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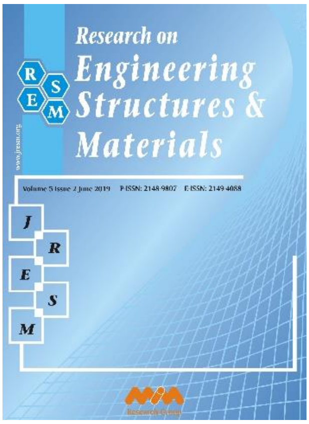

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Online Publication Date: 15 April 2020
URL: http://www.jresm.org/archive/resm2020.177st0120.html
DOI: http://dx.doi.org/10.17515/resm2020.177st0120

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Hysenlliu M, Bidaj A, Bilgin H. Influence of material properties on the seismic response of masonry buildings . *Res. Eng. Struct. Mater.*, 2020; 6(4): 425-437.

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Research Article

Influence of material properties on the seismic response of masonry buildings

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Article Info

Article history:
Received 20 Jan 2020
Revised 9 March 2020
Accepted 13 April 2020

Keywords:

URM buildings;
Pushover methods;
Macro modelling;
Limit states.

Abstract

Recent earthquakes occurred in many parts of the world have shown that unreinforced masonry [URM] buildings constructed according to older codes may constitute an important source of risk. It is known that the mechanical response of the masonry structures depends on several factors including the compressive and shear strength of its constituents, bricks shape as well as the volumetric ratio between the wall texture and components. In this study, the effects of the material choices of a particular type of masonry buildings were studied. The typology chosen in this study represents a typified masonry building of the current Albanian building stock; these buildings were mostly built between 1977-78 and thus were designed without considering the seismic requirements proposed in today's modern codes. This template building has been constructed in different regions of the country with the same architectural and structural configuration in two versions; red clay bricks and silicate bricks. The aim of this study is to investigate the influence of these two different materials on the seismic response of the selected masonry building. The evaluation is based on the use of nonlinear static analyses, performed by using TREMURI software. In order to estimate the reliable seismic response for this typology, extensive research in terms of historical information, structural characterization and the definition of the inherent material parameters has been executed. Upon the evaluation of the obtained results, in contrast to the type of buildings constructed by clay masonry, calcium silicate one showed a stiffer and slightly stronger response. However, at similar values of in-plane, lateral drift they exhibited more brittle response yielding unforeseen damage during seismic excitations.

1. Introduction

Recent damaging earthquakes in eastern Mediterranean countries including Italy (Umbria-Marche; 1997, Abruzzo, 2009), Greece (Grevena-Kozani, 1995, Aigio, 1995, Athens 1999), Cyprus (Paphos, 1995, Lemesos, 1996), Turkey (Izmit, 1999, Van 2011, Elazığ 2020) and Albania (Durres, 2019) resulted in great loses of building stock in historical centers. As a Balkan country in this region, Albania has a building stock dominated by low and mid-rise unreinforced masonry. Particularly, Bilgin and Huta 2018, [1] have shown that the URM is the dominant building typology of the country for both public and private buildings during the socialist era (1944-1990). Most of these current masonry buildings were designed considering merely gravity loads without any consideration of earthquake resistant design rules [2]. Furthermore, previous studies [3-11] and earthquake inspection reports have shown that masonry structures are very susceptible to seismic movements. Consequently, this typology has high seismic vulnerability over the region. This means that a moderate

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DOI: http://dx.doi.org/10.17515/resm2020.177st0120

or big earthquake might produce a catastrophic result associated with the masonry structures in the region.

Recently, masonry structures have been the subject of interest and research with respect to identifying the seismic capacity of these buildings. It is estimated that more than 75% of the building stock in Albania is made of masonry material [12-14]. Thus, they form an important percentage and a typical typology for the country. There are typified buildings all over the country for residential purposes. Most of these masonry structures were constructed according to the earlier codes [15-16] by red clay bricks or calcium silicate bricks. Although this region is generally characterized by low-moderate seismicity hazard, the problem of the induced seismicity is becoming more and more relevant [7]. Therefore, the evaluation of the seismic vulnerability of these types of red clay brick and calcium silicate brick masonry structures is crucial in order to assess the risk generated by the induced seismicity. Since the region was hit recently by a moderate earthquake (November 26, Durres), the common construction practice showed a lack of earthquake proof details.

