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COMPARISON OF NON-DESTRUCTIVE AND SEMI-DESTRUCTIVE METHODS FOR THE POST-EARTHQUAKE ASSESSMENT OF EXISTING MASONRY

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Abstract

After a long period of inactivity, strong seismic events occurred in Croatia. Due to the extensive damage caused by the recent earthquakes, a significant phase of reconstruction and strengthening follows. Determining the actual seismic behavior of existing masonry structures is of great importance for future management and the economical and purposeful strengthening of the load-bearing structure. Modern software solutions and design methods are an essential part of the assessment, but they are only as useful as long as the input parameters are reliable. This is where in-situ test methods come into play, providing useful information about the mechanical properties of the structure. In the paper, the flat-jack method and sonic pulse velocity method are described in more detail and the results of certain tests are presented and compared.

Keywords: assessment, masonry, flat-jack, sonic pulse velocity, NDT, SDT

1. Introduction

After a long period of seismic inactivity, the recent 2020 seismic events in Croatia caused a lot of damage and suffering [1,2]. Despite the great effort made by scientists to raise awareness, the unpreparedness for such a situation was noticeable from several aspects. In response to this, many activities aimed at mitigating the consequences have been initiated. In addition to the rapid damage and usability assessments carried out immediately after the earthquake by volunteer engineers [3], a widespread process of more detailed assessment, restoration and reconstruction of the building stock began. The first inevitable step in this process is certainly the determination of mechanical properties.

Given that old unreinforced masonry (URM) structures that are occupied and mostly located in urban centres suffered the most, the examination of such structures is urgent and therefore most important. Existing URM structures are inherently vulnerable to violent ground motions. Due to its large mass and stiffness, as well as low ductility and poor ability to dissipate energy, it represents a danger to human life [4]. Moreover, the lack of connection between walls and floor structures can lead to the loss of global stability and the collapse of the structure as a whole.

For the assessment, various test methods are used, and one common and useful method is the flat-jack test. The method is semi-destructive, requires specialized equipment and the test itself is time-consuming [5]. With this in mind, comparisons between methods are undertaken with the aim of facilitating and speeding up the testing process. That is why this comprehensive investigative campaign is launched. The testing campaign is carried out following the devastating earthquakes of 2020. The research aimed to identify and compare the elastic properties of solid brick masonry on several case study buildings in Croatia using different testing methods. The experimental campaign was conducted in collaboration of the Faculty of civil engineering in Zagreb and the FENEC association. Most of the tested buildings are currently not operational due to damage caused by the earthquakes, so the investigative work is carried out without interruption. An integral part of this campaign are the case

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studies shown in Figure 1. They are located in the capital Zagreb and its surroundings, and most of them are part of the cultural heritage.

a) CS1

b) CS2

c) CS3

d) CS4

e) CS5

f) CS6

g) CS7

h) CS8

Figure 1. Case study buildings.

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2. Assessment methods

Various non-destructive, semi-destructive and destructive methods are used for the assessment of existing URM structures. The emphasis in this paper is on the flat-jack method and sonic pulse velocity test or sonic test. The methods are explained in more detail in the following chapters. More information about other assessment methods can be found in [6,7].

2.1 Flat-jack method

The method is based on the principle of introducing stress into the masonry using metal flat-jacks of a semioval shape that are inflated like a balloon. This causes the masonry to deform, which is measured using a portable extensometer and a displacement sensor (LVDT). Using the flat-jack method, three useful masonry parameters can be determined, and therefore the test is performed in three phases. The first phase is about the state of vertical stress in the masonry, while the second and third phases provide information about the deformation and shear characteristics of the masonry. A more detailed description of the flat-jack method can be found in [8,9]. Before the aforementioned test phases, flat-jacks need to go through the calibration process due to certain pressure losses that occur as a result of the deformation of the flat-jack itself. The calibration process is carried out in an accredited laboratory and is repeated after every five in-situ tests. The next major concern is finding a favourable location in the structure that can be tested. It is important that the wall is load-bearing, without hidden openings, installations and similar obstacles. Next, all surface layers of the wall are removed until the brick is reached. The surface of the wall should be clean and dry. Wet basement walls are best avoided because of the degradation caused by moisture and the poor maturation of the adhesive, which is necessary for the test.

