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Aleksandar Radević[1], Dragan Nikolić[2], Marko Marinković[3]

TESTING OF MASONRY WALLS FOR STRUCTURAL CONDITION ASSESSMENT AND MASONRY STRUCTURE DESIGN

Summary: The assessment of existing masonry structures requires reliable information on their actual material properties, stress state, stiffness, and load-bearing capacity. This paper presents a methodology for the investigation and characterization of existing masonry walls, combining visual inspection, laboratory testing of masonry units and mortar, and in-situ testing using flat jacks. Particular emphasis is placed on the compliance of the assessment procedures with applicable regulations and Eurocode provisions, as well as on the importance of properly defining the input parameters for structural analysis. Practical examples are presented to illustrate typical problems and the methods used for their identification. The test results are analysed in the context of preparing structural condition assessment reports and their application in engineering practice, with the aim of achieving a more reliable determination of the load-bearing capacity and resistance of masonry structures.

Keywords: existing masonry structures, structural assessment, in-situ testing, flat jack, shear strength

ISPITIVANJE ZIDANIH ZIDOVA U FUNKCIJI PROCENE STANJA KONSTRUKCIJE I PROJEKTOVANJA ZIDANIH KONSTRUKCIJA

Rezime: Procena stanja postojećih zidanih konstrukcija zahteva pouzdane podatke o njihovim stvarnim materijalnim svojstvima, stanju naprezanja, krutosti i nosivosti. U radu je prikazana metodologija ispitivanja i karakterizacije postojećih zidanih zidova, koja obuhvata vizuelni pregled, laboratorijska ispitivanja elemenata za zidanje i maltera, kao i ispitivanja in-situ primenom vazdušnih jastuka (flat jack). Poseban akcenat je na usklađenosti postupaka sa važećim propisima i smernicama Evrokodova, kao i na značaju pravilnog definisanja ulaznih parametara za proračun. Kroz primere iz prakse prikazani su tipični problemi i načini njihove identifikacije. Rezultati ispitivanja analizirani su u kontekstu izrade elaborata procene stanja konstrukcije i njihove primene u projektantskoj praksi, sa ciljem pouzdanijeg određivanja nosivosti i otpornosti zidanih objekata.

Ključne reči: postojeće zidane konstrukcije, stanje konstrukcije, in-situ ispitivanje, flat-jack, nosivost na smicanje, čvrstoća pri smicanju

[1] University of Belgrade, Faculty of Civil Engineering, Belgrade, Serbia, aradevic@grf.bg.ac.rs
[2] Academy of Thechnical and Art Applied Studies-Belgrade, Serbia
[3] University of Belgrade, Faculty of Civil Engineering, Belgrade, Serbia

1. INTRODUCTION

A large proportion of the existing building stock in Serbia and across Europe was constructed several decades ago, in accordance with regulations, construction technologies, and levels of quality control that differ considerably from those applied today. The European Environment Agency estimates that more than 85% of today's buildings will still be in use in 2050 [1]. Consequently, the assessment of existing structures, their rehabilitation, and the extension of their service life will become increasingly important. Reaching the design service life does not automatically mean that a structure is unsafe or that it should be replaced; however, it does mean that the original design assumptions can no longer be relied upon without verification. Before decisions are made regarding a change of use, vertical extension, removal of individual walls, increase in imposed loads, or seismic strengthening, the actual condition of the structure must be assessed and reliable input parameters for structural analysis must be established.

The first step in such a procedure is to review the available technical documentation and conduct an inspection of the structure. An inspection should not be limited to recording visible cracks, but should instead involve the systematic collection of information on the structural system, geometry, support conditions, previous interventions, and all phenomena that may affect load-bearing capacity, stability, serviceability, and durability. During a visual inspection, the location, orientation, and width of cracks and fissures, local crushing, delamination and loss of material, deformations and deflections, signs of settlement, moisture and salt deposits, corrosion of reinforcement and steel components, as well as the condition of connections, floor structures, vaults, foundations, and characteristic structural details are recorded. The findings should be related to the building plans and sections, documented photographically, and classified according to their possible causes and significance. It is particularly important to distinguish between damage that has stabilized and active phenomena, for which additional measurements or monitoring are required.