This study aims at assessing the seismic response of an existing masonry residential building constructed by clay and silicate bricks. For this purpose, based on a survey done on masonry buildings in the capital city of Tirana, a five-story typified masonry building was selected and modelled by using TREMURI software [17]. Mechanical properties of the case study building have been determined experimentally and adopted for the nonlinear analysis. The macroscale structural response of two buildings were then comparatively evaluated through nonlinear-static analyses. Although nonlinear dynamic analysis is capable of giving a deep insight on the inelastic response of the buildings, their application requires more refined and complete approach. Hence, in spite of some inevitable approximations of structural response, macro-element methodology provides an effective means of validating the safety of masonry structure and its vulnerability to extensive damage and collapse. The results of the nonlinear-static analyses performed on two buildings are discussed. Particular attention is paid to the use of nonlinear static procedures as a tool of verification.

2. Development of Structural Models

Typical masonry building stock in Albania are template designs of low to moderate rise buildings. The structure is principally comprised of two parts, namely the load bearing walls and floor and roof diaphragms. The walls are stiff with several openings and the diaphragms are usually constructed of RC slabs. For the scope of the study, a typified URM mid-rise building is selected as a representative in the region. The masonry building, which has been analyzed, has five stories, brick walls of 38 cm for the load bearing walls in the first two stories and reduced to 25 cm in the remaining ones with a 12 cm thickness for other partition walls. It has 1920 cm x 1440 cm dimensions in plan with a story height of 280 cm (Fig. 1). Utilizing this template, two types of structures designed using red clay brick and calcium silicate brick are analyzed. These two types of buildings were chosen to have two fundamentally different scenarios in terms of the material characteristics and lateral deformation mechanisms. For the construction of the mathematical models, solid red clay (Scenario - A) and calcium silicate bricks (Scenario - B) connected with cement mortar are used to build the masonry walls for both buildings, respectively. The floors are in-situ concrete ones with a height of 15 cm and a flat roof. In order to guarantee a better distribution of horizontal and vertical loads, ring beams were constructed to create a continuous connection between load bearing walls and slabs.