In the first stage, three pairs of vertically placed metal points are glued to the wall. An opening will be cut in the horizontal joint between the pairs of points with an eccentric ring saw. By measuring the spacing of the points before and after cutting, the deformation of the part of the wall due to the resulting discontinuity in the material is determined. By inserting a flat-jack into the newly created opening and gradually increasing the pressure, the deflection is reduced (Figure 2a). When the deflection is reduced to zero, i.e. when the wall returns to its initial position, the stress in the flat jack represents the state of vertical stress in the masonry. The obtained stress in the flat-jack is corrected with the coefficient obtained during the calibration process and with the ratio of the area of the flat-jack and the area of the opening in the wall.

In the second phase of the test, the flat-jack from the first phase is used, but another one is added above it (Figure 2b). In this way, a part of the wall is obtained that is in a uniform state of stress, and with the help of flat-jacks, this stress can be controlled. Three displacement sensors are placed between the flat-jacks, which measure the displacement of that part of the wall. The further procedure takes place so that the stress is gradually increased in small increments and the displacement is measured after each step. After a specific number of steps, a certain correlation between vertical stress and strain is obtained and based on this, the elastic property of masonry, i.e. the modulus of elasticity, is obtained.

The third phase (Figure 2c), which is also the last phase of the test, again uses two flat-jacks from the previous phase. Only now an additional third horizontal press is added which will push the selected brick to determine the coefficient of friction and initial shear strength values. The brick will be pushed parallel to the face of the wall and will be pushed along its longest side. To begin with, the level of vertical stress will be increased to a certain level. Then the brick will be pushed horizontally until failure, i.e. until it slips. The level of vertical stress is increased again and the brick is pushed horizontally until failure. This process is repeated several times. As a result, on the shear stress-vertical stress diagram, the best fitting line is obtained whose slope represents the friction coefficient and the intersection with the vertical axis represents the initial shear strength.

More detailed instructions on calibration, the test itself, as well as the processing of the results for determining the deformation properties of masonry, i.e. the modulus of elasticity, can be found in the form of the following guidelines [10,11].

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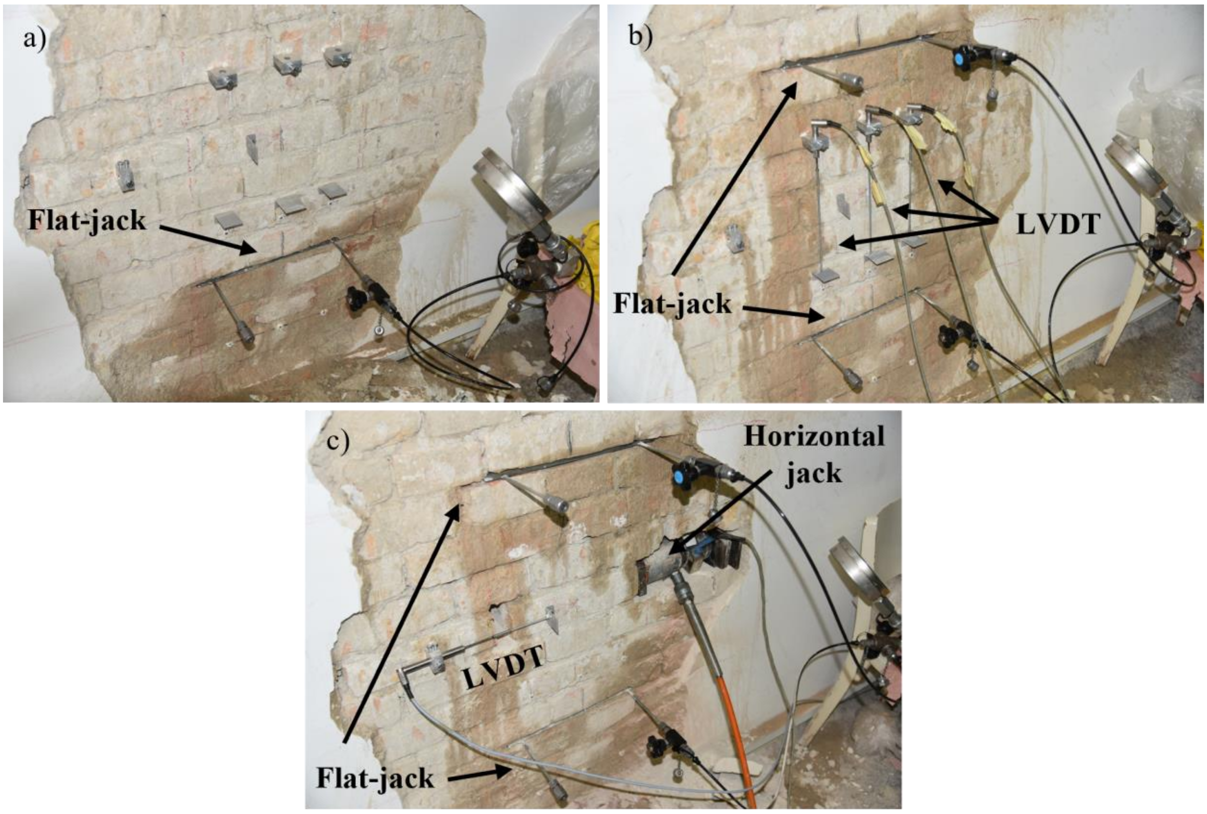

