An insight into The Masonry Quality Index (MQI) method for the visual assessment of existing masonry structures

Hafner, Ivan; Kišiček, Tomislav; Renić, Tvrtko; Ožić, Karlo

1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.188

An insight into The Masonry Quality Index (MQI) method for the visual assessment of existing masonry structures

Ivan Hafner[1], Tomislav Kišiček[2], Tvrtko Renić[3], Karlo Ožić[4]

[1] *Assistant*, University of Zagreb Faculty of Civil Engineering, *ivan.hafner@grad.unizg.hr*
[2] *Professor*, University of Zagreb Faculty of Civil Engineering, *tomislav.kisicek@grad.unizg.hr*
[3] *Assistant*, University of Zagreb Faculty of Civil Engineering, *trenic@grad.unizg.hr*
[4] *Assistant*, University of Zagreb Faculty of Civil Engineering, *karlo.ozic@grad.unizg.hr*

Abstract

A vast majority of buildings built in Croatia are masonry buildings. A fair amount of these buildings was built before the development of seismic codes. Also, most of the structures that are considered to have great historical and cultural value are in fact built in masonry. If all the above is taken into account with the Zagreb earthquake being just the most recent reminder of the seismic fragility of these types of structures, it is safe to say that the assessment and rehabilitation of masonry structures should be one of the greatest priorities in the civil engineering community.
When talking about the assessment process, the visual inspection of a structure is one of the first and most important phases. For the purposes of the visual assessment of masonry structures, a specific analytical method was developed in Italy called the Masonry Quality Index (MQI) method. In this paper an insight into the said method will be given. Also, the use of this method on a typical case study of a masonry building in Zagreb will be shown. Concluding remarks about the quality and usability of the method will be drawn and discussed.

Key words: masonry structures, post-earthquake assessment, visual assessment methodology, cultural heritage

1 Introduction

As it is already well known, on 22nd of March 2020., Zagreb was hit by an earthquake of 5,5 magnitude according to the Richter magnitude scale. Although only a few casualties were reported, the structural damage that the city centre and the entire city sustained was immense. This fact is not that surprising if it is considered that most of the building stock in Zagreb and in Croatia are masonry buildings that were constructed before the development of seismic codes [1]. Furthermore, for most of these buildings it is obvious that no type of renovation or reconstruction methods were implemented throughout the years. The primary reasons for this problem are negligence and the financial aspect of the needed interventions.

A similar situation was found in L'Aquila, Italy, in 2009. With the lessons learned from that event and the ones that came before, a team of experts developed a visual assessment method that is used for a rapid assessment of a masonry wall before or after a seismic event. The method is known as the Masonry Quality Index (MQI method). This type of method can be of extreme help in a post-disaster assessment of a masonry structure when some preliminary results and conclusions of a wall's behaviour should be drawn out.

2 The Masonry Quality Index

The behaviour of a wall, as a heterogenous system, is dependent on a variety of factors such as compressive and shear strength of masonry elements and the mortar between them, the dimensions and shape of wall elements and their texture [2, 3]. Since the number of factors is much greater than the ones mentioned, for a precise determination of the load bearing capacity and the quality of a wall, destructive and semi destructive assessment methods usually need to be implemented [4]. The use of this type of assessment methods in buildings of high cultural and historical significance is unacceptable [5]. To avoid such problems and to provide a clear picture of the wall's quality and behaviour in the fastest possible way, the MQI method was formulated. The basic idea is to establish a simple and systematic approach for the analysis and the assessment of the condition of a masonry wall or structure. This approach is based on the ideal behaviour of a wall and the evaluation of the mechanical properties of the materials used in a wall (stone, brick, mortar etc.). In total, seven parameters are assessed. It should be noted that the MQI method is based on the engineering knowledge and subjective thinking of the engineer conducting the examination of the building. The main task is to place the beforehand mentioned seven parameters into three different categories. The possible categories include: F-Fulfilled, PF-Partially Fulfilled and NF-Not Fulfilled [3]. In the following text seven main parameters will be presented with the instructions how to categorize them.

2.1 Mechanical properties of masonry elements (SM)

This parameter considers the conservation state and the mechanical properties of only bricks and stones. Types of masonry elements and the according categories are given in Table 1.