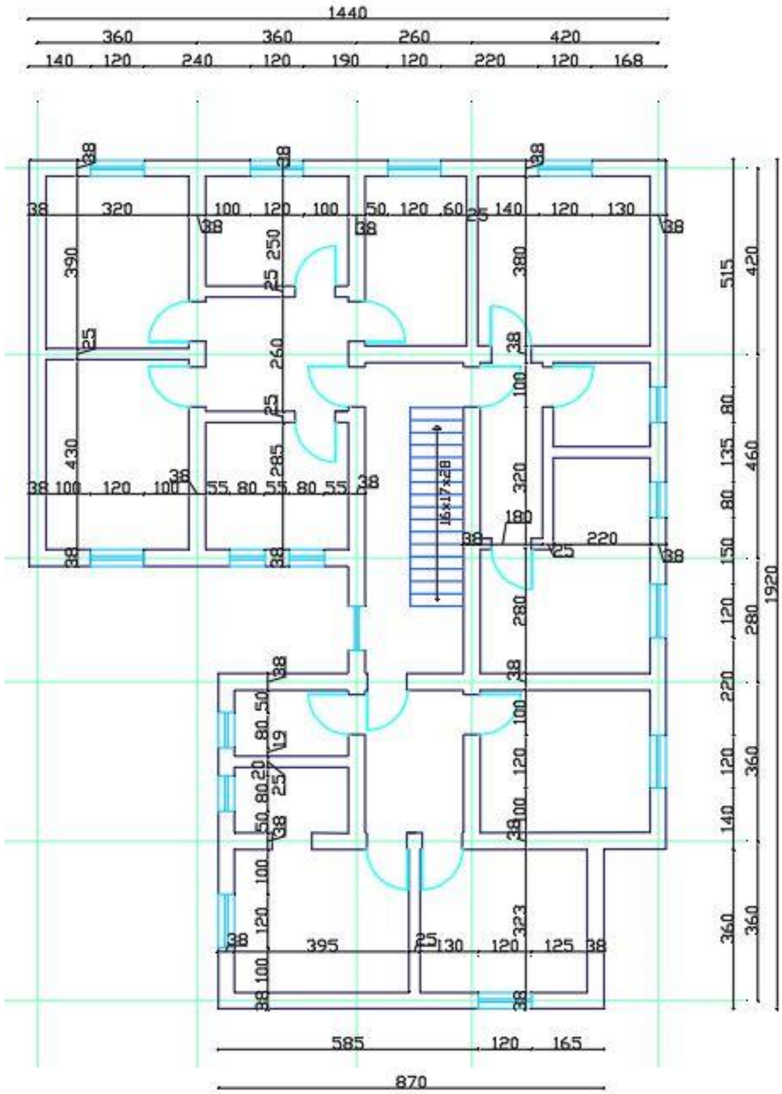
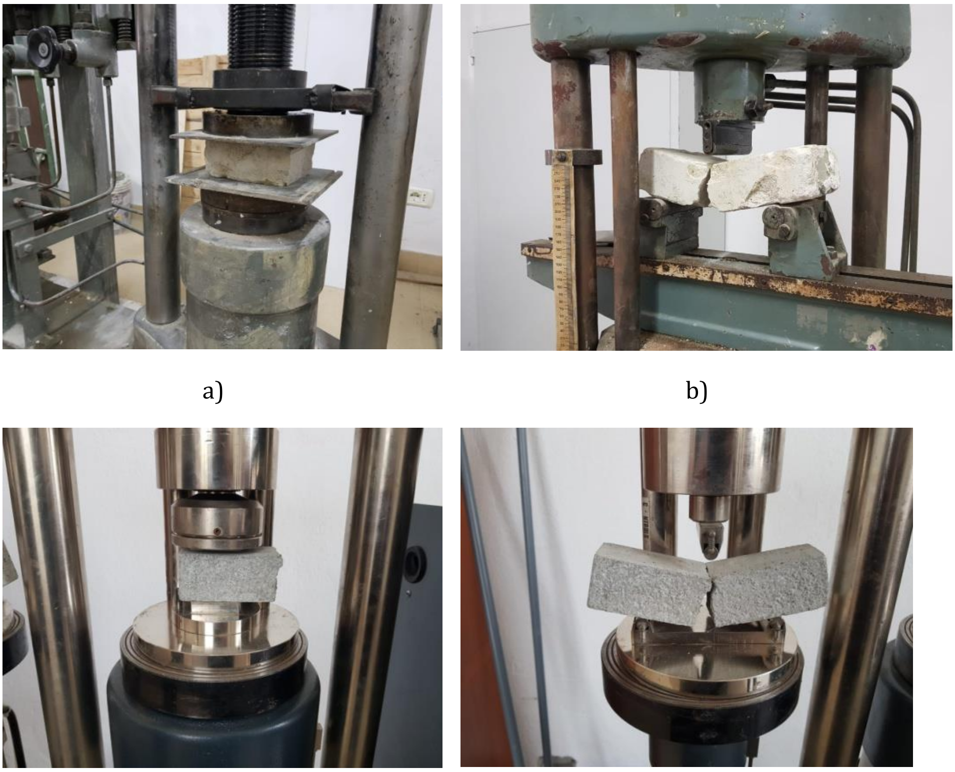


Fig. 1 Typical plan view of the selected masonry building, (units in cm)

In order to accurately characterize the strength and structural integrity of the structure, inherent mechanical characteristics of the masonry material are evaluated from the experimental tests performed on two buildings constructed by red clay brick and calcium silicate brick masonry. It consists of strength tests on brick units and mortar samples, as well as tests on small masonry assemblages, such as compression and shear tests on triplets. The clay and silicate bricks were tested in compression according to EN 772-1 (2000) [18]. The flexural and compressive strength of the mortar were defined according to the prescriptions of EN 1015-11 [19]. These tests allowed the determination of the compressive strength of masonry (f_m), as well as the secant modulus of masonry (E_m) (Fig. 2).



a) b) c) d)