Figure 2. Flat-jack test phases: a) Vertical stress state; b) Elastic properties; c) Shear properties.

2.2 Sonic pulse velocity test

The sonic pulse velocity test method is a procedure used to estimate the elastic properties of masonry, i.e. the modulus of elasticity. The method aims to precisely measure the speed of propagation of an elastic longitudinal wave through the structure. The speed propagation can be then correlated with the dynamic elastic modulus, Poisson's ratio and material density. The wave propagation speed is obtained using the measured travel time of the elastic wave from the emitter to the receiver and assuming a linear distance between them. The receiver is an accelerometer with a sensitivity of 10 V/g and a frequency range from 0.15 Hz to 1000 Hz (measurement range ±0.5g) that is positioned by hand in a pre-marked place on the wall. The emitter is a specialized instrumented hammer that creates an initial signal by striking the wall. It has a specially shaped tip suitable for precise signal generation on the wall. The hammer and accelerometer are connected to a data processing system that is connected to a computer. In principle, the method is similar to the ultrasonic pulse velocity test, which is often used for the mechanical characterization of concrete. The main difference is the frequency (i.e. number of elastic waves emitted per second) of the transducers, which can be sonic or ultrasonic, e.g. frequency higher than 20 kHz is considered ultrasonic. Since there are no sonic test guidelines, the European and American guidelines for ultrasonic pulse velocity test given in [12,13] can serve as a reference.

In general, three different test configurations are possible depending on the position of the hammer and the accelerometer. The first is the direct configuration where the hammer and the accelerometer are placed in the same position but on opposite faces of the wall. The second is an indirect configuration where the hammer and the accelerometer are located on the same face of the wall. In the present research, an indirect configuration (Figure 3a) following a vertical direction was selected, aiming to estimate the vertical modulus of elasticity of the masonry. Tests are carried out at the wall side from where flat-jack tests are performed to take advantage of the surface preparation, which included render removal. The mentioned test procedure is shown in Figure 3b. Similar sonic investigations, but on regular and irregular stone masonry, are carried out in [14,15].

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After testing, it is necessary to process the obtained data. The data display is shown in Figure 3c. The velocity (V_P) is calculated by measuring the travel time between the emission of the signal by the hammer and the reception of the signal by the accelerometer, divided by the distance between the transducers. The propagation velocity is then inserted into Eq. (1) from which the value of the dynamic modulus of elasticity (E_d) is obtained. Additional required data are the density (ρ) and Poisson's ratio (ν) of the masonry. In this study, the values for density and Poisson's ratio are taken from the literature [16,17] for the corresponding masonry typology (solid brick masonry in lime mortar). The density is taken as 1800 kg/m^3 and the Poisson's ratio as 0.2.

