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Seismic response of unreinforced masonry buildings from 1950's

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Abstract

Unreinforced masonry building (URM) are rather vulnerable to the influence of stronger earthquake motions. This was confirmed during recent earthquake which hit the capital of Croatia Zagreb on 22nd of March 2020, as well. The most damages were registered on older masonry structures. During great rebuild after the World War II large stock of multi-storey residential buildings, mostly 3 to 6 storeys high, made of unreinforced masonry, were built all over Europe. They are relatively stiff with limited ductile behaviour. Considering composite structure and relatively uncertain material properties seismic evaluation of existing buildings is not simple engineering task. To gain the knowledge about seismic performance of masonry walls experimental tests followed by numerical analysis are considered as a logical solution. The full-scale tests on unreinforced masonry walls were conducted at the Institute for Materials and Structures at the Faculty of Civil Engineering University of Sarajevo. The wall components, full bricks and mortar, were selected in way to match the material properties of existing multi-storey masonry buildings in Sarajevo, as far as it was possible. The buildings were built in 50's and early 60's of the last century, with main bearing structure consisting of prefabricated concrete floors and URM walls. The experimental results are used to calibrate engineering masonry model, implemented in nonlinear analysis, conducted after the experimental research. Some interesting conclusions about seismic response of existing unreinforced masonry walls, as well as the need for strengthening of the walls, are discussed.

Key words: unreinforced masonry, earthquake, seismic response, experimental test, nonlinear analysis

1 Introduction

The existing buildings in many parts of the European continent are traditionally built as masonry buildings. This is also true for the most of historical buildings, a lot of them belonging to cultural heritage of different countries and regions. If we wanted to calculate, masonry buildings represent the majority of all built residential buildings, even today after decades of expansion of concrete and steel structures [1-3].

The West-Balkan is situated in an active seismic region of South-East Europe. This has been proven with several strong earthquakes that have hit the region in last 50-60 years. Older masonry building are rather vulnerable to the influence of the stronger earthquake motion. This was confirmed during recent earthquake which hit the capital of Croatia Zagreb on 22nd of March 2020, as well as due to the earthquakes in the region of Petrinja (not far from Zagreb) at the end of December 2020.

Leaving aside simple masonry houses made of earth brick or field stone, traditional way of construction of multi-story building, for many decades before the World War II, was masonry building, built as unreinforced masonry (URM) with wooden floors. By the mid 30's of the last century the first art of half-prefabricated reinforced concrete floors were applied in west-Balkan region, which was continued during the great reconstruction immediately after the World War II [2]. Many residential areas, composed of buildings of that type, were erected in all major cities in the region (Fig. 1). Some of them have been even upgraded by one floor in later years.

Figure 1. Residential area "Grbavica" in Sarajevo, Bosnia and Herzegovina

2 Typical URM building from 1950's

The most residential masonry buildings in 1950's had up to 5 stories, but without vertical reinforced concrete confining elements. Seismic resistance was provided by structural walls laid in two mutually orthogonal directions viewed in a plan. Whereby, smaller number of walls in longitudinal direction was caused by functional demands (Fig. 2). After the earthquake in Skopje in 1963, first seismic codes were published and vertical reinforced concrete confining elements were introduced in masonry building. Presently, confined masonry is the common art of masonry structures, applied in construction of multi-story residential buildings [2-4].