Fig. 2 Brick compression and tensile flexural test (a-b); Mortar samples compression and tensile flexural test (c-d)

Table 1. Clacy and silicate brick properties

Building	**Brick properties**			**Mortar properties**		
	Type	f_b $[MPa]$	f_{bt} $[MPa]$	Type	f_m $[MPa]$	f_{mt} $[MPa]$
5- Story	Clay	7.5	1.7	Lime	4.8	1.1
5- Story	Silicate	10.0	2.6	Cement	5.0	1.0

Six masonry prisms produced by silicate and clay bricks were tested (Fig 3.) in compression in the direction perpendicular to the horizontal bed-joints, according to EN 1052-1 [20]. Specimens of both types of masonry were also subjected to the shear test for the determination of the initial shear strength (f_{v0}) and the friction coefficient (μ), according to the guidelines given by EN 1052-3 [20].

a)

b)

c)

d)

Fig. 3 Masonry prism tests (a-b); Red clay brick samples under compression and silicate brick test (c-d)

According to the test results, clay bricks and the mortar inherent characteristics are tabulated (Table 1-2).

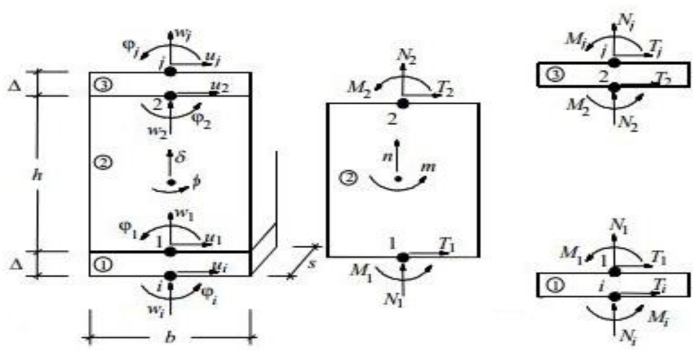
Table 2. masonry wall properties for analysed buildings

Material Type	f_k $[MPa]$	f_{vk} $[MPa]$	f_{vk0} $[MPa]$	f_t $[MPa]$	E $[MPa]$	G $[MPa]$	ν
Clay	2.42	0.36	0.2	0.121	2420	605	0.2
Silicate	2.97	0.4	0.22	0.149	2970	742	0.2

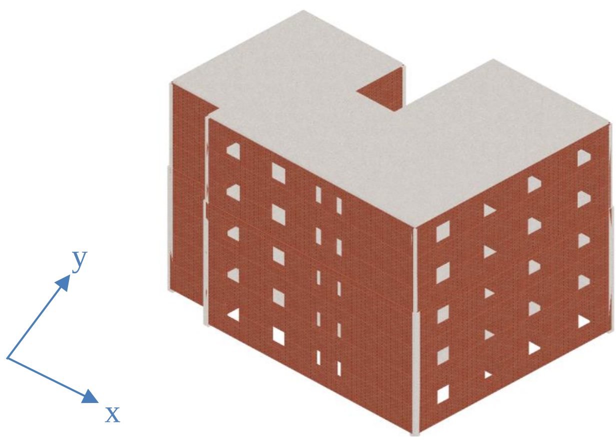
3. Modeling Approach

Masonry is a heterogonous material constituted of two components: the masonry bricks and the mortar. Its mechanical features depend on the inherent properties of its components. Its behavior can be very complicated under simple static loadings. In order to simulate the response of URM structures, numerous assumptions are made, and numerical models are suggested in the literature [21]. The adopted model in this paper is macro-modelling technique. According to this approach, each wall is represented by discretized elements that have equivalent properties. TREMURI [17] software is deployed to conduct the numerical analysis. This is based on a finite element methodology for modelling masonry structures. The nonlinear macro-element approach, representative of a whole masonry panel, proposed by Gambarotta and Lagomarsino [22], permits with a limited number of degrees of freedom, to represent the two main in-plane masonry failure modes, shear-sliding mechanism and bending-rocking, on the basis of the assumptions.

The conventional macro-element used for pushover analyses is schematized with the kinematic model described in Fig 4a. The 3D model of the examined masonry building, where it is apparent that masonry walls are modelled through a mesh of masonry spandrels and piers, is depicted in Fig 4b.