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

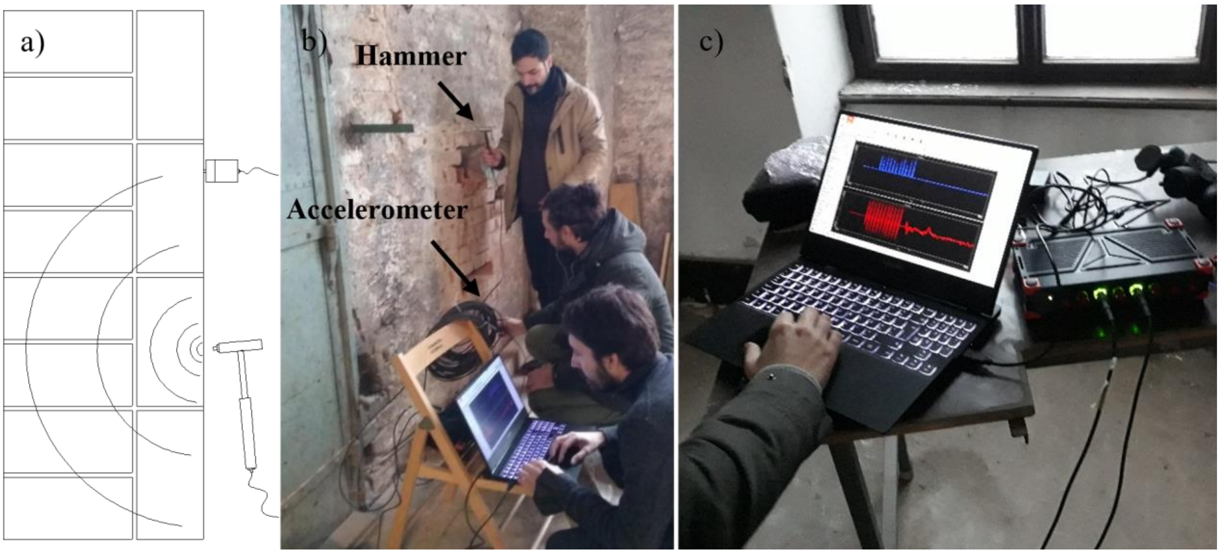

Figure 3. a) In-direct configuration; b) Test procedure; c) Data display.

3. Results

The results are obtained on eight different case study buildings at a total of 22 test locations. Several tests were carried out on each building. The results obtained on the same case study building are shown in the same colour for easier reference. The order of the results corresponds to the order of the case study buildings shown in Figure 1. The results of the flat-jack tests are presented in Figure 4, while Figure 5 presents the results of the sonic tests.

It should be emphasized that the values obtained by the flat-jack method represent the static modulus of elasticity, while the values obtained by the sonic method represent the dynamic modulus of elasticity. As a rule, the dynamic modulus of elasticity is 10-20% higher than the static modulus of elasticity [18]. The empirically observed inequality between static and dynamic modulus of elasticity of masonry and its components has been noted in several studies [19,20], which can be attributed to the different strain rate in the load application [21].

