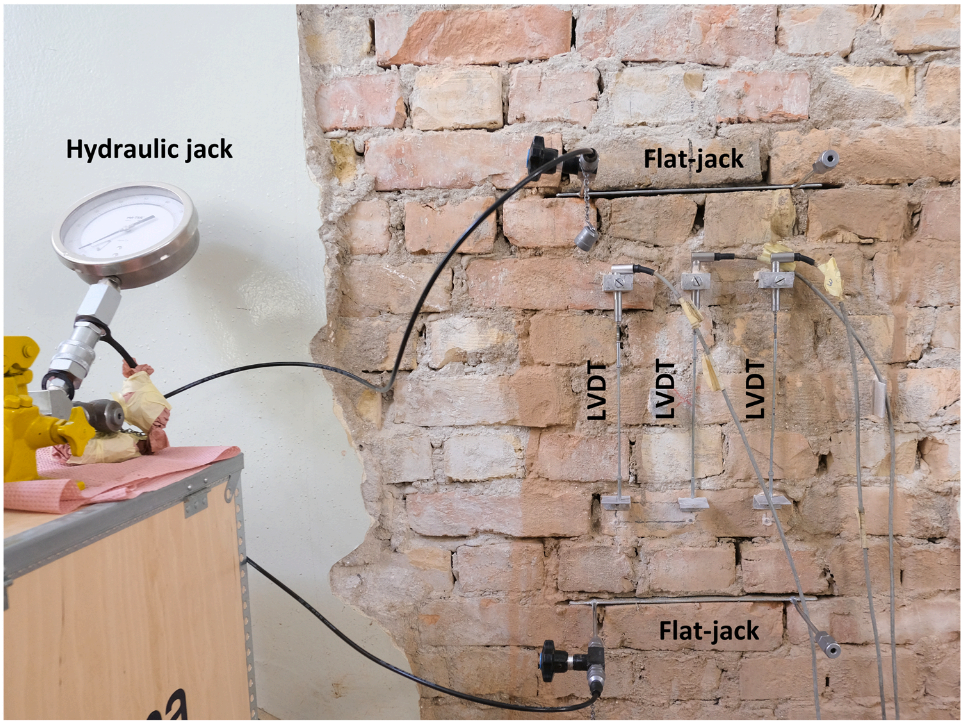


Fig. 2. Test setup for the computation of the elastic modulus using flat-jack tests.

other hand, if in-situ tests are not performed and the values recommended in the literature are used, the structure may be under designed or overdesigned and often invasively strengthened, which is not consistent with the principles of economic efficiency and sustainability.

Flat-jack test results from 8 buildings and 22 test sites are shown below. The data obtained was processed following the guidelines of the ASTM standard [30]. The results are presented graphically for each case study separately in Fig. 3 and a summary is given in Table 2 with mean values, standard deviation and coefficients of variation. The values of modulus of elasticity shown are determined as the slope of a linear regression line of the obtained values from the double flat-jack test. Strain at any point was obtained by dividing the measured displacement by the length of the sensor and calculating the mean value for all three sensors. Stress in masonry between flat-jacks at any point was obtained by multiplying the pressure in the flat-jacks with the dimensionless flat-jack constants obtained by calibration and a factor that takes into account the ratio of the area of the flat-jack to the slot area. Each flat-jack has its own calibration coefficient and each slot has its own surface area ratio coefficient. These coefficients usually vary between 0.75 and 0.80 and 0.85–0.90, respectively.

3.2. Sonic tests

The sonic test is a non-destructive method that can provide a qualitative assessment of existing masonry, based on the introduction of mechanical energy into the construction material using a hitting device (e.g. instrumented hammer). The propagation of the mechanical energy through the material consists mainly of elastic waves [44]. The hitting device thus introduces acoustic waves of low frequency into the material that travel through the material and are received by a receiver (e.g. an accelerometer) located on another point of the solid. In this way, it is possible to measure the travel time of the wave through the solid. The propagation velocity of the elastic wave is calculated by dividing the distance between the hitting device and the accelerometer by the travel time.

The application of sonic tests for the evaluation and diagnosis of masonry structures started in the 1980s [45–47] and arose due to the previously mentioned limitation of ultrasonic waves in penetrating heterogeneous materials like masonry, where high frequency waves rapidly attenuate when going through discontinuities [48,49]. The lower frequencies generated by the impact of a hammer or a similar hitting device allow the waves to penetrate deeper into the material even though they offer a lower resolution, because of the longer wavelengths being larger than inner heterogeneities, e.g. micro cracking at the mortar joints. The technique is easy to perform, requires simple instrumentation, is fully non-destructive and allows the characterization of the elastic wave motions that propagate through the material: compressional (P) waves, shear (S) waves, and surface Rayleigh (R) wave. The sonic test thus proved to be a powerful method to measure the elastic waves propagation velocity within different masonry elements and eventually became one of the most widely used Non-Destructive Technique (NDT) for the evaluation of historical masonry structures [19] However, it was mainly applied in qualitative terms, aiming to characterize the masonry cross-section [20,50–53] or evaluate the effectiveness of repair interventions on masonry elements, specifically grout injections [15,21,54].

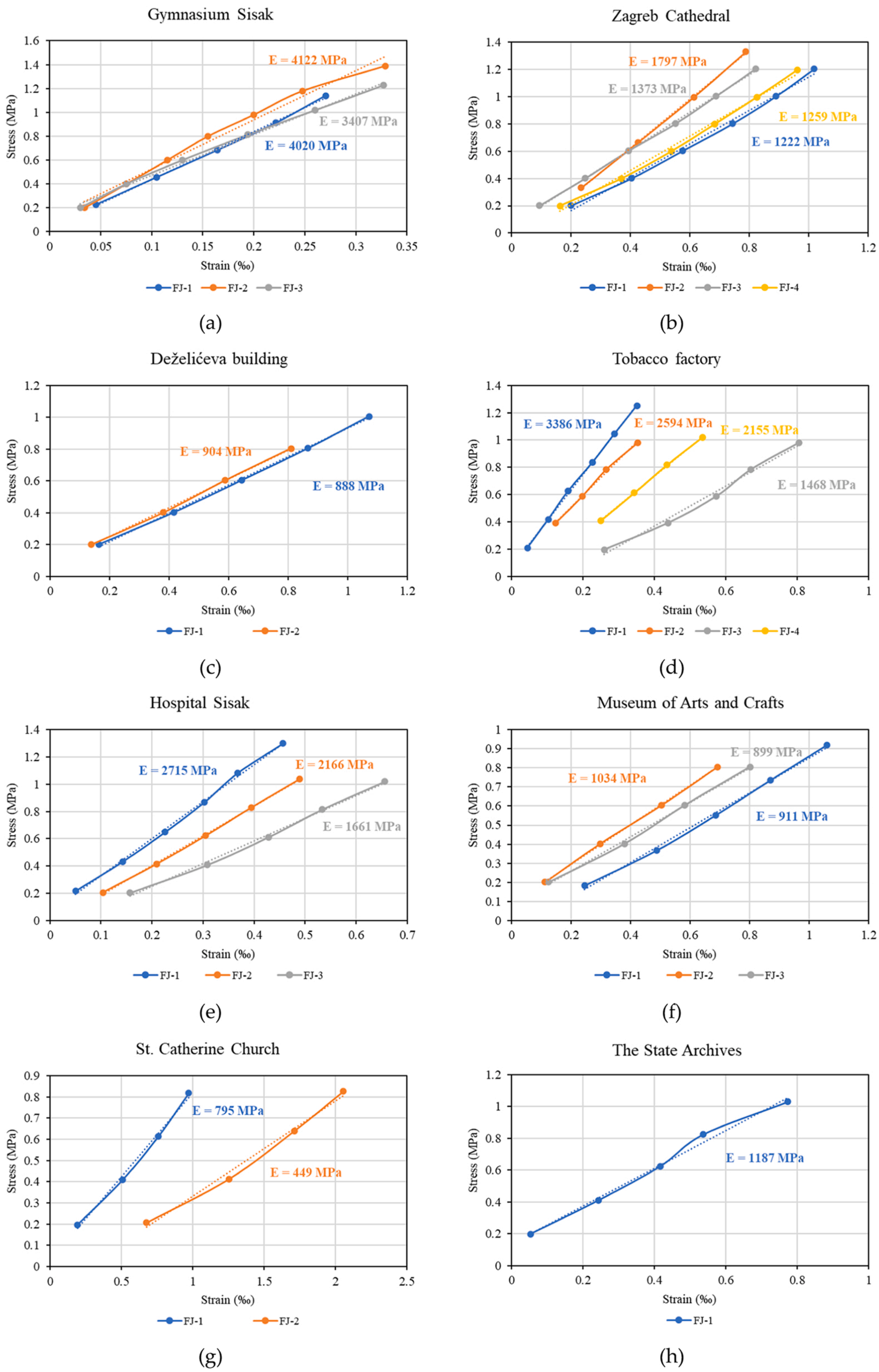


Fig. 3. Flat-jack test results for each case study in terms of calculated modulus of elasticity (MPa).