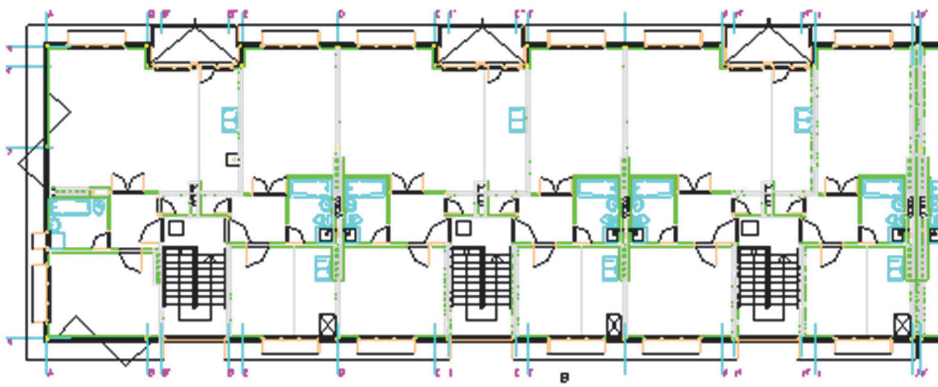

Figure 2. Layout of typical multi-story masonry building from 1950's, ground floor + 4 or 5 floors

The masonry buildings are generally brittle structures, which show relatively satisfactory behaviour up to moderate seismicity. In that case most damages can be predicted and also repaired. But, exposed to very strong earthquakes most of the traditional masonry buildings could suffer heavy structural damages. Within the European Macroseismic Scale [5] there are short descriptions of effects that could be expected for the specific degree of seismic intensity. The classification of damage degrees for buildings is also given within the same scale. Damage degrees are from 1 to 5 that means from irrelevant damages or only damages of non-structural elements that correspond to damage 1, to destruction or even building collapse that corresponds to damage degree 5. The correlations between seismic vulnerability, damage degrees and damages corresponding for various seismic intensities can be analysed. Typical multi-story buildings constructed in 1950's belong to unreinforced masonry (URM) with reinforced concrete floors. It means that in the case of earthquakes corresponding to the seismic intensities VIII and IX, roughly PGA between 0.20 and 0.30-0.35 of *g* (gravitational acceleration), damage grades 3 to 4 could be expected. More precisely, grade 3 means: substantial to heavy damage (moderate structural damage), large and extensive cracks in most walls, roof tiles detach, while grade 4 means: very heavy damage (heavy structural damage), serious failure of walls, partial structural failure of roofs and floors. Damages of URM

buildings with timber floors are classified even worse, damage degrees from 3 to 5. On the contrary, built in of reinforced concrete confinement reduces possible damages at least for one grade [1-5].
The most severe consequences after a strong earthquake are total or partial collapse of the URM building structures, which were observed during Skopje and Banja Luka earthquake (Fig. 3 and 4). Five-story masonry building without vertical reinforced concrete confining elements could not withstand earthquake of the seismic intensity 9 (estimation) and collapsed (Fig. 3). Similar observation can be confirmed by failure of the corner building (Fig. 4).

Figure 3. Total collapse of URM building, Skopje 1963

Figure 4. Partial failure of the masonry building, Banja Luka 1969

Previous considerations have contributed to the decision to conduct tests on unreinforced masonry wall models, typical for the bearing structure of the multi-story masonry buildings from 1950's, in order to gain closer insight in seismic performance of those structure.

3 Tests on unreinforced masonry walls

An extensive program of experimental research has been conducted at the Institute for Materials and Structures of the Faculty of Civil Engineering University of Sarajevo between 2014 and 2017 [6-9]. The ideas was to build the testing model (specimen) that correspond as much as possible to the masonry walls typical for the residential buildings erected in 1950's and beginning of 1960's. This assumed full bricks with the traditional dimensions 250/120/65 mm (length/width/height) and relatively "weak" cement-lime mortar corresponding to the class M2-2.5. The walls and other test elements were built in the traditional way in the test hall of the Institute mentioned above. Firstly, the main mechanical properties of the wall components, brick and mortar were tested. This was followed by testing of masonry prisms (wallets) according to newer European regulations. According to the information available to us, this was the first implementation of masonry prisms testing in Bosnia and Herzegovina. Series of tests are performed at the Institute for Material and Structures in Sarajevo. Tests set up is shown on the Fig. 5, on the left side before imposing the loading and on the right side after the failure.