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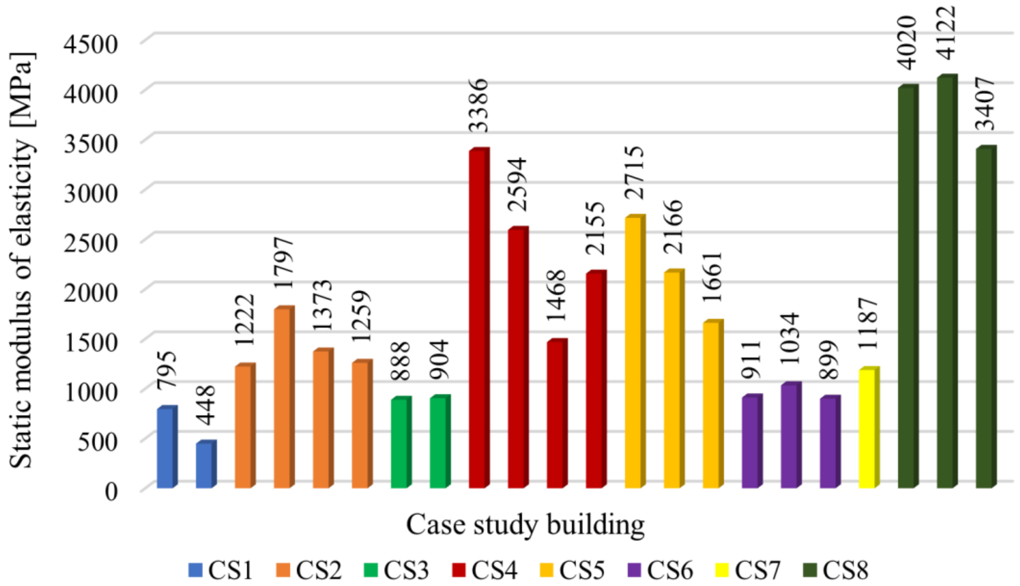

Figure 4. Flat-jack test results.

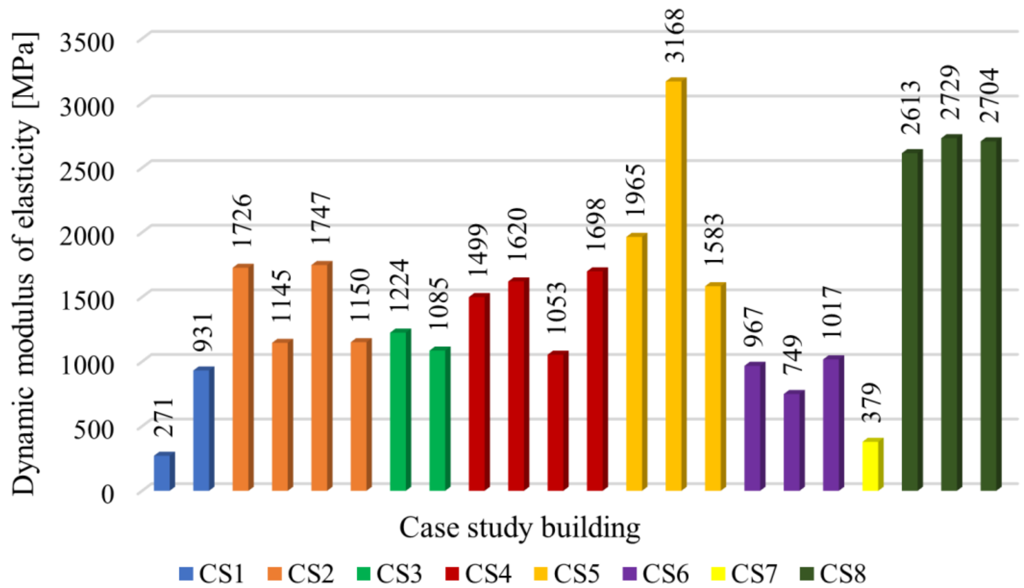

Figure 5. Sonic test results.

From Figure 4 and Figure 5 it can be seen that the results deviate not only from building to building but even, to a certain extent, within the same building. In existing masonry structures, scattering of results is expected and normal occurrence. This is not surprising considering that the mechanical properties are affected by numerous parameters such as material quality, construction quality, maintenance, degradation over time and similar effects. This is also why fast testing methods that allow an estimation of the variability of the masonry throughout the building are particularly important.

Figure 6 illustrates the mean values of the modulus of elasticity obtained by the sonic and flat-jack methods for each case study building. Flat-jack test results are shown in blue, while sonic test results are shown in orange. Below the graph, the exact values for each case study are shown in tabular form.