Table 2
Flat-jack tests results summary.

No.	Building	Floor	Test site	Modulus of elasticity [MPa]	Mean value [MPa]	St. dev. S [MPa]	CoV [%]
1.	Gymnasium Sisak	Ground	FJ-1	4020	3849.7	386.7	10.0
			FJ-2	4122			
		1st	FJ-3	3407			
2.	Zagreb Cathedral	Roof	FJ-1	1222	1412.8	263.0	17.1
			FJ-2	1797			
			FJ-3	1373			
			FJ-4	1259			
3.	Deželićeva building	Ground	FJ-1	888	896.0	11.3	1.3
		1st	FJ-2	904			
4.	Tobacco factory	Ground	FJ-1	3386	2400.8	803.8	33.5
		1st	FJ-2	2594			
		2nd	FJ-3	1468			
		1st	FJ-4	2155			
5.	Hospital Sisak	Basement	FJ-1	2715	2180.7	527.2	24.2
		Ground	FJ-2	2166			
		1st	FJ-3	1661			
6.	Museum of Arts and Crafts	Ground	FJ-1	911	948.0	74.7	7.9
		1st	FJ-2	1034			
			FJ-3	899			
7.	St. Catherine Church	Ground	FJ-1	795	621.5	245.4	39.5
			FJ-2	448			
8.	The State Archives	Ground	FJ-1	1187	1187.0	-	-

Particularly interesting in structural engineering terms is the fact that the propagation velocity of the elastic waves through the material is correlated with its mechanical properties, namely the density (ρ), the dynamic modulus of elasticity (E_d) and the Poisson's ratio (ν). There is a RILEM standard to estimate the sonic pulse velocity for masonry [55] but its scope is the qualitative evaluation of the masonry, e.g. locate flaws or voids. The physical principle is the same that applies to another non-destructive method that is well established in several international standards for the inspection of concrete elements: the Ultrasonic Pulse Velocity (UPV) test [56,57]. It is also based on the measurement of the travel time of elastic waves that, in this case, are emitted and received by ultrasonic transducers (i.e. transducers with a significantly higher frequency of the mechanical vibrations emitted, typically superior to 20 kHz). The UPV test standard is applicable to measure the dynamic modulus of elasticity of concrete (E_d) because of the abovementioned relationship between wave velocity and elastic properties of the material. Nevertheless, the penetration capacity of acoustic waves depends on their frequency. Ultrasonic waves cannot penetrate heterogeneous materials with many interfaces and voids, such as stone and brick masonry. For this, sonic lower frequencies are necessary when the thickness or attenuation of the material does not allow the propagation of ultrasonic waves.

The proposed research aims to investigate the capability of sonic tests to estimate its elastic mechanical properties through their correlation with the propagation velocity of an elastic wave. The use of acoustic test methods to determine the elastic properties of the media under investigation is based on the fundamental physics of the elasticity of materials. The relationship between the wave velocities (e.g. P-wave velocity, V_P) and the dynamic modulus of elasticity (E_d) is described as:

$$V_P = \sqrt{\frac{E_d}{\rho}\frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)}} \tag{1}$$

where ρ is the density of the material and υ is the Poisson's ratio. It is noted that these expressions are originally developed for solid, elastic, isotropic and homogeneous materials, which is not the case of masonry. Local conditions, voids and the differences between masonry components may affect the local velocity measurements while having little influence on the modulus of elasticity. Therefore, the expressions demand further investigation and data on the use of sonic testing to characterize heterogeneous materials like masonry are needed and may lead to the calibration of the expression, as occurs for concrete [58–60].

Moreover, sonic tests provide an estimation of the dynamic modulus of elasticity, which cannot be directly compared with the values of static modulus of elasticity that are obtained from the flat-jack tests. There is a theoretical inequality between static and dynamic modulus of elasticity of the masonry and its components [61], but specific correlations do not exist. These are difficult to determine because they may vary significantly for each masonry typology, which raises the need for calibration on a case-by-case basis. Recent works have performed sonic tests in parallel to experimental campaigns involving laboratory mechanical compression tests [22,24,62] or in-situ campaigns involving flat-jack tests [16,63], which allowed to compare the results and validate the capability of sonic tests. This is also the approach selected in the present research work, which also explores the relationship between the static modulus of elasticity obtained from a flat-jack testing campaign with the dynamic modulus of elasticity obtained from sonic tests for the specific brick masonry typology under study. Performing flat-jack test in a few locations allows obtaining an estimation of the static modulus of elasticity and, subsequently, extract correlations between the static modulus and the dynamic one estimated by the sonic tests, which can be carried faster, causing less damage and covering a larger number of elements throughout the inspected structure. This shows the great potential of the technique to estimate the mechanical properties of historical masonry in a non-invasive manner, but still requires further research and experimental testing to consolidate and validate the method.

There are two main types of transmission methods that are typically used when performing a sonic test: direct and indirect (Fig. 4). Direct tests consist of aligning the hitting device with the accelerometer in two opposite surfaces of the investigated element. For indirect tests, the hitting device and accelerometer are placed on the same surface of the construction element (Fig. 4a). The latter is the most appropriate configuration to adopt when the objective is to estimate the elastic properties of the masonry because it allows to estimate the properties for different loading directions, which, in the case of masonry, an anisotropic material, can be important. For example, when testing a masonry wall, the test should be done in the vertical direction, allowing to evaluate the vertical load bearing properties. Moreover, this is also a convenient configuration for on-site measurements because many times there is no access to opposite surfaces of the construction element.

The common testing apparatus used for the sonic test consists of a hitting device (e.g. instrumented hammer), a transducer able to record the mechanical response on the material (e.g. accelerometer), a data acquisition system (DAQ), a computer and connecting cables. In the present research work, a PCB instrumented hammer (model 086D05) with a measurement range of ± 22,240 N pk was used. The receiving transducer is a PCB accelerometer (model 393B12) with a measurement range of ± 0.5 g and a sensitivity of 10 V/g (± 5 %). The data acquisition system is a DEWE-43A from Dewesoft. The sampling frequency is 200 kHz to allow for a detailed recognition of the arrival time of the wave. Fig. 4b and c show some photographs of the test being carried on-site. Essentially, three persons are required to operate the hammer, accelerometer and computer.

3.2.1. *Sonic test data post-processing*

The propagation velocity of the elastic wave under investigation, which is the longitudinal stress wave or primary wave (V_P), is calculated by dividing the distance between the hitting device and the accelerometer (L) by the travel time (dt):

$$V_P = \frac{\mathbf{L}}{dt} \tag{2}$$

The travel path distance (L) is defined as the distance between emitter and receiver. This is a necessary conservative assumption given the uncertainty in estimating the real travel path of the wave. Therefore, to further reduce uncertainties in the calculation, the errors in the determination of the travel time should be minimum. Typically, the interpretation of the results of sonic tests is still done manually and is thus highly dependent on the operator, which can lead to a large scatter in the results [64].

The travel time is measured by detecting the arrival of the primary wave, which is considered to be the first disturbance in time domain above a given threshold. Nevertheless, there are different criteria of defining the exact arrival time of the sonic wave, e.g., first deflection, first zero crossing, major first peak, maximum amplitude of the envelope, etc. The present research estimates the arrival time of the wave front by detecting the first apparent deviation (first deflection) from the horizontal axis, using a threshold criterion defined next. This is the most common approach observed in the literature and practice for the inspection of concrete and masonry structures with ultrasonic and sonic testing [27,64–67].

(a) (b) (c)

Fig. 4. (a) Typical indirect sonic test transmission method; and (b,c) on-site application of sonic tests.

In the present work, the random errors associated with the identification of the arrival time of the wave are minimized using an automated procedure for the data processing, which is similar to other automated procedures proposed by other authors in the literature [64,66]. The procedure is based on establishing a variable acceleration threshold that depends on the distribution of the white noise in the signal, following a statistical approach, instead of using an ad hoc acceleration threshold for the estimation of the arrival time. The procedure analyzes the distribution of the white noise with data recorded by the accelerometer before the hammer hits and determines the mean and standard deviation. Then, a threshold value can be established as a factor of the standard deviation. Additionally, a number of consecutive observations that exceed the threshold is also defined to avoid possible single outliers, increasing the robustness of the algorithm. The threshold value adopted for the present research work is equal to two times the standard deviation of the white noise and the number of consecutive observations is five. The suggested automated approach can reduce the uncertainties and inherent subjectivity related to the human factor and increase the test's reliability. Moreover, it greatly reduces the post-processing time typically employed when the signals are processed manually.