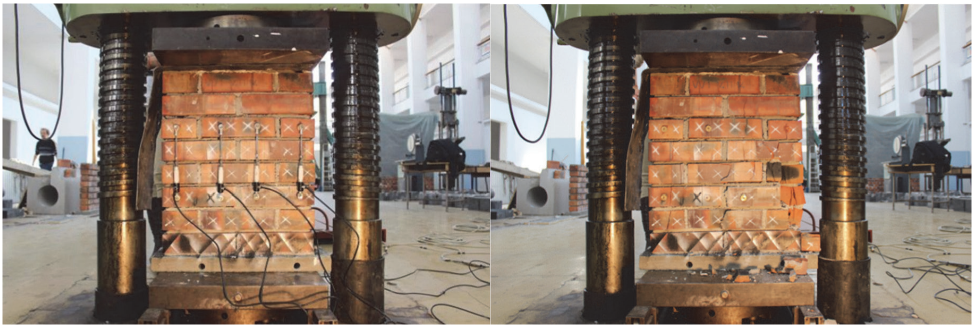

Figure 5. Testing of masonry prisms, Institute for Materials and Structures, Sarajevo

Four measuring instruments – LDVTs were installed on the both sides. The average compressive strength is 6.48 N/mm^2 and the coefficient of variation amounts to 36 %. Significant deviation of results can be attributed to numerous factors, not only to variation of pure mechanical properties of masonry constituents (geometric imperfections of specimens and testing machine, transport, varying execution of the mason etc.) The average value of the modulus of elasticity is 4024 N/mm^2, while the coefficient of variation equals to 46 %. Based on the measured values, it can be concluded that the modulus of elasticity is considerably smaller than the recommendation given in EC6 [10] according to which $E_m = 1000\ f_k$. However, according to some authors [11] the modulus of elasticity may vary within the limits $100\ f_k \leq E_m \leq 1000\ f_k$.

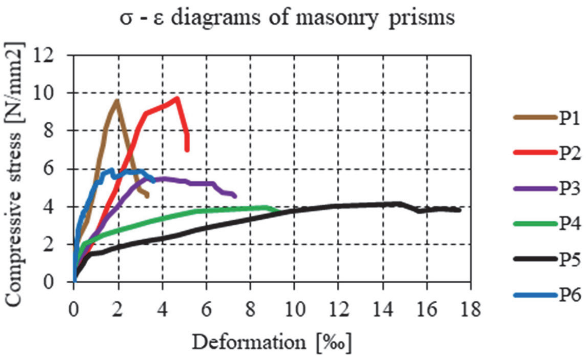

Figure 6. Masonry prisms: stress-strain diagrams due to vertical compression

As it was mentioned in introduction, unreinforced masonry wall without vertical confinement is a typical way of construction for multi-story residential buildings, erected after the World War II. That was the reason to build full scale models (specimens) of typical bearing wall from those buildings. It is made of full brick and mortar, previously described and tested, taking into account the typical story height of 2.5 m and the wall thickness of 25 cm. Two full scale cyclic tests were performed on unreinforced masonry walls with dimensions length/height/thickness = 233/237/25 cm, see Fig. 7.

Figure 7. Full scale model (specimen) of URM wall, before and after the test

The wall specimen was exposed to constant vertical compression equal to 0.4 N/mm^2. Horizontal load was applied at the top of the wall in the wall plane direction as static cycle loading. Following Fig. 8 illustrates the testing protocol, displacement at the top of the wall vs. time, in the form of controlled displacement, gradually increased up to 2 cm, whereby the identical shift is repeated three times in both directions.

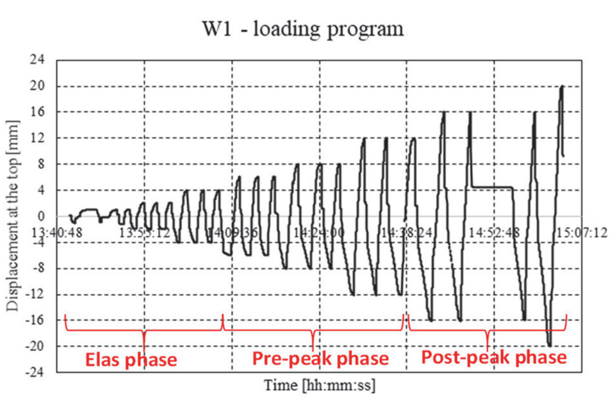

Figure 8. Protocol for horizontal loading at the top of the wall

The obtained hysteretic loop is shown in Fig. 9. One can notice significant capacity of ductile behavior of the tested URM wall. This differs significantly from traditional recommendations on very limited ductile behaviour of the unreinforced masonry walls without confinement. It is to repeat here that seismic codes prescribe average behaviour factor for URM walls without confinement equal to 1.5, which seems to be rather conservative, when compared to the results of the test.