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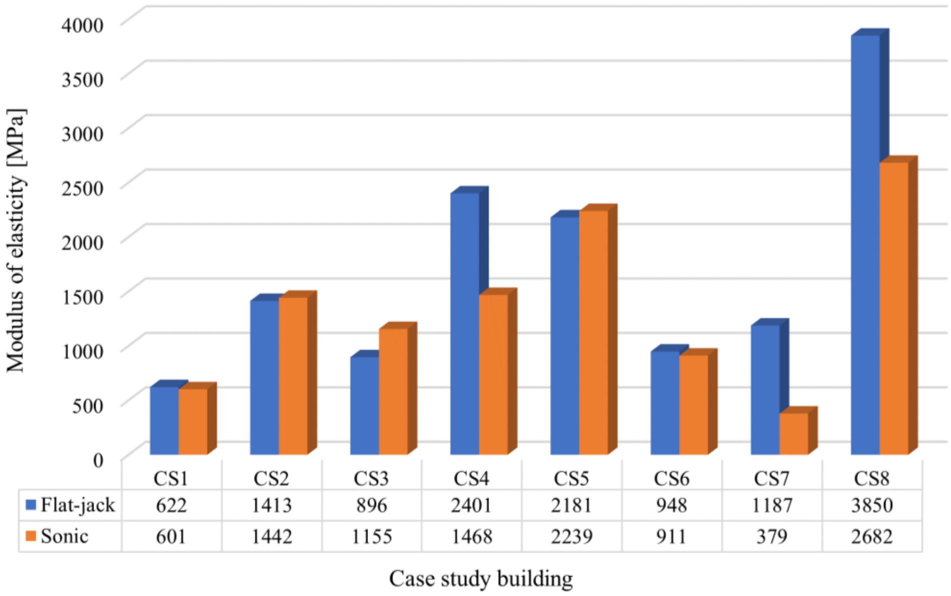

Figure 6. Comparison of results obtained by the sonic and flat-jack method.

Results of the flat-jack testing campaign will be published in more detail in [22] and more extensive insight into the comparison between flat-jack and sonic test results can be found in [23].

4. Discussion

Determining the actual seismic behavior of existing masonry structures is of great importance for future management and the economical and purposeful strengthening of the load-bearing structure [24]. Modern software solutions and design methods are an essential part of the assessment, but they are only as useful as long as the input parameters are reliable. This is where in-situ test methods come into play, providing useful information about the mechanical properties of the structure.

The sonic method is quite straightforward and the preparation as well as conducting of the test is relatively simple compared to the flat-jack method, not to mention the speed that is incomparable in favor of the sonic method, which allows measuring more locations within the same building and assess the variability of the masonry properties. The non-destructive nature of the test is also quite a big advantage, considering that it is only necessary to remove a layer of plaster in order to reach the masonry. But on the other hand, the flat-jack method also provides other useful parameters such as the vertical stress state as well as the shear properties of the masonry. Similar research combining NDT and SDT methods, but only at one test location, was carried out in [25].

The sonic method has been found to have the potential to be an indispensable part of the research arsenal when dealing with existing masonry. It was also shown that there is a certain correlation between the results obtained by the two methods. Incorporating the sonic method into a standard application during the assessment process can result in less destructive, more economical, but equally valuable investigative testing. In this way, the next phases such as design and strengthening will not be disturbed, and the entire reconstruction process will be more efficient. In addition to strengthening, it is of great importance to think about aspects of energy efficiency [26,27] and the preservation of cultural heritage [28,29] as well.

5. Conclusions

This research presents a comparison of the elastic properties of existing solid brick masonry obtained by different test methods. Sonic pulse velocity test and flat-jack test methods are used and presented. A comprehensive research campaign was undertaken on the continental part of Croatia on eight existing

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unreinforced masonry structures. The tested structures are damaged in the recent earthquakes and are currently undergoing rehabilitation and strengthening. The presented work yielded new insights into the elastic properties of the existing unreinforced solid brick masonry buildings in Croatia.

The following list summarizes the main conclusions obtained from the research:

- The results deviate considerably in some cases, which is in the expected range considering that the existing masonry is tested, as well as the fact that these are different buildings with their inherited intrinsic differences and built in different times.
- The test results obtained by the mentioned two test methods have a positive correlation.
- The sonic method has the potential to be used in more locations given the faster procedure, which allows to assess the variability of the masonry elastic properties within a building.

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