(a)



(b)

Fig. 4 a) The macro-element kinematic model; b) the 3D building model with macro-elements setup through the TREMURI software.

Seismic capacity of the URM buildings is obtained by pushover analyses. Member sizes were used to model the selected building without making any simplifications.

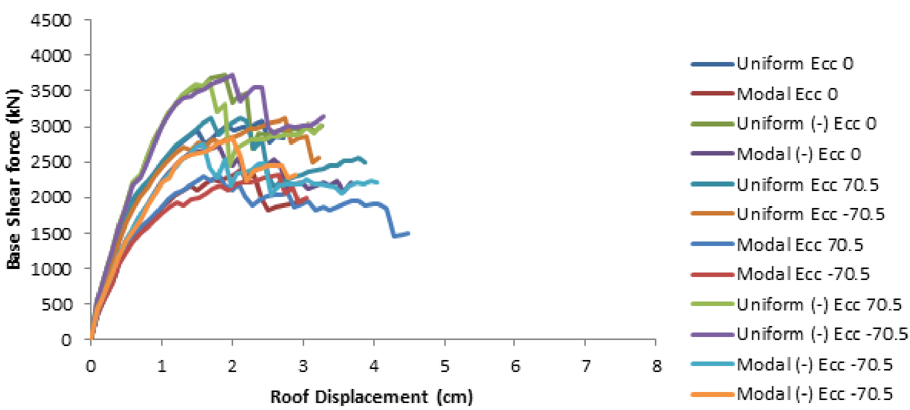
5. Analysis Results

5.1 Capacity Evaluation

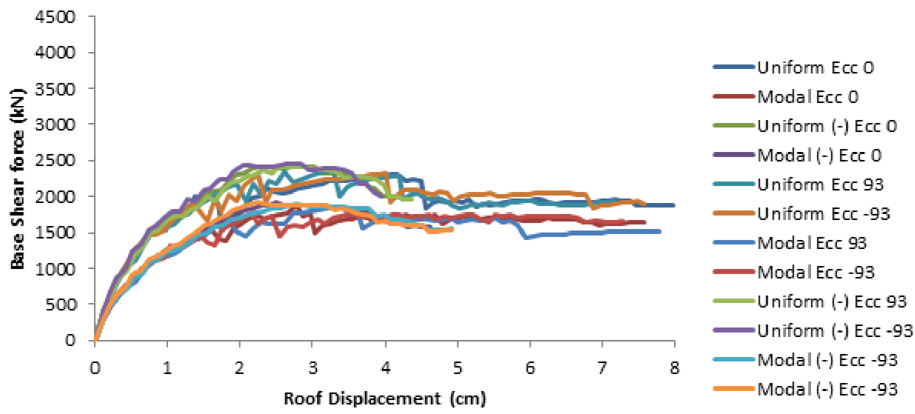
The nonlinear static analysis is an analysis method which permits defining the structural behavior under the seismic and gravity loads exerted on the structures. The behavior of the structure is represented through the pushover curve which typically gives the relation between the base shear force and roof displacement. It could be also mapped in ADRS format together with the demand curve and estimate the top displacement under the design earthquake to find the performance point of the structure. The scales of the seismic forces are increased in a stepwise manner in order to monitor the yielding cycles and the development of the overall capacity curve. A pushover analysis is performed at each step till the structure loses its stability.

In TREMURI approach are two load patterns applied: first mode shape distribution (static), based on the fundamental mode shape of the structure, and a uniform load distribution to all stories. The two are performed in two directions X- and Y- and with positive and negative values. So, in total eight analysis: +x MF1, +x uniform, -x MF1, -x uniform, +y MF1, +y uniform, -y MF1, -y uniform. These analyses were done for each combination. Without eccentricity of gravity load and with eccentricity of two different levels. For both simulations representing the red clay and silicate brick designed buildings, are computed 24 analyses, for all load combinations, earthquake direction, with and without eccentricity. The worst cases were chosen as representing the pushover curves for both x- and y-direction of buildings.