Table 1. Criteria for the analysis of stone/brick mechanical properties (SM)

Category	Type of masonry
NF	a) Degraded/damaged elements (>50% of total number) b) Hollow bricks (solid <30%) c) Mud bricks d) Unfired bricks
PF	a) Degraded/damaged elements (10-50% of total number) b) Hollow bricks (solid 30-55%) c) Sandstone or tuff elements
F	a) Undegraded or degraded/damaged elements (<10% of total number) b) Hollow bricks (solid >55%) c) Solid fired bricks d) Concrete blocks e) Hardstone

2.2 Stone/bricks dimension properties (SD)

This parameter considers the dimensions of bricks and stones. Types of masonry elements and the according categories are given in Table 2 and Figure 1.

Table 2. Criteria for the analysis of stone/brick dimensions (SD)

Category	Type of masonry
NF	a) Presence of more than 50% of elements with dimensions < 20 cm
PF	a) Presence of more than 50% of elements with large dimensions 20-40 cm b) Co-presence of elements with different dimensions
F	a) Presence of more than 50% of elements with large dimensions > 40 cm

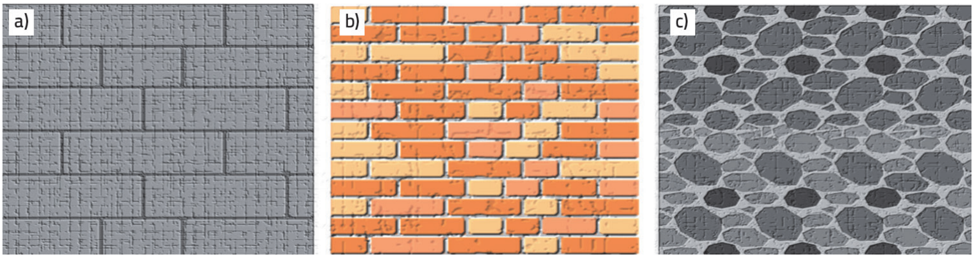

Figure 1. Masonry element dimension properties (SD): (F) (PF) (NF)

2.3 Stone/bricks shape (SS)

This parameter considers the dimensions of bricks and stones. Types of masonry elements and the according categories are given in Table 3.

Table 3. Criteria for the analysis of stone/brick shape (SS)

Category	Type of masonry
NF	a) Rubble or predominant pebble stonework on both masonry leaves
PF	a) Co-presence of rubble or pebble stonework and barely/perfectly cut stones and bricks on both masonry leaves b) One masonry leaf made of perfectly cut stones or bricks c) Masonry made from rubble, rounded or pebble stones but with presence of pinning stones
F	a) Barely/perfectly cut stones on both masonry leaves or brickwork

2.4 Wall leaf connections (WC)

This parameter considers the connection between adjacent leaves of a wall. This connection has considerable effect on the global behaviour of a masonry structure. This parameter can be determined through a qualitative and quantitative analysis.
In the qualitative analysis, where the wall section is not visible, the out-of-plane behaviour of a wall is assessed through the presence of headers between two masonry leaves. Headers are masonry elements that are placed perpendicular to the way in which the wall is laid as shown in Figure 2. Types of masonry wall configurations vis-à-vis the wall leaf connections are given in Table 4.

Table 4. Criteria for the analysis of wall leaf connections (WC) – qualitative analysis

Category	Type of masonry
NF	a) Small stones compared to the wall thickness b) No headers or less than 2 headers/m^2
PF	a) Presence of headers (2-5 headers/m^2) b) Wall thickness larger than the stone larger dimension
F	a) Wall thickness larger than the stone larger dimension b) Systematic presence of headers (more than 5 headers/m^2)

On the other hand, if the wall section is visible, the quantitative analysis may be performed. This method is based on the value of "minimum length" M_l measured between two points. This non-dimensional value is the ratio between the minimum distance to connect two points on the wall's surface passing only through mortar joints and the straight distance between those two points. This ratio is shown in Figure 3. The straight distance that was just mentioned is equal to 1 m but can go down to the value of 50 cm. The categorization of walls by the value of M_l is given in Table 5.

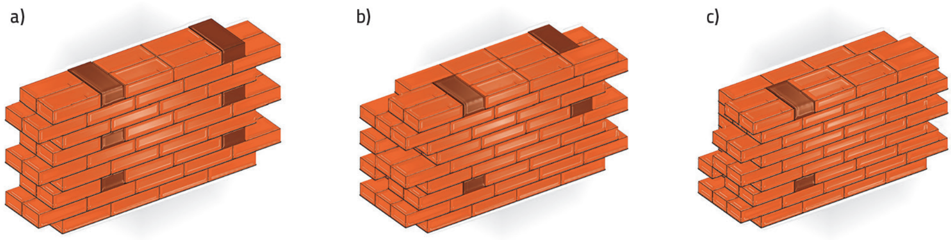

Figure 2. Wall leaf connections parameter (WC)