The importance of inspection is also recognized by the Regulation on Construction Structures [2]. Articles 21–23 prescribe basic and detailed inspections aimed at determining and assessing the condition of a structure. A basic inspection includes a review of the available documentation and a visual inspection of the main structural elements, whereas a detailed inspection includes a thorough examination of foundations, load-bearing elements, structural geometry, supports, corrosion protection, utility connections, and other components relevant to the safety and functioning of the building. Where deficiencies that may affect the fulfilment of the basic requirements are identified during an inspection, the Regulation requires additional checks and testing. Accordingly, a visual inspection should be regarded as the basis for developing an investigation programme, rather than as a substitute for testing and structural analysis.

A testing report represents an important, and often indispensable, source of information. It contains a description of the measurement locations, the methods applied, the results obtained, their statistical analysis, and an expert assessment of the tested materials and structural elements. However, without developing a structural analysis model and verifying the structure, a final conclusion regarding the global load-bearing capacity and stability of the building cannot be drawn solely from such a report. In the authors' previous practice, the majority of assignments involved the preparation of such reports, which were subsequently used as input data by structural designers. A clear distinction between these two levels of documentation is also important for the investor, as it prevents the expectation that partial testing alone constitutes a comprehensive assessment of the condition of the structure.

The scope of testing is determined by the structural type, the planned interventions, and the findings obtained during the inspection. For masonry structures, it is necessary to determine the wall thickness and interconnection, the quality of connections with transverse walls and floor structures, the presence of tie beams, the condition of lintels and areas surrounding openings, as well as the properties of masonry units and mortar. Laboratory testing can be used to determine the normalized strength of masonry units and the compressive strength of mortar, while in-situ testing can provide information on the existing stress state, modulus of elasticity, and initial shear strength of masonry. The results obtained are used to determine the design properties of masonry in accordance with Eurocode 6 [3] and to develop a realistic structural model. The testing programme should therefore include representative walls from different storeys, orientations, thicknesses, load levels, and states of preservation, rather than being limited to the most accessible measurement locations.

SRPS EN 1998-3 [4] bases the assessment of existing structures on the available documentation, geometry, structural details, and material properties, with the extent of available knowledge affecting the knowledge level and the reliability of the structural analysis. When original documentation is unavailable or the as-built condition differs from the design, assumed values may lead to two equally undesirable outcomes: overestimation of safety or an unnecessarily conservative strengthening design. The structural designer requires data that can be directly incorporated into the analysis, together with a clearly defined method of determination and an indication of the scatter of the results. For the investor, the same data provide a basis for assessing the technical feasibility, risks, scope of works, costs, and consequences of the planned reconstruction before a decision is made.

The visual impression of structural quality is often insufficient. Concrete may have a compact and undamaged surface while core samples reveal low or highly variable strength due to its composition, placement procedures, segregation, or subsequent deterioration. Similarly, in older masonry buildings, the masonry units may be of relatively good quality, while lime-based or degraded mortar may result in low initial shear strength and unfavourable behaviour of the wall under horizontal actions. Therefore, the properties of an individual material should not automatically be extrapolated to the behaviour of the structural element as a whole, nor should the condition of the facade or finishing layers be equated with the condition of the load-bearing structure.

This paper presents methods for characterizing existing masonry walls and selected results obtained from buildings of different types and ages. Particular emphasis is placed on the relationship between inspection findings, experimentally determined properties, and their application in structural analysis. The aim is to demonstrate that a reliable assessment of the condition of an existing structure cannot be derived from a single method or individual test result, but rather from an integrated procedure that combines documentation, inspection, targeted testing, engineering interpretation, and structural verification.

2. METHODOLOGY FOR TESTING THE MATERIAL PROPERTIES OF MASONRY WALLS

2.1. PROPERTIES OF MASONRY UNITS AND MORTAR

For a comprehensive characterization of masonry walls, it is necessary to investigate not only the properties of the walls themselves, but also the characteristics of the masonry units (most commonly bricks) and mortar. In order to obtain brick specimens with their full nominal dimensions, the specimen must first be exposed and separated from the surrounding masonry on all sides. This process is usually accompanied by localized damage to the wall in the sampling area. The specimens obtained in this way must be carefully cleaned of mortar residues, taking particular care to avoid damaging the original brick material during this procedure (Figure 1). Subsequently, a thin layer of cement mortar is applied to both bearing surfaces of the brick specimens. Once the mortar has hardened, the specimens are ready for testing.