3.2.2. Sonic test results

Sonic tests were performed in all buildings described in Table 1. Taking advantage of the previous works carried out to perform the flat-jack tests (e.g. plaster removal), we performed sonic tests at the exact same locations (Fig. 5). Note that the removal of the plaster was important because indirect sonic tests should be carried out by placing the emitter and the receiver directly on the masonry surface. Otherwise, depending on the characteristics of the plaster (e.g. if the wave propagation velocity through the plaster is higher than the one through the masonry), the identified waves could travel through the plaster instead of the masonry. The sonic tests were carried out months after the flat-jack tests, avoiding locations with visible disruption (cracks or missing bricks). For example, tests in the location shown in Fig. 5a were carried out in the bottom area and, similarly, in the bottom right area at the location shown in Fig. 5b.

In each location where a flat-jack test was carried out, several sonic tests were performed. The indirect sonic tests were carried out in the vertical direction (orthogonal to the mortar bed joints) to assess the modulus of elasticity along the vertical axis, which is the same direction of the load applied during the flat-jack tests. At least, two sonic tests were carried out in various locations of each tested wall section, with an average of 4–5 tests per location. The distance between the emitter and the receiver typically varied between 0.5 and 1 m. The criterion to select the distance was based on the expected velocity (500–1000 m/s) and frequency of the sonic pulse (700–1000 Hz). The dimensions of the test area were selected to be within the range of the wavelengths of the emitted sonic waves (pulse velocity divided by the frequency).

To further reduce errors associated with the identification of the arrival wave, the data was analyzed statistically. At least 10 hits were done per test, to obtain an average value and standard deviation. At each case, outliers caused by anomalies in the testing procedure were identified and discarded. As an outlier we consider results increasing the standard deviation such that the estimated COV becomes above 10 %.

Fig. 6 shows an example of the wave analysis carried out during the automated post-processing of the sonic test. The determination of t0 (generation of the wave by the hammer) and t1 (arrival of the wave at the receiver) was done automatically. The travel time (dt)

(a) (b)

Fig. 5. Sonic tests were carried out at the same location of flat-jack tests: (a) Museum of Arts and Crafts; (b) Zagreb cathedral.

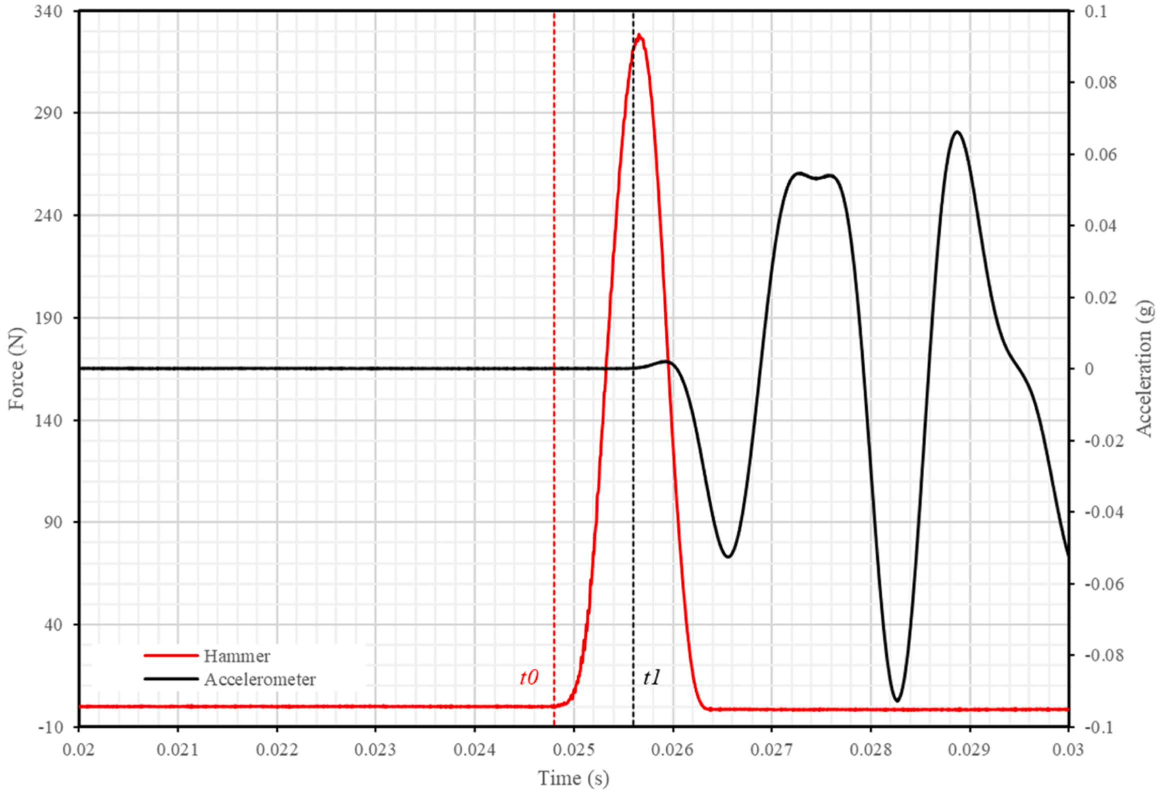


Fig. 6. Example of the hammer (red line) and accelerometer (black line) signals measured using the automated procedure for the data processing and calculation of the travel time between emitter and receiver.

that is needed for the calculation of the velocity (Eq. (2)) is simply calculated as t1-t0.

The results of the sonic tests from the 8 buildings are shown in Fig. 7, displayed graphically for each case study separately. Table 3 lists the average values, standard deviation and additional information necessary to relate to Table 2 from the flat-jack test campaign. The dynamic modulus of elasticity presented is calculated using Eq. (1) and assuming values of density of 1800 kg/m^3 and a Poisson's ratio of 0.2, in the absence of specific data from the masonry under evaluation. Nevertheless, Section 4.2 shows a sensitivity analysis to assess how the uncertainty related to these two parameters affect the results.

The results show a significant variation among the masonries from the different sites. The highest velocities (and subsequent highest mean dynamic modulus of elasticity) are observed at the two buildings in Sisak (the gymnasium and the hospital), exceeding 2000 MPa (2682 MPa in the case of the gymnasium). The lower values are observed at the Museum of Arts and Crafts (900 MPa), St. Catherine Church (601 MPa) and the State Archives (379 MPa). Note that the latter refers to a single location, where only one sonic test could be performed so the results might not be representative of the masonry. In any case, these three buildings are part of the historical city center of Zagreb and are the oldest buildings among the selected case studies (see Table 1). Indeed, St. Catherine Church and the State Archives are buildings from the 18th century. The museum, the factory, the cathedral and the residential building at Deželićeva are from the late 19th century and the velocities obtained from these buildings lie within the same range (1000–1500 MPa). Finally, the two buildings in Sisak are from the mid-20th century, where the highest velocities were observed. Therefore, the masonry used in the different time periods could be similar and present similar mechanical properties.

The coefficient of variation presented in Table 3 illustrates the degree of homogeneity of the masonries tested within each building. The variation is overall low with values lower than 10 % (in the residential building and the gymnasium in Sisak) or close to 20 %. The greatest variation was observed at St. Catherine Church, but it should be noted that again only one setup could be performed when testing at FJ-1, the location that presents the lower value. Thus, this specific result may correspond to particularities of the masonry at that specific location (e.g. damaged masonry due to the flat-jack test). It is also noted that this location showed signs of eroded brick due to rising damp at lower courses of brick, which might have affected the integrity of the masonry at this location.

It is noted that the dataset with raw sonic test results obtained on-site is publicly available for future studies in https://doi.org/10.5281/zenodo.7128546.

4. Comparison of the results and discussion

After the individual analysis of both techniques, the present section aims to compare the results obtained and identify a possible