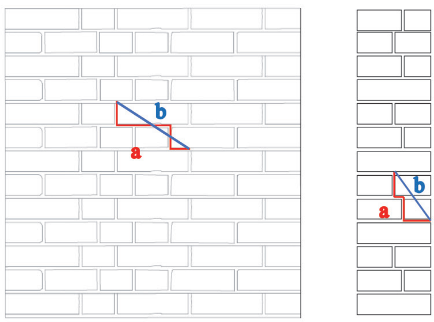

Figure 3. Calculation of value M_l

Table 5. Criteria for the analysis of wall leaf connections (WC) – quantitative analysis

Category	Type of masonry
NF	a) $M_l < 1{,}25$ b) Small stones for any value of M_l
PF	a) $1{,}25 < M_l < 1{,}55$
F	a) $M_l > 1{,}55$

2.5 Horizontal bed joint characteristics (HJ)

This parameter considers the horizontality of bed joints that may highly affect the lateral and compression strength of a masonry wall panel. Types of masonry walls regarding their horizontality are shown in Figure 3 and the according categories are given in Table 6.

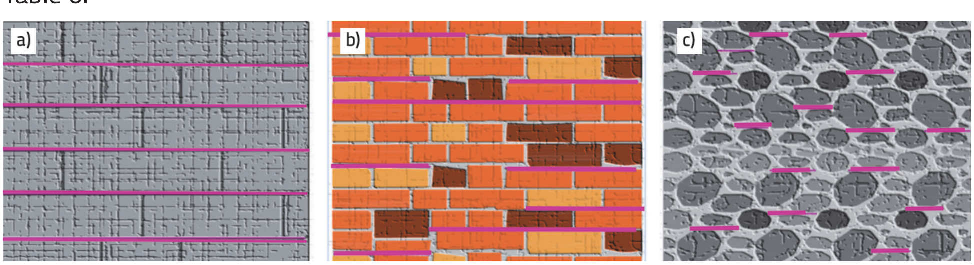

Figure 4. Horizontality of bed joints

Table 6. Criteria for the analysis of horizontality of bed joints (HJ)

Category	Type of masonry
NF	a) Bed joints not continuous
PF	a) Intermediate case between NF and F b) For double leaf wall One leaf with continuous bed joints
F	a) Bed joints continuous

2.6 Vertical joint characteristics (VJ)

This parameter can be determined through a qualitative and quantitative analysis.
In the qualitative analysis, the position of vertical joints is assessed. Types of masonry wall configurations vis-à-vis the staggering of vertical joints are given in Figure 5 and Table 7.

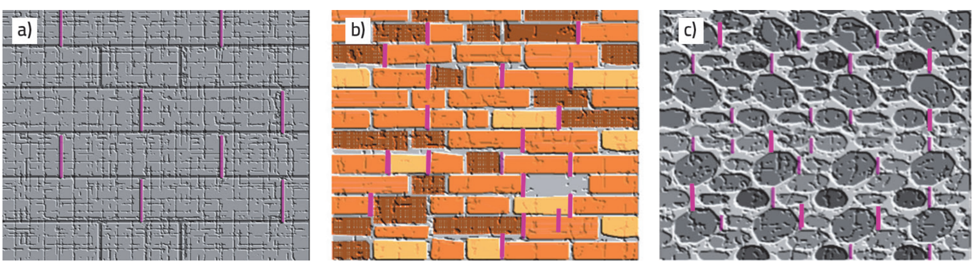

Figure 5. Staggering of vertical joints

Table 7. Criteria for the analysis of stagger properties (VJ) – qualitative analysis

Category	Type of masonry
NF	a) Aligned vertical joints b) Aligned vertical joints for at least two large stones c) Solid brick wall made of only headers
PF	a) Partially staggered vertical joints (vertical joint between two bricks is not placed in the middle of adjacent upper and lower brick)
F	a) Properly staggered vertical joints (vertical joint between two bricks is placed in the middle of adjacent upper and lower brick)

On the other hand, the quantitative analysis is based on the value of "minimum length" M_l that was mentioned before. The only difference is the usage of only vertical joints in the process of determining the value of M_l. The categorization of walls by M_l value is given in Table 8.

