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OUT-OF-PLANE BEHAVIOUR OF FRAMED-MASONRY WALLS WITH OPENING AS A RESULT OF SHAKING TABLE TESTS

D. Penava[(1)], V. Sigmund[(2)]

[(1)] Assistant Professor, Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, davorin.penava@gfos.hr
[(2)] Full Professor Tenure, Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, vladimir.sigmund@gfos.hr

Abstract

Reinforced concrete frame structure infilled with masonry walls was built in a scale 1/2.5 and tested on shaking table under earthquake excitation. It consisted of three storeys with two longitudinal frames in the direction of earthquake excitation and three transverse bays perpendicular to the direction of earthquake excitation. The both longitudinal and central transverse reinforced concrete frames were infilled with masonry walls throughout the entire height of the structure. The masonry walls were made of clay block masonry units and masonry mortar. The structure model was excited in sequences with increasing earthquake peak acceleration by each sequence. Observed were masonry walls placed in the central transverse bay that were exposed to the out-of-plane excitation. They had door opening in the ground floor and window openings in the first and the second floor. The existing simplified model to verify the out of plane resistance of complete masonry walls without openings was applied before the tests. As the tests revealed, they incorrectly estimated their resistance since different failure mechanisms occurred. Position of the failed infilled masonry wall with opening and its failure mechanisms were opposite to the current perceptions for out-of-plane infilled walls behaviour. Detailed description of observed behaviour and measures that could be used for improvement of their behaviour under earthquake excitation is presented.

Keywords: out of plane behaviour, framed-masonry, openings, shaking table tests

1. Introduction

Masonry is often used as an infill fully integrated with the surrounding frame. Infill would therefore have to be considered as structural element. Henceforth, no gap should be left between the infill and the frame, infill should be the full height of the aperture in which they are built and the top of the infill should be structurally connected to the structure above. As is usually the case in this form of construction, the infill is built after the upper frame member has been constructed. Placing of vertical structural connection is obviously difficult in clay block masonry construction and therefore usually omitted. Due to structural interaction with the frame, the infill and the frame will have equal drift deformations. However, if infill is made of brittle materials such as clay block masonry, in strong earthquakes the response of such a structure will be strongly influenced by the damage sustained by the infill [1].

The earthquake damage instances to both the frame members and infill are related to in- and out-of-plane response or their combination. Additionally, considerable uncertainties are involved in estimation of the seismic interaction between infill walls and structural frames, especially when openings are present [2,3]. To fully simulate the earthquake response of a framed-masonry structure, with or without openings in infill walls, and to verify existing analysis techniques as well as construction behaviour improvement measures, shaking table tests would be necessary.

This study is about the shaking table test results of a framed-masonry structure shown in Fig. 1. It consisted of three storeys with two longitudinal frames in the direction of earthquake excitation and three transverse bays perpendicular to the earthquake excitation. The both longitudinal and central transverse reinforced concrete frames were infilled with masonry walls throughout the entire height of the structure. The structure model was excited in sequences with increasing earthquake peak acceleration by each sequence. Observed were masonry walls placed in the central transverse bay that were exposed to the out of plane excitation. They had door opening in the ground floor and window openings in the first and the second floor. The existing simplified model to verify the out of plane resistance of complete masonry walls without openings was applied before the tests [4].

As the tests revealed, they estimated their resistance different since unexpected failure mechanisms occurred. Position of the failed infilled wall with opening and its failure mechanisms were opposite to the current perceptions for the out-of-plane infilled walls behaviour. Detailed description of observed behaviour and measures that could be used for improvement of their seismic performance under earthquake excitation is presented.

Due to structural interaction with the frame would the infill and the frame would have to be considered as one composite structural element framed-masonry.

2. Design and detailing of the model structure

The framed-masonry structure built in a scale 1/2.5 with its significant dimensions and cross-sections shown in Fig. 1.

The scaling method of artificial mass simulation was applied in which the prototype and the model construction materials are the same. The total model mass required for the correct simulation of the inertia forces is determined based on the scaling law $S_M = S_l^2 = 1/2.5^2 = 1/6.25$. In order to obtain this relationship the additional mass of 4.8 t was added on the top of each floor by placing steel ingots (see Fig. 1). Because of the restrictions of the shaking table for the mass that is allowed to carry, and with attention to the earthquake excitation, the mass was added only up to the amount to properly scale the self-weight of the structure. However, as a consequence, additional mass that would belong to the walls was not applied there.