Figure 1: Prepared brick specimens

Unlike brick specimens, it is not possible to prepare standard mortar prisms with dimensions of 40×40×160 mm from existing masonry. Namely, mortar in masonry walls is present in the joints between adjacent masonry units, and the thickness of these joints is typically in the range of 10–20 mm. Nevertheless, in order to obtain information on the compressive strength of the mortar, prismatic specimens can be prepared from mortar extracted from the joints by subsequent processing, and these specimens can then be subjected to the relevant tests. For this purpose, the Laboratory for Materials applies an in-house method developed by the Institute for Materials and Structures, according to which mortar fragments extracted from masonry joints are processed into small "cubes" with edge lengths of 10–20 mm, and the compressive strength of the mortar is determined by testing these specimens (see Figure 2).

Figure 2: Processed specimens of mortara

The measured compressive strength can subsequently be converted into the normalized compressive strength, f_b, which is used in structural design. The measured compressive strength is multiplied by the shape factor d, assigned according to the dimensions of the specimens measured after surface preparation (Table 1).

$$f_b = d \cdot f_{m,deklarisano} \tag{1}$$

Table 1: Shape factor d for determining the normalized compressive strength [5]

Width (mm) / Height (mm)	50	100	150	200	≥250
40	0,80	0,70	-	-	-
50	0,85	0,75	0,70	-	-
65	0,95	0,85	0,75	0,70	0,65
100	1,15	1,00	0,90	0,80	0,75
150	1,30	1,20	1,10	1,00	0,95
200	1,45	1,35	1,25	1,15	1,10
≥250	1,55	1,45	1,35	1,25	1,15

Based on the results of the experimental tests, the compressive strength of the masonry under consideration can subsequently be determined using the empirical relationships provided in Eurocode 6. The characteristic compressive strength of masonry, f_k, according to Eurocode 6 is determined as:

$$f_k = K \cdot f_b^{\alpha} \cdot f_m^{\beta} = 0.55 \cdot f_b^{0.7} \cdot f_m^{0.3} \quad (2)$$

where:

K = 0.55, α = 0.70, β = 0.3,

f_b is normalized compressive strength of the brick,

f_m is compressive strength of the mortar.

2.2. IN-SITU STRESS STATE IN MASONRY WALLS

Prior to any in-situ testing, the test locations must be prepared by removing the surface finish and mortar layer down to the brick units (Figure 3). The mortar should be removed carefully and without applying excessive impact energy in order to avoid damaging the masonry units or disturbing the integrity of the masonry.

The determination of the existing stress state in masonry walls is defined in the RILEM Recommendation MDT. D. 4: *In-situ Stress Tests Based on the Flat Jack* [6]. The test is performed in a series of steps, as shown in Figure 4. After selecting the test location, measurement gauges are installed on the wall at equal distances from the mortar joint that will be removed in one of the subsequent steps. In the second step, the distances between the measurement points are recorded. The selected mortar joint is then removed, and the distances between the measurement points are measured again. The difference between these two measurements represents the deformation of the wall surface caused by the removal of the mortar joint. This deformation is subsequently compensated for using a hydraulic fluid-filled flat jack, which is inserted into the slot created at the location of the removed joint. In the final step, the pressure within the flat jack required to compensate for the deformation of the wall surface caused by the removal of the mortar joint is measured.

Figure 3: Preparation of the test location

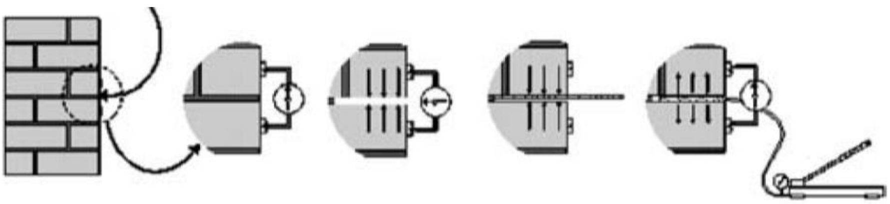

Figure 4: Test procedure according to RILEM Recommendation MDT. D. 4 [6]

Figure 5: Test arrangement for determining the stress state in masonry walls

Once the hydraulic pressure (p) in the flat jack has been measured, the corresponding stress in the wall (S_r) is calculated, i.e., the existing stress state in the masonry wall is determined using the following equation:

$$S_r = K_e \cdot p \cdot A_{slot} / A_{je} \tag{3}$$

where:
K_e is coefficient accounting for the geometry and position of the flat jack and the mortar joint,
A_{slot} is area of the cut in the wall (the area where the mortar joint has been removed),
A_{je} is effective area of the flat jack.