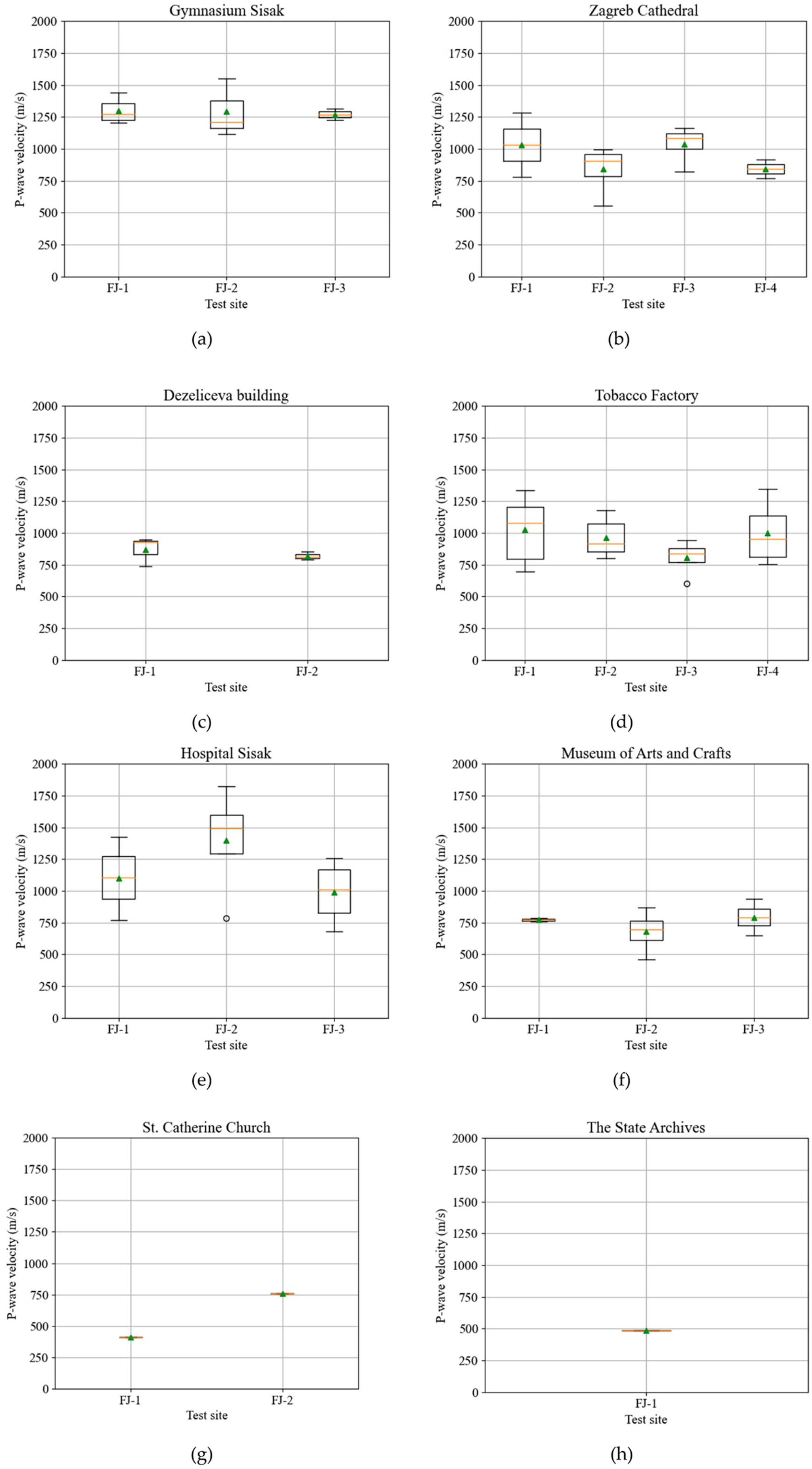


Fig. 7. Box-plots of the sonic test results for each case study in terms of calculated P-wave velocity (m/s). Triangle corresponds to the mean and the orange line to the median values, respectively.

Table 3
Sonic tests results summary.

No.	Building	Floor	Test site	P-wave velocity [m/s]	Dynamic modulus of elasticity [MPa]	Mean value [MPa]	STD [MPa] (CoV)
1.	Gymnasium Sisak	Ground	FJ-1	1298	2613	2682	61
			FJ-2	1292	2729		(2 %)
		1st	FJ-3	1270	2704		
2.	Zagreb Cathedral	Roof	FJ-1	1032	1726	1442	340 (24 %)
			FJ-2	841	1145		
			FJ-3	1038	1747		
			FJ-4	842	1150		
3.	Deželićeva building	Ground	FJ-1	869	1224	1155	98
		1st	FJ-2	818	1085		(8 %)
4.	Tobacco factory	Ground	FJ-1	1024	1499	1468	288
		1st	FJ-2	962	1620		(20 %)
		2nd	FJ-3	806	1053		
		1st	FJ-4	1000	1698		
5.	Hospital Sisak	Basement	FJ-1	1101	1965	2239	827
		Ground	FJ-2	1398	3168		(37 %)
		1st	FJ-3	988	1583		
6.	Museum of Arts and Crafts	Ground	FJ-1	772	967	911	143
		1st	FJ-2	680	749		(16 %)
			FJ-3	792	1017		
7.	St. Catherine Church	Ground	FJ-1	409	271	601	467
			FJ-2	758	931		(78 %)
8.	The State Archives	Ground	FJ-1	484	379	379	0
							(0 %)

correlation between the mechanical property estimated using them, namely the modulus of elasticity of the masonry. First, the analyses are assessed on a case-by-case basis to conclude on the possible correlation. This section also assesses the uncertainties related to the estimation of the modulus of elasticity using sonic test through a brief sensitivity analysis. The section then reflects on the possible correlation between the static modulus of elasticity obtained through the flat-jack method and the dynamic one obtained from the sonic test. The conclusions are important to point out practicability issues on how to perform condition assessment and characterization of mechanical properties of the materials in existing masonry buildings.

4.1. Sonic vs flat-jack

From the data shown in Tables 2 and 3, a case-by-case comparison of the results can be carried out (Fig. 8a). The graph in Fig. 7a already shows a significant correlation between the results obtained from both techniques. Overall, the sonic test results follow well the trend observed in the flat-jack test results. The highest sonic test E values are computed where the highest E values were obtained from the flat-jack tests and the same occurs with the lowest ones. Moreover, the E values obtained using both methods are similar in most cases. Note that the graph displays the static modulus of elasticity in the case of flat-jack tests and the dynamic one in the case of the sonic tests. The greatest discrepancy occurs for: (1) the state archives (case study 8), which may be due to the previously mentioned scarcity of sonic data; (2) the tobacco factory; and (3) the Sisak gymnasium. In the case of the latter, the modulus of elasticity obtained

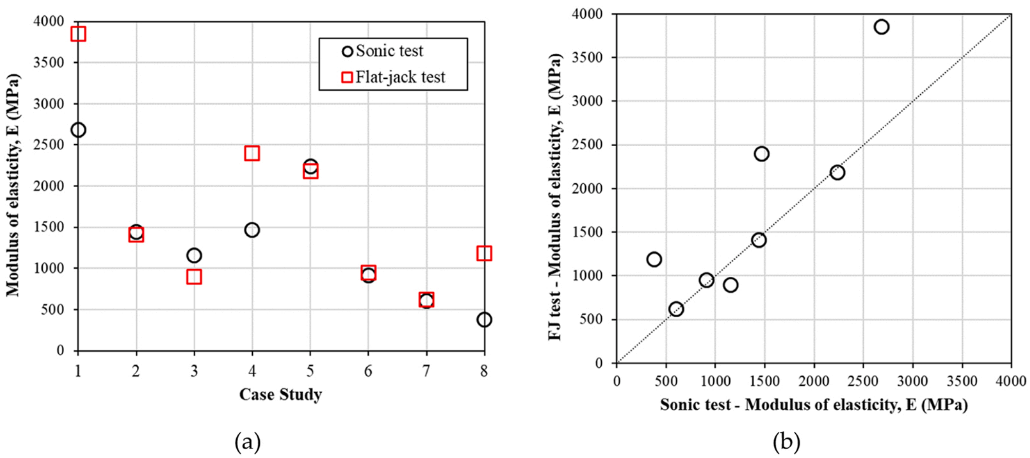


Fig. 8. (a) Case by case comparison of the mean values of modulus of elasticity obtained from both methods (numbers in the x-axis correspond to the case studies reported in Tables 2 and 3); and (b) Flat-jack (FJ) versus sonic test values of modulus of elasticity.

from the flat-jack tests was higher than expected, exceeding the common range that can be found in the literature for brick masonry, e.g. range defined by the Italian code [68].

Fig. 8b shows a direct comparison between average values obtained from the sonic and the flat-jack tests. The good correlation previously commented becomes more evident and the three locations where greater discrepancies were found are also highlighted. In any case, the mean absolute error ($MAE = \frac{1}{n}\sum|E_{sonic} - E_{FJ}|$) is 414 MPa and the coefficient of determination (R^2), a measure of the correlation, is 0.76. Despite the need for more data and further validation, the results show that for the studied cases the sonic tests provide a similar estimation of the mechanical properties of the brick masonry to the one obtained through flat-jack testing. Fig. 9 shows a direct comparison between flat-jack and sonic test results using all results per location tested instead of average values for buildings. The positive correlation is still visible, even though the coefficient of determination is reduced (0.57). The mean absolute error is 613 MPa.

Concerning the correlation between the dynamic modulus of elasticity (results from sonic tests) and static one (results from flat-jack), an average ratio of 0.92 is observed (taking into account all results and not average values). However, excluding the two locations where the greatest discrepancies are observed (i.e. state archives and Sisak gymnasium), the average ratio between the dynamic and the static modulus computed is 0.99.