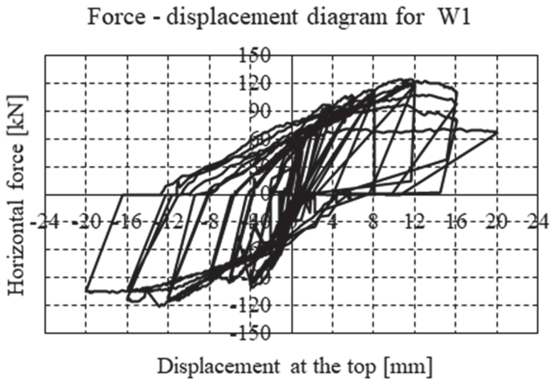

Figure 9. Horizontal force vs. horizontal displacement at the top of the wall W1

Diagonal cracks, typical damage on masonry walls caused by earthquake motion, were observed at the end of the test (see right photo on Fig. 7). Diagonal cracks generally follows the vertical and horizontal mortar joints. The crack width reaches several cm at some specific points. The diagonal cracks could be more clearly observed on the Fig. 10 for one side of the wall specimen.

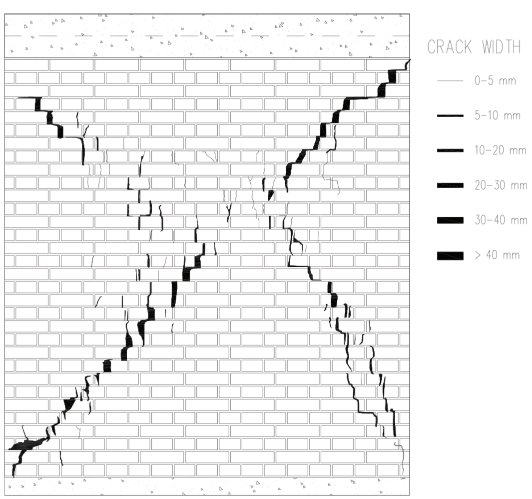

Figure 10. Diagonal cracking pattern and crack width

In order to increase seismic resistance and to improve seismic performance of the URM walls, they could be strengthened with reinforced concrete jacketing. In normal case R.C. jacketing is built in on the both sides of the wall. However there are some exception, e.g. historical buildings, where it could be applied one sided. Series of experiments were conducted on strengthened wall specimen at the Institute for material and Structures in Sarajevo, two strengthened full scale walls jacketed on both sides with 5cm thick concrete and reinforced with Q196 steel mesh, as well as twelve reduced scale walls L/H/D = 100/100/25 cm. Some of the results are discussed in [8].

4 Numerical analysis

Masonry is a highly heterogeneous material, composed of bricks and mortar, two building materials with rather different mechanical properties. And already by moderate earthquake the structure moves to the nonlinear range of the behavior. This means that numerical modelling of the masonry wall is not an easy task. One of the solution is to implement macro-modeling or to approximate masonry as homogeneous building material. The mechanical properties should be estimated by appropriate tests on masonry wall models or wallets. Engineering masonry model from FEM software DIANA [12] was implemented in this research. It is calibrated with previously described test results. Detailed descriptions of the model could be found in the literature [6, 8, 9]. Horizontal loading scheme (Fig. 11) is similar or equivalent to the experimental loading protocol.