The frame members abutting the infill wall were of reinforced concrete designed in compliance with EN 1998-1 provisions [5,6] as moment-resisting frames by considering the medium ductility form of seismic construction detailing. Infill walls were made of clay block masonry and masonry mortar which satisfy seismic design requirements for unreinforced structural masonry. The properties of material of construction, based on [5,6] requirements, are given in Table 1.

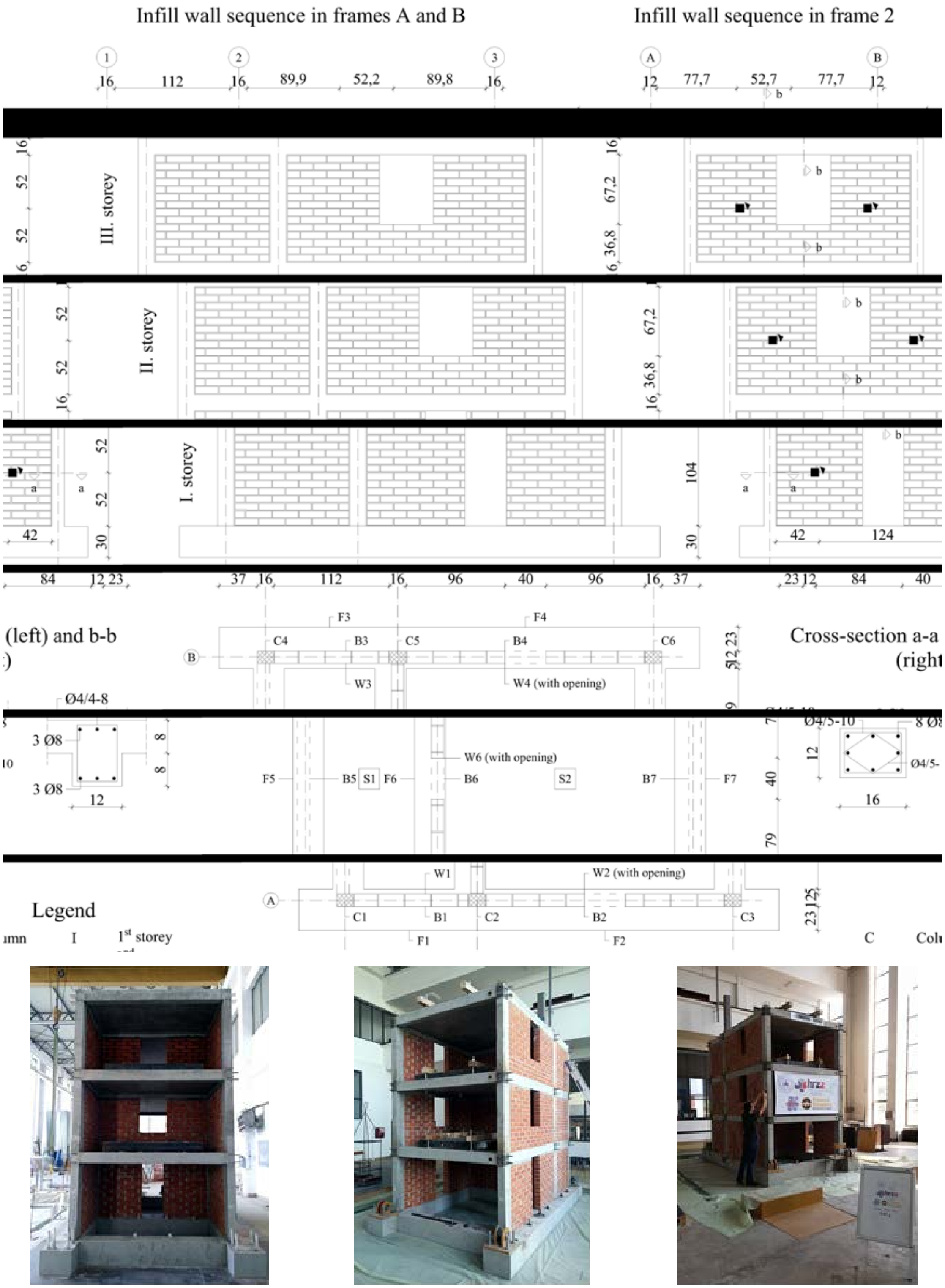


Fig. 1 – Tested composite framed-masonry structure (measures in cm)