Fig. 10 shows a more detailed comparison of the results, showing the results per location tested instead of average values for buildings. Again, the results show a reasonable agreement. Nevertheless, greater discrepancies can be found looking at the results individually. This highlights the importance of performing a significant amount of sonic tests in each location to avoid local measurements that may not be representative of the entire masonry. Both tests are sensitive to local features of the masonry (e.g. damaged or deteriorated masonry, presence of voids, etc.). Moreover, sonic tests also have a significant variability within each test and that is why 10 hits are done per test, to minimize errors and reduce the variation. In conclusion, the results highlight the importance of performing multiple tests in each location and to estimate the mechanical properties in terms of average values.

Another recommendation is to carry out the sonic tests at the exact same locations as the flat-jack tests, before the latter are performed. The sequence of the investigations in this campaign is acknowledged as a limitation of the study since the sonic tests were performed after the flat-jack tests. The load applied during the flat-jack tests can have a sizeable influence on the masonry around the location, creating a slight movement of the mortar in the adjacent joints. Performing sonic tests before the flat-jack tests would avoid having to: (1) test at a slightly different position; and (2) test over an already altered masonry. If sonic tests are carried out before the flat jack tests (therefore on unaltered masonry), results might have led to slightly higher values of velocity and should be explored in future works.

4.2. Sensitivity analysis

The estimation of the dynamic modulus of elasticity through sonic tests also entails uncertainty related to the assumed material parameters, namely Poisson's ratio and density, that are necessary to use Eq. 1. In the absence of specific information about the evaluated masonries, values of 1800 kg/m^3 and 0.2 were assumed for the density and Poisson's ratio in all cases. Since the real values are not known but some variability is expected, a sensitivity analysis was carried out to assess their influence on the final dynamic modulus of elasticity calculated.

The variations considered are ± 200 kg/m^3 for the density (range of 1600–2000 kg/m^3) and ± 0.05 for the Poisson's ratio (range of 0.15–0.25), which are considered as plausible ranges of variations of the evaluated properties. The influence of these variations is studied in three cases: (1) the Sisak Gymnasium, corresponding to the location where the highest values were obtained; (2) the Zagreb Cathedral, which is a location where middle values were observed; and (3) the Museum of Arts and Crafts, where lower values of the dynamic modulus of elasticity were calculated.

Fig. 11 shows the variations with respect to the reference case in the computed dynamic modulus of elasticity according to the

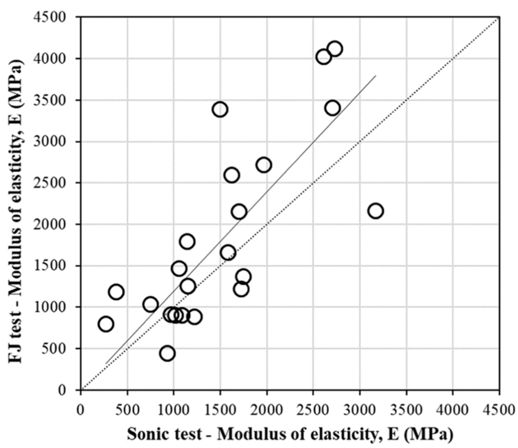


Fig. 9. Flat-jack (FJ) versus sonic test values of modulus of elasticity taking into account all results per location.

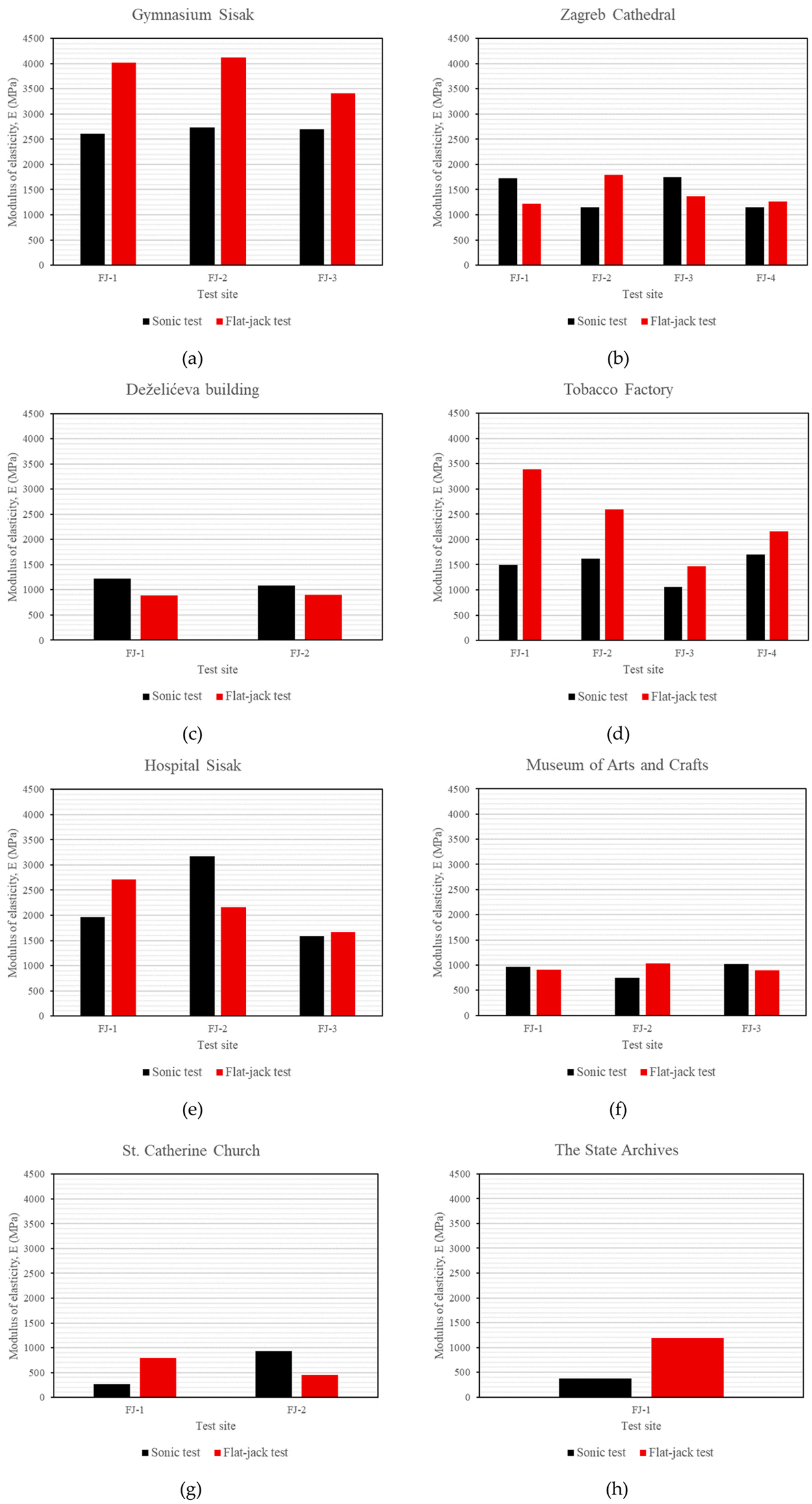


Fig. 10. Comparison of sonic test results with flat-jack test results for each location in each case study, in terms of estimated modulus of elasticity, E (MPa).

previously defined variations in density and Poisson's ratio. Since density and Poisson's ratio are independent variables in Eq. (1), the proportional variation of the dynamic modulus of elasticity is the same in all cases (see Table 4). That is why, in absolute values, the variations are more notable for greater values of velocity (e.g. Gymnasium of Sisak). The highest variation results after the variation of both parameters at the same time (i.e. increasing density and decreasing Poisson's ratio and decreasing density and increasing Poisson's ratio), which is approximately ± 17 % and leads to approximately ± 500 MPa in the case of the Gymnasium of Sisak and ± 150 MPa in the museum of Arts and Crafts.

In conclusion, the material properties that are necessary to estimate the dynamic modulus of elasticity with the sonic test have a significant weight (up to 17 % for the studied case). A parallel experimental campaign to characterize at least the density would be beneficial to improve the reliability on the results. In any case, the results of the sonic tests can also be provided in statistical terms according to the expected variations of density and Poisson's ratio, e.g. as a normal distribution.

4.3. *Static vs dynamic modulus of elasticity*

Regarding the theoretical inequality between static and dynamic modulus of elasticity of masonry, the results shown in Fig. 8 cannot lead to major conclusions. As previously discussed and shown in Fig. 8b, the results are almost coincidental for most locations. It is noted that in those locations where there are higher discrepancies, the static modulus obtained through the flat-jack tests is indeed higher. However, the empirically observed inequality between both moduli typically that is reported in the literature revealed a higher dynamic modulus of elasticity, even though most studies available relate to rock properties, within the geophysical context [69,70] and specific correlations for masonry are not established. Some authors have proposed ratios of 1.2 and 1.3 between the dynamic and the static modulus [71,72]. Also, some standards establish ranges varying from 1.1 to 2 [73].