Upon completing the analytical modeling process, the pushover curves of the clay and silicate brick buildings were determined by carrying out nonlinear static analysis in TREMURI (Fig 5-6.). For the scope of the analyses, lateral load distribution proportional with the mode shapes were applied to the mass center of each storey considering the seismic weight. Seismic weight of the masonry buildings was calculated by considering the combination of Dead (G)and Live (Q) loads (G + 0.3 Q).

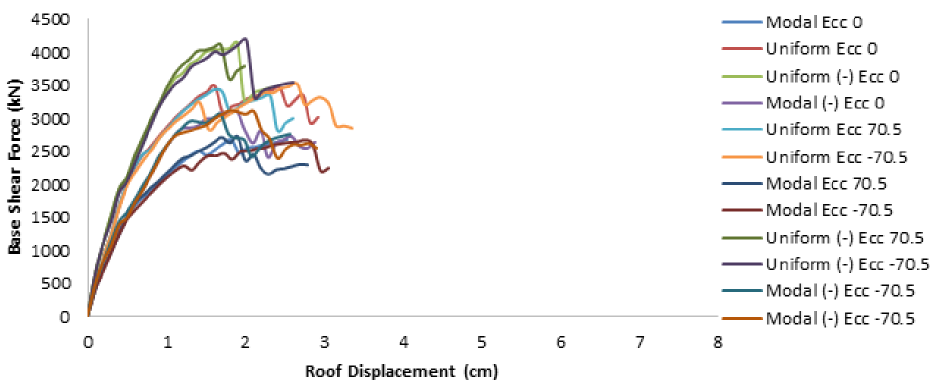


a) *x*- direction

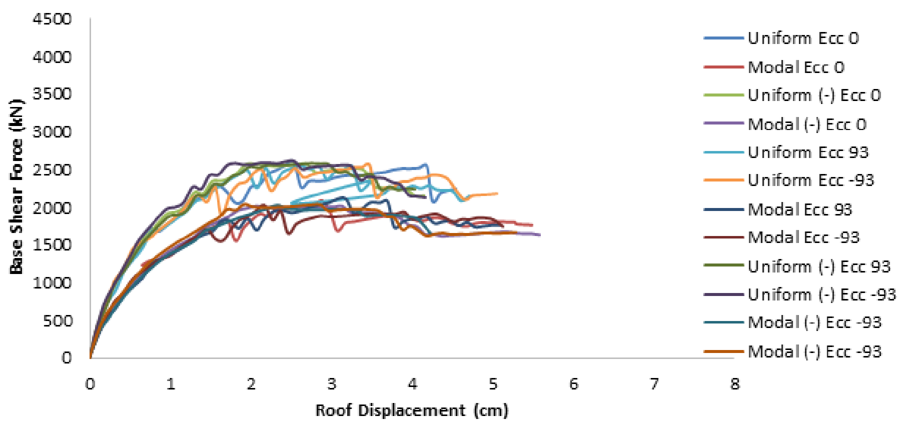


b) *y*- direction

Fig 5. Capacity curves for clay brick masonry buildings



a) *x*- direction



b) *y*- direction

Fig 6. Capacity curves for silicate masonry building

Subsequently, following the outlined criteria in Eurocode 8, Part 3 damage limit states of the studied buildings were calculated, and seismic capacities were determined. The capacity evaluation of the investigated buildings was performed using Part 3 of Eurocode 8 [23]. Three limits states levels, i.e, "Damage Limitation (DL)", "Significant Damage (SD)" and "Near Collapse (NC)" are defined for performance evaluation (Fig 7.).

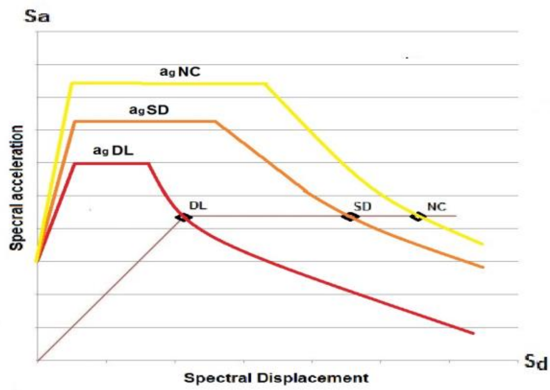


Fig 7. Schematized Calculation of "a_g" for different damage limit states levels (simplified figure)

In the present study, the seismic demand estimations for the seismic performance evaluation of the considered buildings are done considering the soil Type C with a moderate seismicity (*0.20g*) according to Eurocode 8 [23] and its corresponding spectra considering Soil category II and medium seismicity (*0.22g*) in KTP-N2-89 [16]. For both buildings, these limit states were calculated, and maximum "a_g" values were compared for each limit states. Pushover analysis data and criteria of suggested in EC 8 were used to determine the damage limit states of each building in both directions.