Figure 6: Test arrangement for determining the modulus of elasticity

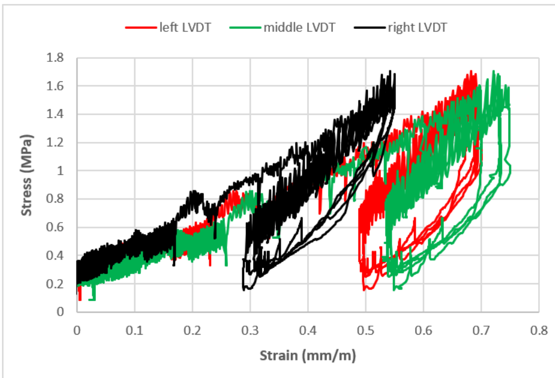

Figure 7: Stress–strain relationship

2.3. MODULUS OF ELASTICITY

The determination of the modulus of elasticity of masonry walls is defined in RILEM Recommendation MDT. D.5 – *In-Situ Stress–Strain Behaviour Tests Based on the Flat Jack* [7]. The test is performed according to the arrangement shown in Figure 6, using three LVDT devices for measuring deformation. After selecting the test location, measurement gauges are installed on the wall at equal distances between two mortar joints, which are subsequently removed. After removing the selected mortar joints, flat jacks are inserted at the respective locations. The LVDT devices are then installed to measure the resulting deformations.

The test procedure involves cyclic loading and unloading of the masonry specimen within the working stress range, effectively conditioning the test area through repeated loading cycles (Figure 7). During the loading and unloading cycles, the pressure in the flat jacks and the deformations measured by the LVDT devices are simultaneously recorded. In accordance with the provisions of the recommendation, the measured values are subsequently converted into stress and strain values in the masonry wall.

Figure 8: Test arrangement for determining the initial shear strength of masonry walls

2.4. INITIAL SHEAR STRENGTH OF MASONRY WALLS

The determination of the initial shear strength of masonry walls is defined by *ASTM C1531-15 – Standard Test Methods for In Situ Measurement of Masonry Mortar Joint Shear Strength Index [8]*. The test is performed according to the arrangement shown in Figure 8. After selecting the test location (the reference brick unit), the adjacent brick units are removed on both its left and right sides to provide sufficient space for installing the testing jack. After the adjacent brick units have been removed, LVDT devices are installed to measure the resulting deformations.

After adjusting the initial compressive stress in the flat jacks, the pressure applied by the testing jack is gradually increased until the shear strength is reached, i.e., until the brick unit subjected to the lateral force slips relative to the surrounding masonry. The force at which the brick unit begins to slip is recorded.

It should be noted that all of the above-mentioned tests are complex, both in terms of preparing the test locations and in terms of conducting the tests themselves. This is primarily due to the often irregular masonry bond patterns and the orientation of the brick units, which may require extensive and demanding destructive interventions to create clearly defined shear planes. In addition, all of the aforementioned tests require appropriate field and laboratory equipment with the required level of measurement accuracy.

3. SELECTED CASE STUDIES OF TESTED STRUCTURES

The following section presents several representative structures on which the previously described testing methods were applied. The obtained values of the investigated parameters are presented in Table 2.

Table 2: Values of the investigated parameters for masonry structures in different buildings

Structures	Hotel Union, Belgrade (Fig. 3.1)	Tunnel beneath the Petrovaradin Fortress (Fig. 3.2)	Former Railway Station in Belgrade (Fig. 3.3)
The normalized compressive strength of the brick	11.3 - 9.4 MPa	11.3 MPa	11.3 MPa
The compressive strength of the mortar	0.5 – 7.7 MPa, (average 2.9 MPa)	0.2 – 2.2 MPa, (average 1.3 MPa)	0.7 – 3.2 MPa, (average 1.7 MPa)
The characteristic compressive strength of masonry, f_k	1.9 – 4.4 MPa, (average 2.9 MPa)	2.2 – 2.8 MPa, (average 2.5 MPa)	2.4 – 3.6 MPa, (average 2.9 MPa)
The modulus of elasticity of the masonry walls	2.8 – 4.5 GPa, (average 3.7 GPa)	4.9 – 8.8 GPa, (average 6.2 GPa)	2.3 – 5.9 GPa, (average 4.3 GPa)
The stress levels within the masonry walls	-	0.39 - 0.92 MPa, (average 0.78 MPa)	0.35 – 1.27 MPa, (average 0.87 MPa)
The initial shear strength of the masonry walls	0.06 - 0.46 MPa, (average 0.18 MPa)	0.29 - 0.65 MPa, (average 0.48 MPa)	0.08 - 0.34 MPa, (average 0.21 MPa)