Thus, the results obtained in the present research led to an inverse correlation in relation to the existing literature. Using the data from Fig. 9 and taking all tests into account, a ratio of 0.92 between the dynamic and the static modulus of elasticity is observed (0.99 if the locations with greater discrepancies are not taken into account). Since this is not the common pattern observed for other materials in the literature (even though there are no specific studies about these correlations for historic brick masonry), this cannot be observed as a conclusive result and further research is needed, including experimental laboratory testing. As highlighted previously, if sonic tests were carried out before the flat jack tests (therefore on unaltered masonry), the results might have led to slightly higher values of velocity.

4.4. *Operational and practicability issues*

An important aspect of on-site investigations and condition assessment is the operability of the methods that are applied. In this regard, the flat-jack test is a consolidated method with specific standards, which facilitates its application by practitioners. Nevertheless, it is a minor destructive and time-consuming method and its application in many locations could be limited due to preservation issues. In fact, repairs and patching are needed after the test and not all building owners are willing to undertake this level of intervention.

On the other hand, sonic testing is a non-destructive technique, even though the removal of plaster is necessary for some test configurations. The average time of performing a sonic test is in the order of minutes, whereas a single flat-jack test can take up to 3–5 h. In this regard and in the light of the results obtained in the present research, sonic tests appear to be a promising complementary technique for condition assessment. The use of minor destructive tests (flat-jack testing) in combination with sonic tests can help to perform a more thorough material characterization of one site [63]. When inspecting a site, flat-jack tests can be performed in a few locations, which allows obtaining an estimation of the static modulus of elasticity and, subsequently, extract correlations between the modulus of elasticity estimated by the sonic tests. Then, since sonic tests can be carried out in a more expeditious way and with less harm to the material fabric of the building, they can be performed in a larger number of elements throughout the inspected structure.

Sonic tests can also be complemented with other non-destructive evaluation techniques, e.g., in-situ dynamic identification tests, to estimate masonry material properties [26,74]. They can be a useful tool to have a preliminary estimation of material properties but should be complemented with other non-or minor destructive approaches. If complementary tests are not carried out, results should be interpreted with care and mainly serve for comparative purposes, e.g., to qualitatively assess the variation of different masonry qualities within the same building.

5. Conclusions

The main objective of the paper was to evaluate the correlation between non- and semi-destructive techniques when estimating the deformability of unreinforced brick masonry in existing buildings. The paper specifically evaluated the use of sonic pulse velocity tests (non-destructive) and flat-jack tests (minor destructive tests that is easily repairable). The use of such approaches is essential to protect the valuable fabric of masonry heritage structures. The research has presented the results obtained in an extensive field campaign that allowed to collect data from eight different buildings in Zagreb and Sisak, in Croatia, affected by the recent 2020 earthquakes, providing a wide set of data for comparison between the two studied techniques. The characterization of the material condition and properties of the affected buildings is essential to take subsequent informed decisions on possible intervention measures at an urban scale. Therefore, determining proper tools that allow for a rapid, efficient and reliable characterization is a necessity for the post-earthquake assessment. The paper aims to show different tools that can be used for that purpose.

After a brief presentation of the inspected buildings, the paper presented the results obtained from each test independently,

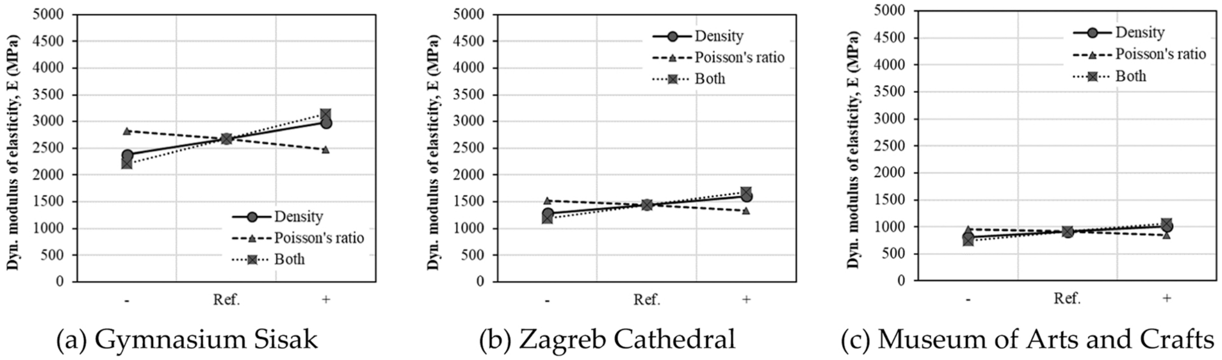


Fig. 11. Variations of the dynamic modulus of elasticity according to the variations of the density and Poisson's ratio assumed for the materials in three case studies.

Table 4
Variation of dynamic modulus of elasticity (in percentage) according to typical variations in density and Poisson's ratio.

	Poisson's ratio (ν)		Density (ρ)		Both	
Value	0.15	0.25	1600	2000	$\nu = 0.25$ $\rho = 1600$	$\nu = 0.15$ $\rho = 2000$
Variation of E (%)	+ 5.23 %	- 7.41 %	- 11.11 %	+ 11.11 %	- 17.70 %	+ 16.92 %

explaining both the equipment and methods to carry out the tests. Both techniques were used to estimate the modulus of elasticity of all buildings and showed a great variability among the masonries of the different buildings. A significant correlation was observed between the quality of the fabric and the age of construction. The highest moduli of elasticity were computed for the buildings belonging to more recent periods (i.e. 20th century).

Addressing the main objective of the research, the paper then compared the results obtained from both tests and studied the correlations among them. The case-by-case comparison showed a significant correlation between the results obtained from both techniques. There is a general correlation across structures, as the computed values of modulus of elasticity were similar in most cases with a coefficient of determination (R^2), a measure of the correlation, of 0.76. The possibility of using sonic tests (notably faster, easier to implement and non-destructive) to characterize the masonry shows a great potential, both as an independent technique and as a complementary technique to flat-jack testing. The combination of both methods for the condition assessment of masonry buildings allows carrying out flat-jack testing in a few locations to establish correlations between sonic and flat-jack data and sonic test in a more extended area to evaluate a large number of elements of the building. The paper illustrates the need for more research in this field to further validate the technique, find appropriate correlations and eventually define standards for sonic testing so professionals can gain confidence on the method and allow its widespread use for conservation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Raw data related with the sonic tests are available as open source at: https://doi.org/10.5281/zenodo.7128546.

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References

[1] A. Penna, P. Morandi, M. Rota, C.F. Manzini, F. da Porto, G. Magenes, Performance of masonry buildings during the Emilia 2012 earthquake, Bull. Earthq. Eng. 12 (5) (2014) 2255–2273, https://doi.org/10.1007/s10518-013-9496-6.
[2] S. Mazzoni, et al., 2016–2017 Central Italy earthquake sequence: seismic retrofit policy and effectiveness, Earthq. Spectra 34 (4) (2018) 1671–1691, https://doi.org/10.1193/100717EQS197M.

[3] H. Bilgin, N. Shkodrani, M. Hysenlliu, H. Baytan Ozmen, E. Isik, E. Harirchian, Damage and performance evaluation of masonry buildings constructed in 1970s during the 2019 Albania earthquakes, Eng. Fail Anal. 131 (2022), 105824, https://doi.org/10.1016/j.engfailanal.2021.105824.

[4] G. Vlachakis, E. Vlachaki, P.B. Lourenço, Learning from failure: damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece), Eng. Fail Anal. 117 (2020), 104803, https://doi.org/10.1016/j.engfailanal.2020.104803.

[5] K.O. Cetin, et al., The site effects in Izmir Bay of October 30 2020, M7.0 Samos Earthquake, Soil Dyn. Earthq. Eng. 152 (2022), 107051, https://doi.org/10.1016/j.soildyn.2021.107051.

[6] M. Stepinac, P.B. Lourenço, J. Atalić, T. Kišiček, M. Uroš, M. Baniček, M. Šavor Novak, Damage classification of residential buildings in historical downtown after the ML5.5 earthquake in Zagreb, Croatia in 2020, Int. J. Disaster Risk Reduct. 56 (2021), 102140, https://doi.org/10.1016/j.ijdrr.2021.102140.

[7] L. Lulić, K. Ožić, T. Kišiček, I. Hafner, M. Stepinac, Post-earthquake damage assessment-case study of the educational building after the Zagreb earthquake, Sustainability 13 (11) (2021), https://doi.org/10.3390/su13116353.

[8] M. Milić, M. Stepinac, L. Lulić, N. Ivanišević, I. Matorić, B. Šipoš, Y. Endo, Assessment and rehabilitation of culturally protected prince Rudolf infantry barracks in Zagreb after major earthquake, Buildings 11 (11) (2021), https://doi.org/10.3390/buildings11110508.