Table 3. Drift capacities and seismic spectral acceleration capacities of the template masonry buildings obtained from pushover analyses for the considered performance levels

Building	Direction	Global Drift (cm)			Seismic Spectral acceleration "a_g" (m/s^2)		
		DL	SD	NC	DL	SD	NC
Clay Brick	x	0.82	2.26	3.01	1.382	2.235	2.818
	y	0.95	2.45	3.27	1.404	2.219	2.814
Silicate Brick	x	0.78	1.9	2.53	1.367	2.001	2.499
	y	1.04	3.18	4.24	1.267	2.281	2.908

The two structures made of clay brick and silicate brick in this study show different levels of seismic response. As can be seen from Table 3-4, building constructed by clay bricks has a superior seismic capacity than silicate one. The peak ground acceleration (a_g) that can be sustained for the *NC* state for the clay building is near 0.24g meanwhile for the silicate building is near 0.2g. Even though silicate bricks have higher compressive strength than clay bricks, bonding between clay brick and mortar is stronger than silicate bricks and mortar.

Table 4. Performance levels their corresponding PGAs for the studied buildings

Building	0.14g	0.16g	0.18g	0.2g	0.22g	0.24g
Clay Brick	DL	SD				NC
Silicate Brick	SD				NC	

5.2 Discussion of the results

Building constructed with silicate bricks has better material characteristics including f_b, f_m and f_k however, the bonding connection is stronger in clay bricked specimens compared to silicate one. Due to the higher density of the silicate bricks, this building has 10% more weight (Table 5). Compared with each other, the silicate building has higher strength capacities in both directions whereas, the displacement capacity of the clay brick structure is better. Both buildings have higher displacement capacities in *y*- direction due to the distribution of the load bearing walls in this orientation.

Table 5. Comparative assessement of the clay and silicate brick masonry parameters obtained from experimental tests and pushover analyses

	Building Scenario - A (Clay Bricked)	**Building Scenario – B (Silicate Bricked)**
Brick compressive strength, (f_b)	7.5 MPa	10 MPa
Mortar compressive strength, (f_m)	4.8 MPa	5 MPa
Masonry compressive strength, (f_k)	2.42 MPa	2.97 MPa
Shear strength of masonry, (f_{vk})	0.36 MPa	0.4 MPa
Total weight, (W)	13202 kN	14175 kN
Max. Force (x- direction), (F_y^*)	2184.6 kN	2624 kN
Max. Displacement (x-direction), (d_m^*)	3.05 cm	2.53 cm
Max. Force (y-direction), (F_y^*)	1857 kN	1961 kN
Max. Displacement (y-direction), (d_m^*)	4.62 cm	4.24 cm
Displacement/Height (x-direction), d_m^*/H	0.22%	0.18%
Displacement/Height (y-direction), (d_m^*/H)	0.33%	0.30%

A comparison between the two buildings' failure mechanism from pushover analysis is shown below (Fig. 8). From the failure scheme of the two buildings in *x*- direction, can be noted that the perimeter walls fail in both buildings in the upper floors from bending failure.

The clay bricked building shows a more ductile behavior than the silicate one. Failure is reached when all the right part of the perimeter wall fails in bending and also the wall in the back part of upper levels, whereas in the silicate model, the failure mechanism is reached before. The perimeter wall was taken in consideration, since it has the failure mechanism of both buildings. From the progression of the damage mechanisms, it was observed that the silicate building reached its ultimate capacity when some parts of the same wall was undamaged. This shows a brittle failure mode compared with the clay brick building.