Table 1 – Properties of material of construction

Property name	Value		Units
Mean concrete cylinder strength	36.6		MPa
Mean reinforcing steel yield / ultimate tensile strength	Ø 4 mm	753 / 780	MPa
	Ø 6 mm	564 / 589	
	Ø 8 mm	591 / 621	
Mean masonry compressive strength	1.53		MPa
Mean masonry tensile strength	0.08		MPa
Mean masonry initial shear strength	0.05		MPa
Mean secant modulus of elasticity of masonry	1800		MPa

3. Model structure excitation and testing

In seismic regions, geotechnical site characteristics have a profound influence on site as well as well as on the proposed or existing construction [1].Therefore, due to geology and soil conditions of the region, ground motion recorded at the Herceg-Novi station during the 1979 Montenegro earthquake was selected as earthquake excitation for shaking table tests. To comply with the scaling law adopted the duration i.e. time of the excitation is reduced by dividing it with √2.5.

The structure was tested under sequence of earthquake excitations with ten different peak ground accelerations (a_g/g), namely 0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 0.7, 0.8, 1.0, 1.2 (see Figs. 2 and 3). Additionally, excitation of the structure by sweep motion was conducted prior to and after the earthquake excitation tests in order to obtain the fundamental vibration period of the structure in undamaged and damaged state, respectively.