[9] T. Kišiček, M. Stepinac, T. Renić, I. Hafner, L. Lulić, Strengthening of masonry walls with FRP or TRM, Gradjevinar, Union Croat. Civ. Eng. Tech. 72 (10) (2020) 937–953, https://doi.org/10.14256/JCE.2983.2020.

[10] M.L. Beconcini, P. Croce, P. Formichi, F. Landi, B. Puccini, Experimental evaluation of shear behavior of stone Masonry Wall, Materials 14 (9) (2021) 2313, https://doi.org/10.3390/ma14092313.

[11] M.L. Beconcini, P. Formichi, L. Giresini, F. Landi, B. Puccini, P. Croce, Modeling approaches for the assessment of seismic vulnerability of masonry structures: the E-PUSH program, Buildings 12 (3) (2022) 346, https://doi.org/10.3390/buildings12030346.

[12] L. Binda, M. Lualdi, A. Saisi, Non-destructive testing techniques applied for diagnostic investigation: syracuse Cathedral in Sicily, Italy, Int. J. Archit. Herit. 1 (4) (2007) 380–402, https://doi.org/10.1080/15583050701386029.

[13] V. Bosiljkov, M. Uranjek, R. Žarnić, V. Bokan-Bosiljkov, An integrated diagnostic approach for the assessment of historic masonry structures, J. Cult. Herit. 11 (3) (2010) 239–249, https://doi.org/10.1016/j.culher.2009.11.007.

[14] B. Conde, L.F. Ramos, D.V. Oliveira, B. Riveiro, M. Solla, Structural assessment of masonry arch bridges by combination of non-destructive testing techniques and three-dimensional numerical modelling: application to Vilanova bridge, Eng. Struct. 148 (2017) 621–638, https://doi.org/10.1016/j.engstruct.2017.07.011.

[15] M.R. Valluzzi, E. Cescatti, G. Cardani, L. Cantini, L. Zanzi, C. Colla, F. Casarin, Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls, Constr. Build. Mater. 192 (2018) 272–286, https://doi.org/10.1016/j.conbuildmat.2018.10.073.

[16] A. Grazzini, Sonic and Impact Test for Structural Assessment of Historical Masonry, Appl. Sci. 9 (23) (. 2019) 5148, https://doi.org/10.3390/app9235148.

[17] R. Martini, J. Carvalho, A. Arêde, H. Varum, Validation of nondestructive methods for assessing stone masonry using artificial neural networks, J. Build. Eng. 42 (2021), 102469, https://doi.org/10.1016/j.jobe.2021.102469.

[18] D. Pirchio, K.Q. Walsh, E. Kerr, I. Giongo, M. Giaretton, B.D. Weldon, L. Ciocci, L. Sorrentino, An aggregated non-destructive testing (NDT) framework for the assessment of mechanical properties of unreinforced masonry Italian medieval churches, Constr. Build. Mater. 342 (2022), 128041, https://doi.org/10.1016/j.conbuildmat.2022.128041.

[19] L. Binda, A. Saisi, C. Tiraboschi, Application of sonic tests to the diagnosis of damaged and repaired structures, NDT E Int. 34 (2) (2001) 123–138, https://doi.org/10.1016/S0963-8695(00)00037-2.

[20] G. Leucci, N. Masini, R. Persico, F. Soldovieri, GPR and sonic tomography for structural restoration: the case of the cathedral of Tricarico, J. Geophys. Eng. 8 (3) (2011) S76–S92, https://doi.org/10.1088/1742-2132/8/3/S08.

[21] F. Autiero, G. de Martino, M. di Ludovico, A. Prota, Mechanical performance of full-scale Pompeii-like masonry panels, Constr. Build. Mater. 251 (2020), 118964, https://doi.org/10.1016/j.conbuildmat.2020.118964.

[22] L. Miranda, L. Cantini, J. Guedes, A. Costa, Assessment of mechanical properties of full-scale masonry panels through sonic methods. Comparison with mechanical destructive tests, Struct. Control Health Monit. 23 (3) (2016) 503–516, https://doi.org/10.1002/stc.1783.

[23] H. Maccarini, G. Vasconcelos, H. Rodrigues, J. Ortega, P.B. Lourenço, Out-of-plane behavior of stone masonry walls: experimental and numerical analysis, Constr. Build. Mater. 179 (2018) 430–452, https://doi.org/10.1016/j.conbuildmat.2018.05.216.

[24] R. Martini, J. Carvalho, A. Arêde, H. Varum, Correlation between sonic and mechanical test results on stone Masonry Walls, Struct. Anal. Hist. Constr. (2019) 456–464.

[25] A. Grazzini, G. Lacidogna, Mechanical properties of historic masonry stones obtained by in situ non-destructive tests on the St. Agostino Church in Amatrice (Italy), Appl. Sci. 11 (14) (2021) 6352, https://doi.org/10.3390/app11146352.

[26] A. Vuoto, J. Ortega, P.B. Lourenço, F. Javier Suárez, A. Claudia Núñez, Safety assessment of the Torre de la Vela in la Alhambra, Granada, Spain: the role of on site works, Eng. Struct. 264 (2022), 114443, https://doi.org/10.1016/j.engstruct.2022.114443.

[27] L.F. Miranda, J. Rio, J. Miranda Guedes, A. Costa, Sonic Impact Method – a new technique for characterization of stone masonry walls, Constr. Build. Mater. 36 (2012) 27–35, https://doi.org/10.1016/j.conbuildmat.2012.04.018.

[28] M. Stepinac, L. Lulić, D. Damjanović, I. Duvnjak, M. Bartolac, P.B. Lourenço, Experimental evaluation of unreinforced brick masonry mechanical properties by the flat-jack method – an extensive campaign in Croatia, Int. J. Archit. Herit. (2023) 1–18, https://doi.org/10.1080/15583058.2023.2208542.

[29] ASTM, ASTM C1196 - 09: Standard Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flatjack Measurements, 2009.

[30] ASTM, ASTM C1197 - 14a: Standard Test Method for In Situ Measurement of Masonry Deformability Properties Using the Flatjack Method, 2014.

[31] ASTM, ASTM C1531 - 16: standard test methods for in situ measurement of masonry mortar joint shear strength index, Changes 04 (2003) 1–7.

[32] RILEM, RILEM Recommendation MDT. D. 4: In-situ stress tests based on the flat jack, Mater. Struct. 37 (7) (2004) 491–496.

[33] RILEM, RILEM Recommendation MDT. D. 5: In-situ stress - strain behaviour tests based on the flat jack, Mater. Struct. 37 (2004) 497–501.

[34] RILEM, RILEM Recommendations MS-D.6: In-situ measurement of masonry bed joint shear strength, Mater. Struct. 29 (1996) 459–475.

[35] A. Moretić, M. Stepinac, P.B. Lourenço, Seismic upgrading of cultural heritage – a case study using an educational building in Croatia from the historicism style, Case Stud. Constr. Mater. 17 (2022), e01183, https://doi.org/10.1016/j.cscm.2022.e01183.

[36] V. Alecci, A.G. Ayala, M. de Stefano, A.M. Marra, R. Nudo, G. Stipo, Influence of the masonry wall thickness on the outcomes of double flat-jack test: Experimental and numerical investigation, Constr. Build. Mater. 285 (2021), 122912, https://doi.org/10.1016/j.conbuildmat.2021.122912.

[37] F.F.S. Pinho, R.J.G. Serra, A.F.L. Saraiva, V.J.G. Lúcio, Performance of single and double flat jacks in stone masonry lab tests, J. Build. Eng. 42 (2021), 102465, https://doi.org/10.1016/j.jobe.2021.102465.

[38] P. Gregorczyk, P.B. Lourenco, A Rev. Flat-Jack Test. (2000).

[39] L. Lulić, M. Stepinac, M. Bartolac, P.B. Lourenço, Review of the flat-jack method and lessons from extensive post-earthquake research campaign in Croatia, Constr. Build. Mater. 384 (2023), 131407, https://doi.org/10.1016/j.conbuildmat.2023.131407.

[40] P. Croce, M.L. Beconcini, P. Formichi, F. Landi, B. Puccini, V. Zotti, Bayesian methodology for probabilistic description of mechanical parameters of Masonry Walls, ASCE ASME J. Risk Uncertain. Eng. Syst. A Civ. Eng. 7 (2) (. 2021), https://doi.org/10.1061/AJRUA6.0001110.

[41] N. Viale, G. Ventura, P.B. Lourenço, J. Ortega, Linear and non-linear FEM analyses to assess a shear flat-jack test for masonries, J. Build. Eng. 43 (2021), 103169, https://doi.org/10.1016/j.jobe.2021.103169.

[42] D. Łątka, P. Matysek, The estimation of compressive stress level in brick Masonry using the flat-jack method, Procedia Eng. 193 (2017) 266–272, https://doi.org/10.1016/j.proeng.2017.06.213.