Figure 9: Hotel Union in Belgrade

Figure 10: Petrovaradin Fortress

Figure 11: Example of testing at the Former Railway Station in Belgrade

Finally, it is important to emphasize that, when assessing the condition of a structure and designing interventions for masonry structures, testing should not be limited to the masonry walls. All other structural elements that may be made of different materials, such as concrete, steel, timber, and similar materials, should also be investigated. In practice, masonry structures are often combined with reinforced concrete (RC) elements, such as horizontal and vertical tie beams, ribbed floor systems, and columns. Given that such structures are typically several decades old, practical experience has shown that the quality of concrete in these structures is often very low. This may lead to the conclusion that the existing concrete does not satisfy the compressive-strength requirements corresponding to structural concrete strength classes.

4. CONCLUSIONS

The assessment and testing of masonry structures represent essential and indispensable activities in evaluating their condition, as they enable a reliable assessment of the actual stress state and load-bearing capacity of masonry walls, some of which may be more than 100 years old. Masonry structures constitute a significant proportion of the existing building stock, particularly among historic and older buildings constructed using bricks, stone, or masonry units of varying quality. Over their long service life, these structures are exposed to a variety of effects, including variable loads, moisture, temperature variations, chemical processes, foundation settlement, and occasional seismic actions. These effects may result in the development of fissures, cracks, deformations, and reductions in load-bearing capacity. Therefore, detailed testing is of particular importance for establishing the actual condition of a structure and identifying, at an early stage, any forms of deterioration that may compromise its stability and safety. The results of testing provide a basis for engineering decisions concerning the need for and methods of repair, rehabilitation, strengthening, or changes in the use of the building. Without adequately performed testing, it is not possible to assess with sufficient confidence whether an existing structure can safely sustain the current or newly proposed loads.

Modern assessment procedures involve the application of both destructive and non-destructive methods. Non-destructive methods allow the structure to be investigated without significantly compromising its integrity, whereas destructive methods provide more precise information on the mechanical properties of materials through laboratory testing of extracted specimens. By combining these methods, reliable information can be obtained regarding masonry strength, mortar quality, the properties of masonry units, the degree of deterioration, and the overall homogeneity of the structure.

The testing of masonry structures is particularly important for buildings located in seismically active areas, where their resistance to earthquake actions must be assessed. Numerous studies have shown that masonry structures are among the most vulnerable structural systems when they have not been designed or constructed in accordance with modern standards. Consequently, test results provide an essential basis for developing numerical models, performing seismic analyses, and designing appropriate strengthening measures. In addition to the safety aspect, the testing of masonry structures also has an important economic role. Early detection of damage can prevent its further progression, reduce rehabilitation costs, and extend the service life of a building. This contributes to more rational building management, preservation of cultural and historical heritage, and improved reliability of structures throughout their service life. Such investigations require careful preparation of test locations, the engagement of a qualified expert team, the use of specialized field and laboratory equipment, as well as the processing and interpretation of data using appropriate software tools. Consequently, the cost of such investigations cannot be expected to be low; however, they represent a justified investment in a reliable assessment of structural condition and in preventing substantially higher costs resulting from incorrect design decisions.

Test results do not necessarily lead to a greater extent of strengthening. An equally important role of testing is to confirm favourable properties that could not be safely assumed without measurements. In the masonry walls of the Hotel Union in Belgrade, significantly different values of initial shear strength were obtained, ranging from 0.06 MPa to 0.46 MPa, with an average value of 0.18 MPa. In certain walls, including those in basement areas, the more favourable results enabled a more realistic verification of load-bearing capacity compared with an analysis based on general and conservative assumptions. Such findings can directly reduce the number and extent of strengthening measures and, consequently, the cost and duration of works, as well as the loss of original and authentic material. Conversely, low measured values indicate locations where intervention is genuinely required. Testing should therefore not be regarded merely as a cost incurred prior to structural design, but rather as a tool for managing both technical and financial risk.

This paper provides a concise overview demonstrating that a properly planned combination of visual inspection, field testing, and laboratory investigations can provide reliable input data for a realistic assessment of the condition and load-bearing capacity of existing masonry structures. The application of such data enables both the structural designer and the investor to make technically justified and economically rational decisions regarding the continued use, reconstruction, rehabilitation, or strengthening of an existing building.

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