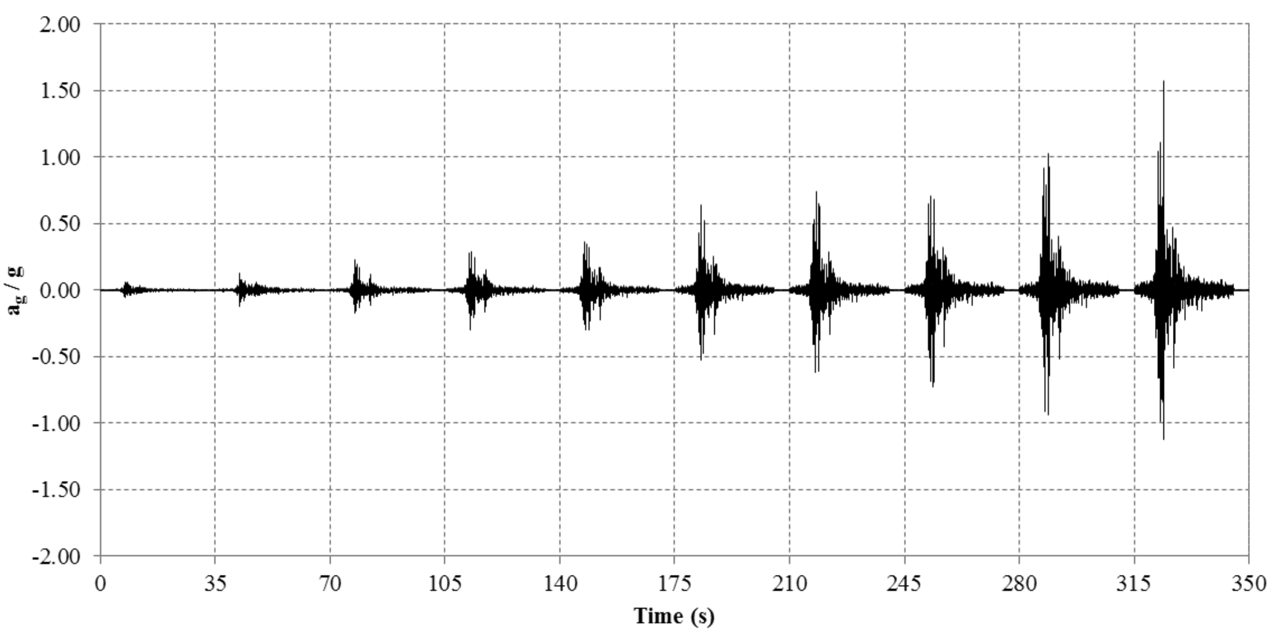


Fig. 2 – Earthquake excitation sequence for shaking table tests

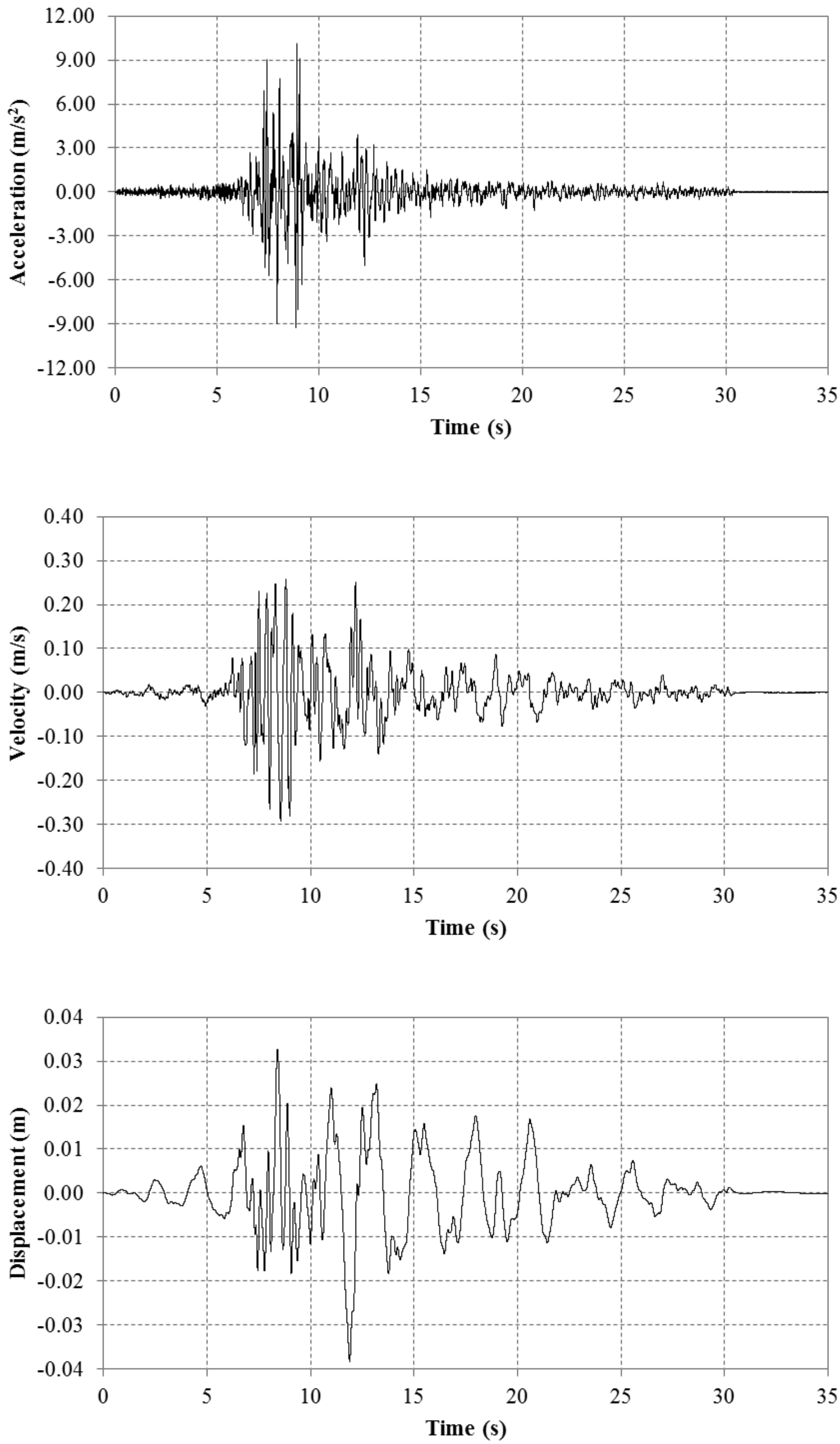


Fig. 3 – Earthquake excitation used for shaking table tests with a_g / g = 1.0

4. Out-of-plane response of framed-masonry walls

The structural response of masonry walls placed in the central transverse bay that were exposed to the out-of-plane excitation was observed by six accelerometers and by visual inspection. On each wall placed were two accelerometers, on both sides of the opening in mass centre of the walls (see Fig. 1).

The most vulnerable to earthquake damage was the ground floor masonry wall which appeared first at excitation of $a_g/g = 1.0$. The damage occurred was the separation of the top bedjoint in contact with the frame. At excitation of $a_g/g = 1.2$ the top row of clay block masonry was demolished (see Fig. 4). The masonry wall placed on the third storey had experienced the separation of the wall from the beam at $a_g/g = 0.8$, however, the damage hasn't been increased further in following excitation sequences.

In Fig. 5 it is visible that the accelerations of the walls were up to three times higher than those of the shaking table, independent of the storey height.