[43] A. Simões, R. Bento, A. Gago, M. Lopes, Mechanical characterization of masonry walls with flat-jack tests, Exp. Tech. 40 (3) (2016) 1163–1178, https://doi.org/10.1007/s40799-016-0114-9.

[44] J.M. Lorenzo, Mark E. Everett: Near-surface applied geophysics, Mar. Geophys. Res. 35 (2) (2014) 175, https://doi.org/10.1007/s11001-014-9218-8.

[45] J.L. Noland, R.H. Atkinson, J.C. Baur, An Investigation Into Methods of Nondestructive Evaluation of Masonry Structures, Springfield, Virginia, 1982.

[46] F. Komeyli, M.C. Forde, H.W. Whittington, Sonic Investigation of Shear Failed Reinforced Brick Masonry, Masonry Industry, 1989.

[47] M. Berra, L. Binda, L. Anti, A. Fatticioni, Utilization of sonic tests to evaluate damaged and repaired masonry, Conf. Nondestruct. Eval. Civ. Struct. Mater. (1992).

[48] Maierhofer, C., Ziebolf, A., Kopp, C., ONSITEFORMASONRY - A European Research Project: On-site investigation techniques for the structural evaluation of historic masonry, 2003.

[49] Schuller, M.P., Nondestructive testing and damage assessment of masonry structures. NSF/RILEM Workshop. In-Situ Evaluation of Historic Wood and Masonry Structures. Prague, Czech Republic, Jul. 10, 2006.

[50] L. Binda, M. Lualdi, A. Saisi, Investigation strategies for the diagnosis of historic structures: on-site tests on Avio Castle, Italy, and Pišece Castle, Slovenia, Can. J. Civ. Eng. 35 (6) (2008) 555–566, https://doi.org/10.1139/L07-143.

[51] L.F. Ramos, A.C. Núñez García, F.M. Fernandes, P.B. Lourenço, Evaluation of structural intervention in the Quartel das Esquadras, Almeida (Portugal), Int. J. Archit. Herit. 12 (3) (2018) 465–485, https://doi.org/10.1080/15583058.2017.1323975.

[52] V. Perez-Gracia O. Caselles J. Clapes, Ground penetrating radar assessment of historical buildings: the study of the roofs, columns and ground of Santa Maria del Mar, in: Proceedings of Barcelona, in 2015 IEEE 15th Mediterranean Microwave Symposium (MMS), Nov. 2015, pp. 1–4. ⟨https://doi.org/10.1109/MMS.2015.7375496⟩.

[53] G. Luchin, L.F. Ramos, M. D'Amato, Sonic tomography for masonry walls characterization, Int. J. Archit. Herit. 14 (4) (2018) 589–604, https://doi.org/10.1080/15583058.2018.1554723.

[54] L. Binda, A. Saisi, C. Tiraboschi, S. Valle, C. Colla, M. Forde, Application of sonic and radar tests on the piers and walls of the Cathedral of Noto, Constr. Build. Mater. 17 (8) (2003) 613–627, https://doi.org/10.1016/S0950-0618(03)00056-4.

[55] MS-D.1 Measurement of mechanical pulse velocity for masonry, Mater. Struct. 29 (8) (1996) 463–466, https://doi.org/10.1007/BF02486277.

[56] EN 12504, EN 12504-4. Testing Concrete - Part 4: Determination of ultrasonic pulse velocity. European Committee for Standardization (CEN), Brussels, Belgium, 2006.

[57] ASTM, C. ASTM, Standard Test Method for Pulse Velocity Through Concrete, 597, ASTM International, West Conshohocken, 2016, p. 16.

[58] D. Breysse, Nondestructive evaluation of concrete strength: an historical review and a new perspective by combining NDT methods, Constr. Build. Mater. 33 (. 2012) 139–163, https://doi.org/10.1016/j.conbuildmat.2011.12.103.

[59] M. Diaferio M. Vitti, Correlation curves to characterize concrete strength by means of UPV tests, in: Proceedings of 1st International Conference on Structural Damage Modelling and Assessment. Lecture Notes in Civil Engineering, 110, 2021, pp. 209–218. ⟨https://doi.org/10.1007/978-981-15-9121-1_16⟩.

[60] K. Ali-Benyahia, Z.-M. Sbartaï, D. Breysse, M. Ghrici, S. Kenai, Improvement of nondestructive assessment of on-site concrete strength: influence of the selection process of cores location on the assessment quality for single and combined NDT techniques, Constr. Build. Mater. 195 (2019) 613–622, https://doi.org/10.1016/j.conbuildmat.2018.10.032.

[61] N. Makoond, A. Cabané, L. Pelà, C. Molins, Relationship between the static and dynamic elastic modulus of brick masonry constituents, Constr. Build. Mater. 259 (2020), 120386, https://doi.org/10.1016/j.conbuildmat.2020.120386.

[62] H. van Eldere, L.F. Ramos, E. Verstrynge, N. Shetty, K. van Balen, C.E. Barroso, D. v Oliveira, The application of sonic testing on double-leaf historical portuguese masonry to obtain morphology and mechanical properties, in: R. Aguilar, D. Torrealva, S. Moreira, M.A. Pando, L.F. Ramos (Eds.), Structural Analysis of Historical Constructions, 18, Springer, Cham, 2019, pp. 661–668, https://doi.org/10.1007/978-3-319-99441-3_71.

[63] T.M. Ferreira, J. Ortega, H. Rodrigues, Chapter 6 - Geometrical, constructive, and mechanical characterization of the traditional masonry buildings in the historic city center of Leiria, Portugal, in: R. Rupakhety, D. Gautam (Eds.), Masonry Construction in Active Seismic Regions, Woodhead Publishing, 2021, pp. 147–174, https://doi.org/10.1016/B978-0-12-821087-1.00004-1.

[64] E. Cescatti, L. Rosato, M.R. Valluzzi, F. Casarin, An Automatic Algorithm for the Execution and Elaboration of Sonic, in: R. Aguilar, D. Torrealva, S. Moreira, M. A. Pando, L.F. Ramos (Eds.), Pulse Velocity Tests in Direct and Tomographic Arrangements, in Structural Analysis of Historical Constructions, 18, Springer, Cham, 2019, pp. 716–724, https://doi.org/10.1007/978-3-319-99441-3_77.

[65] J.S. Popovics, W. Song, J.D. Achenbach, J.H. Lee, R.F. Andre, One-sided stress wave velocity measurement in concrete, J. Eng. Mech. 124 (12) (1998) 1346–1353, https://doi.org/10.1061/(ASCE)0733-9399(1998)124:12(1346).

[66] J.D. Rodríguez-Mariscal, J. Canivell, M. Solís, Evaluating the performance of sonic and ultrasonic tests for the inspection of rammed earth constructions, Constr. Build. Mater. 299 (2021), 123854, https://doi.org/10.1016/j.conbuildmat.2021.123854.

[67] I.O. Yaman, G. Inci, N. Yesiller, H.M. Aktan, Ultrasonic pulse velocity in concrete using direct and indirect transmission, Acids Mater. J. (2001) 450–457.

[68] NTC-Circolare 21 Gennaio 2019 N. 7C.S.LL.PP. Istruzioni Per L'applicazione Dell'aggiornamento Delle "Norme Tecniche Per Le Costruzioni" Di Cui Al D.M. 17/01/2018, Consiglio Superiore Dei Lavori Pubblici.

[69] A. Ahmad, M. Pamplona, S. Simon, Ultrasonic testing for the investigation and characterization of stone – a non-destructive and transportable tool, Stud. Conserv. 54 (sup1) (2009) 43–53, https://doi.org/10.1179/sic.2009.54.Supplement-1.43.

[70] E. Mashinskii, Differences between static and dynamic elastic moduli of rocks: physical causes, Geol. i Geofiz. 44 (2003) 953–959834.

[71] A. D'Ambrisi, V. Mariani, M. Mezzi, Seismic assessment of a historical masonry tower with nonlinear static and dynamic analyses tuned on ambient vibration tests, Eng. Struct. 36 (2012) 210–219, https://doi.org/10.1016/j.engstruct.2011.12.009.

[72] M. Ripepe, M. Coli, G. Lacanna, E. Marchetti, M.T. Cristofaro, M. de Stefano, V. Mariani, M. Tanganelli, P. Bianchini, Dynamic response of the giotto's bell-tower, Firenze, Italy, Eng. Geol. Soc. Territ. 8 (2015) 323–327.

[73] BSI Natural stone test methods—Determination of sound speed propagation. British Standards Institution (BSI), London, UK, 2004.

[74] M. Núñez García, S. Saloustros, F. Mateos Redondo, J.A. Alonso Campanero, J. Ortega, F. Greco, C. Aranha, I. Martínez Cuart, Seismic retrofit of existing structures based on digital surveying, non-destructive testing and nonlinear structural analysis: the case of Gjirokastra Castle in Albania, Appl. Sci. 12 (23) (2022) 12106, https://doi.org/10.3390/app122312106.