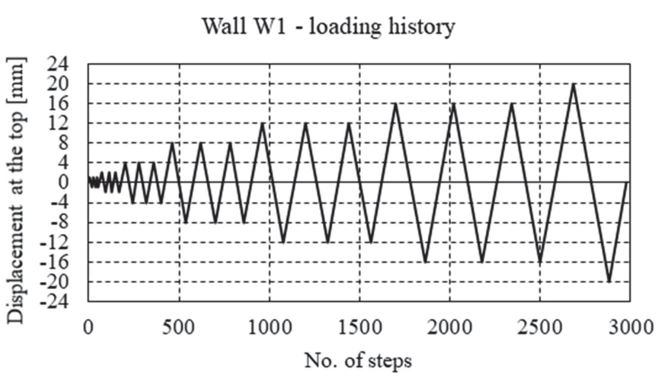

Figure 11. Horizontal loading scheme for the numerical analysis

Engineering masonry model can simulate compression, tension and shear failure mechanism and present development of the cracks. Hysteretic curve showing relation between total horizontal force and displacement at the top of the wall is presented on the Fig. 12.

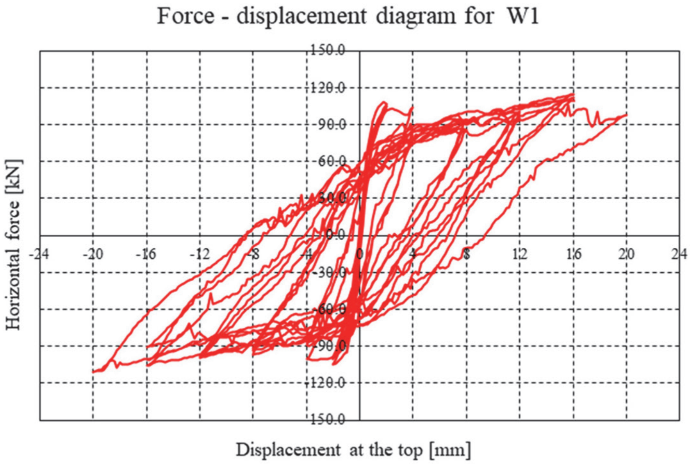

Figure 12. Numerical analysis of the masonry wall, horizontal force vs. top displacement

One of the advantage of the engineering masonry model is that it can be implemented in the seismic analysis of the whole masonry building, comprising several floors. The application could be extended for seismic evaluation of existing masonry building and implementation of different strengthening methods. This is shown in [12] on the example of the building damaged during the war actions.

6 Conclusions

A lot of multi-story masonry buildings built in the immediately after the World War II belong to the class of unreinforced masonry without vertical reinforced concrete confining elements. It is of interest to estimate their seismic resistance and performance. The results of comprehensive tests on full scale models of masonry walls, representing typical bearing wall structure, were presented in the paper, as well as some major results of the numerical analysis of the same walls. Unreinforced masonry is considered as relatively brittle structure, with very limited ductile behaviour. However, the experimental results of the wall subjected to horizontal cyclic loading show that the ductile behaviour of the unreinforced masonry was somehow underestimated.

The hysteretic curves obtained by experimental and numerical analysis showing relations between total horizontal force and displacement at the top of the wall are overlapped and presented on the Fig. 13. Good matching between experiments and numerical analysis can be observed.

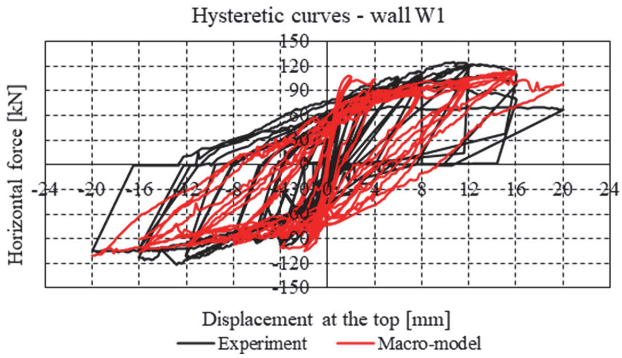

Figure 13. Experimental vs. numerical results, hysteretic nonlinear behaviour of URM wall

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