Table 8. Criteria for the analysis of stagger properties (VJ) – quantitative analysis

Category	Type of masonry
NF	a) Single-leaf wall (M_l < 1.4) b) Double-leaf wall (M_l < 1.4 for one masonry leaf, M_l < 1.6 for the second one) c) Wall made of very small stones
PF	a) Single leaf wall 1.4 < M_l < 1.6 b) Double-leaf wall: (b1) Both leaves 1.4< M_l <1.6 (b2) For at least one leaf M_l > 1.6 (b3) First leaf M_l > 1.6 (b4) Second leaf 1.4 < M_l < 1.6
F	a) Single leaf wall M_l > 1.6 b) Double-leaf wall (both leaves M_l > 1.6)

2.7 Mortar mechanical properties (MM)

This parameter considers the mechanical properties of mortar and the quality of the bond between the mortar and the stones/bricks. Types of the mortars used, and the according categories are given in Table 9.

Table 9. Criteria for the analysis of mortar properties (MM)

Category	Type of masonry
NF	a) Very weak mortar, dusty mortar with no cohesion b) No mortar (rubble or pebble stonework) c) Large bed joints made of weak mortar (thickness comparable to stone/brick thickness) d) Porous stones/bricks with weak bonding to mortar
PF	a) Medium quality mortar, with bed joints not largely notched b) Masonry made of irregular (rubble) stones and weak mortar, but with presence of pinning stones
F	a) Good quality and non-degraded mortar, regular bed joint thickness or large bed joint thickness made of very good quality mortar b) Masonry made of large perfectly cut stones with no mortar or very thin bed joint thickness

Based on the fulfilment of the categories defined above, numerical values are given to each parameter ranging from 0 to 3 depending on the load conditions. The mentioned values are given in Table 10.

Table 10. Numerical values according to the load conditions [3]

	Vertical loading (V)			Horizontal in-plane loading (I)			Horizontal out-of-plane loading (O)		
	NF	**PF**	**F**	**NF**	**PF**	**F**	**NF**	**PF**	**F**
HJ	0	1	2	0	0,5	1	0	1	2
WC	0	1	1	0	1	2	0	1,5	3
SS	0	1,5	3	0	1	2	0	1	2
VJ	0	0,5	1	0	1	2	0	0,5	1
SD	0	0,5	1	0	0,5	1	0	0,5	1
MM	0	0,5	2	0	1	2	0	0,5	1
SM	0,3	0,7	1	0,3	0,7	1	0,5	0,7	1

Based on these values, a numerical value for MQI is calculated by the following equation [6]:

$$MQI = r \cdot SM \cdot \left(SD + SS + WC + HJ + VJ + MM \right) \tag{1}$$

where factor r takes into account that for brickwork masonry the quality of mortar is more important than for a stonework masonry wall (r=1 for stonework masonry). This parameter was analysed in detail in [7] depending on the load conditions.
Based on the results of Equation 1, the masonry wall can be placed into one of three quality categories shown in Table 11 that is the basic idea of the MQI method.

Table 11. Numerical values according to the load conditions

Category	**A (inadequate behaviour of masonry)**	**B (behaviour of average quality of masonry)**	**C (good behaviour of masonry)**
Vertical actions (V)	0<MQI<2,5	2,5<MQI<5	5<MQI<10
Out-of-plane actions (O)	0<MQI<4	4<MQI<7	7<MQI<10
In plane actions (I)	0<MQI<3	3<MQI<5	5<MQI<10

Besides the quality of a masonry wall, important mechanical properties can be obtained through this simple method such as the compressive strength f_m, shear strength τ_0 and modulus of elasticity E. The determination of this parameters will be explained on a typical masonry building in the city of Zagreb that was assessed after the March earthquake.

3 Catholic Faculty of Theology - Case study

Building of Catholic Faculty of Theology is located in Zagreb, and has a basement, ground floor, three floors and an attic. The building is built of solid bricks of the old format used in the late 19th century. The load-bearing walls' thickness is 51 cm on the ground floor, 43-51 cm 1st to 3rd floor and 28 cm on the attic.

Figure 6. Masonry wall – Catholic Faculty of Theology

After the rapid assessment was conducted in the entire building, the MQI method was performed on a typical wall section shown in Figure 6 with the results of seven parameters shown in Table 12. According to the categories shown in Table 12, a value of MQI was calculated for three different loading conditions using the values given in Table 10. The results are shown in Table 13. It is clear that the quality of masonry is satisfactory since the values of the MQI index show good behaviour of masonry.