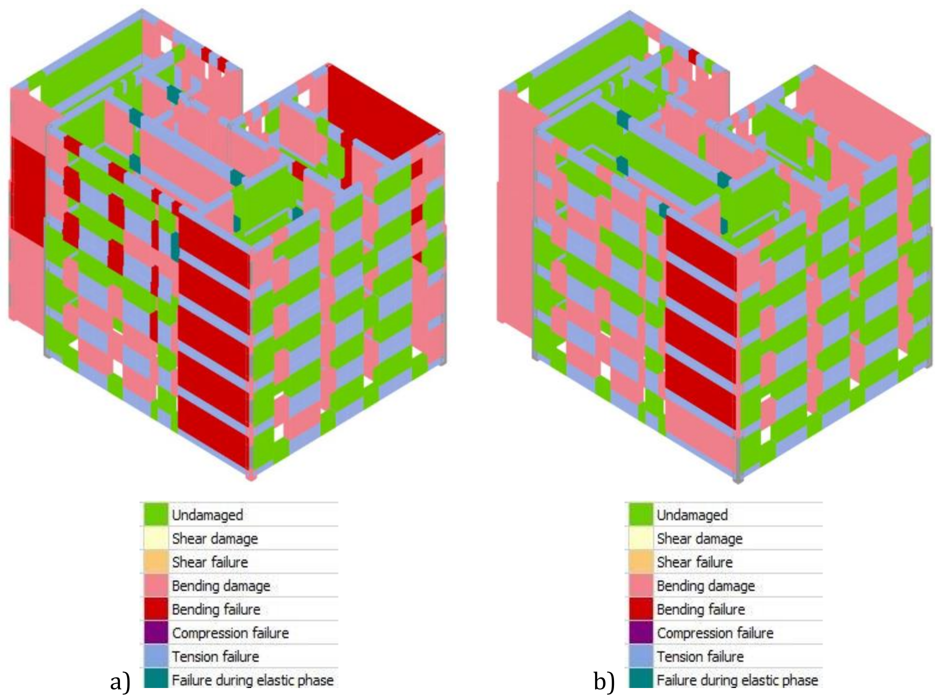


Fig 8. Comparison of the failure mechanism of both buildings; a) Clay brick; b) Silicate brick

6. Conclusion

This paper aims at presenting and discussing the results of an analytical study on two URM structures constructed by calcium silicate bricks and clay bricks. These types of materials are common in Balkans like in many European countries characterized by low-moderate seismic hazard. As a result of the recent earthquakes hit the region, the evaluation of the seismic vulnerability of masonry buildings including clay and calcium silicate bricks became necessary.

In this research, the influence of the material characteristics on a typical URM building response has been investigated. The models are investigated using non-linear static analyses. The seismic capacity of the building was evaluated by a structural model that uses macro elements for masonry panels. The results of these analyses, expressed in terms of shear distributions and displacements, are compared with each other. The seismic demand has been defined by the response spectra proposed by the EC 8 and the corresponding Albanian seismic codes of practice. The mechanical properties of the materials used are obtained from experimental tests. Based on the laboratory test results done on the clay and silicate clay bricks, analytical models of the URM structures were developed by TREMURI software.

Damage thresholds were determined according to EC 8. The performance points were obtained and comparatively assessed. According to the analysis results; capacity curves obtained by non-linear static analysis demonstrate that URM building constructed by the clay bricks performed better than the silicate bricked one. It does also show a greater ductile response. This could be expressed by the better bonding between the clay and mortars.

Based on the capacity evaluation; in contrast to the type of building constructed by clay masonry, calcium-silicate one showed a stiffer and slightly stronger response. Yet, at similar values of in-plane, lateral drift, they exhibited more damage based on the analytical simulations. This observation was also monitored during the recent earthquake which hit Albania on November 26, 2019. Since the material is stiffer, the increased damage was not unforeseen, but the building also displayed a more brittle response during this earthquake. This appears to suggest that buildings built of calcium-silicate brick are more vulnerable to damage. Such observations were observed on wall specimens tested in northern Europe, as well [24].

Acknowledgement

The authors acknowledge that this study is supported by the Albanian General Directorate of the Institute for Construction (http://www.institutindertimit.al/).

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