Table 12. Parameters with assigned categories for the wall section in Figure 6

Parameter	Description	Category
SM	Degraded/damaged elements <10 %; solid fired bricks	F
SD	Presence of more than 50 % of elements with large dimensions 20-40 cm; Co-presence of elements with different dimensions	PF
SS	Brickwork	F
WC	Small stones compared to the wall thickness; No headers or less than 2 headers/m^2	NF
HJ	Bed joints continuous	F
VJ	Double-leaf wall (M_l < 1.4 for one masonry leaf, M_l < 1.6 for the second one)	NF
MM	Good quality and non-degraded mortar, regular bed joint thickness or large bed joint thickness made of very good quality mortar	F

Using the values of the MQI from Table 13, an estimation of the mechanical properties of a wall can be made using the values shown in Table 14 that was constructed using the equations given in [6]. The final results are shown in Table 15.

Table 13. Category according to the load conditions

	V	I	O
MQI	8,5	5,5	5,5
Category	C	C	B

Table 14. Estimation of mechanical properties of masonry

MQI(V)	$f_{m, min}$	$f_{m, max}$	E_{min}	E_{max}	MQI(I)	$\tau_{0, min}$	$\tau_{0, max}$
0,5	1,05	1,86	598	891	0,5	0,021	0,033
1	1,17	2,06	652	967	1	0,024	0,037
1,5	1,31	2,27	712	1049	1,5	0,027	0,041
2	1,46	2,51	776	1139	2	0,030	0,046
2,5	1,64	2,78	847	1236	2,5	0,033	0,050
3	1,83	3,07	924	1341	3	0,037	0,056
3,5	2,05	3,39	1007	1455	3,5	0,040	0,061
4	2,29	3,74	1099	1579	4	0,045	0,067
4,5	2,56	4,13	1199	1713	4,5	0,050	0,074
5	2,86	4,56	1307	1859	5	0,057	0,083
5,5	3,20	5,04	1426	2017	5,5	0,063	0,091
6	3,58	5,56	1556	2189	6	0,070	0,100
6,5	4,00	6,15	1697	2375	6,5	0,078	0,110
7	4,47	6,79	1851	2578	7	0,087	0,123
7,5	5,00	7,50	2019	2797	7,5	0,096	0,135
8	5,59	8,28	2202	3035	8	0,108	0,148
8,5	6,25	9,15	2402	3294	8,5	0,120	0,165
9	6,98	10,10	2620	3574	9	0,134	0,183
9,5	7,81	11,16	2858	3878	9,5	0,147	0,201
10	8,73	12,33	3118	4208	10	0,165	0,222

Table 15. Estimation of mechanical properties of masonry

	V		I
MQI	8,5	8,5	5,5
	f_m [MPa]	E_m [MPa]	τ_0 [MPa]
min-max	6,25-9,15	2402-3294	0,063-0,091

To conclude, it is important to mention that the destructive methods for the assessment of shear strength conducted on the Catholic Faculty of Theology have shown similar results as the MQI method which will be further discussed in future papers. This type of validation combined with the simplicity and ease with which the MQI method is conducted, make the MQI method a recommended type of visual assessment that should be conducted in a post-disaster assessment of masonry structures.

Acknowledgements

This research was funded by Croatian Science Foundation, grant number UIP-2019-04-3749.

References

[1] Stepinac, M. et al. (2020): Methods for the assessment of critical properties in existing masonry structures under seismic loads-the ARES project. Appl. Sci., 10, doi: 10.3390/app10051576.

[2] Marino, M. et al. (2014): Experimental Data of Friction Coefficients for some Types of Masonry and its Correlation with an Index of Quality Masonry (IQM), Second Eur. Conf. Earthq. Eng. Seismol., Istanbul, Turkey, 12 pages.

[3] Borri, A. et al. (2015): A method for the analysis and classification of historic masonry. Bull. Earthq. Eng., 13, 2647–2665, doi: 10.1007/s10518-015-9731-4.

[4] Boschi, S. et al. (2016): Mechanical characterization of particular masonry panels in tuscany, Brick Block Mason. Trends, Innov. Challenges - Proc. 16th Int. Brick Block Mason. Conf. IBMAC 2016, Padua, Italy, 8 pages.

[5] Foti, D. (2014): Non-destructive techniques and monitoring for the evolutive damage detection of an ancient masonry structure. Key Eng. Mater., 628, 168–177, doi: 10.4028/www.scientific.net/KEM.628.168.

[6] Borri, A. et al. (2018): Calibration of a visual method for the analysis of the mechanical properties of historic masonry," Procedia Struct. Integr., Florence, Italy, 10 pages.

[7] Borri, A. et al. (2020): The Failure of Masonry Walls by Disaggregation and the Masonry Quality Index. Heritage, 3, 1162-1198, doi:10.3390/heritage3040065.