Fig. 4 – Damage of the framed-masonry wall with opening due to exposure to out-of-plane excitation

5. Out-of-plane resistance of framed-masonry walls

The vulnerability of the structure is dependent upon the structural form and construction materials as well as of the type of earthquake excitation. The performance of the structure that is to be achieved is implied by the code provisions. In attempt to properly assess the earthquake response of the structure the designer applies the simplified methods of analysis.

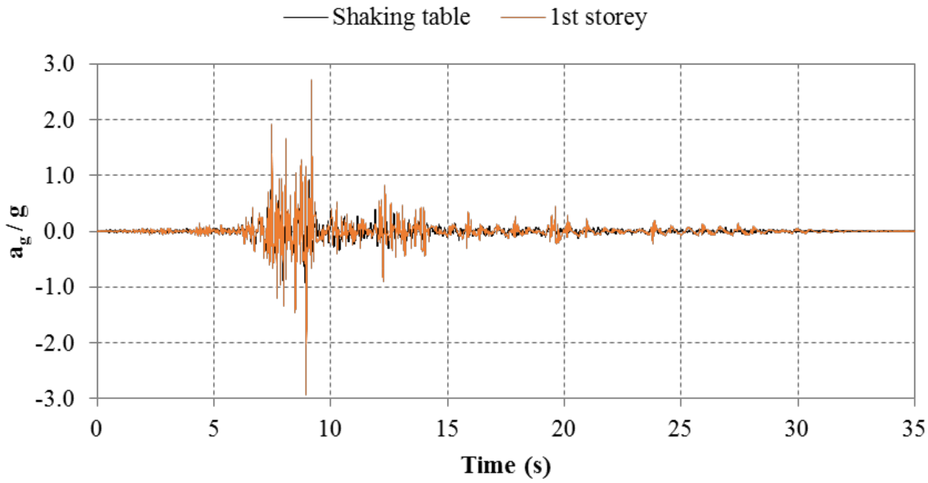
The current perception regarding the out-of-plane behaviour of infill walls, considers walls in the top floor as those that are the most vulnerable. In compliance with EN1998-1 and EN1996-1-1 provisions the force acting on the masonry wall in out-of-plane direction was calculated as

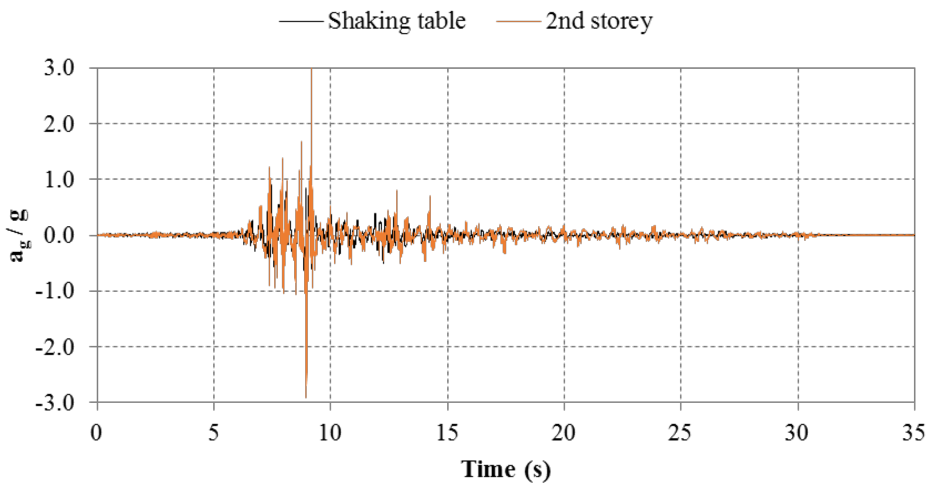
$$F_a=(S_a \cdot W_a \cdot \gamma_a) / q_a \tag{1}$$

where F_a is the horizontal seismic force, acting at the centre of mass of the non-structural element in the most unfavourable direction; $W_a = l_w \cdot h_w \cdot w_w \cdot \gamma_w = 0.84 \cdot 1.04 \cdot 0.12 \cdot 10.0 = 1.05$ kN is the weight of the element; S_a is the seismic coefficient applicable to non-structural elements; $\gamma_a = 1.0$ is the importance factor of the non-structural element and $q_a = 2.0$ is the behaviour factor of the element.

The seismic coefficient S_a may be calculated using the following expression

$$S_a = \alpha \cdot S \cdot [3(1 + z/H) / (1 + (1 - T_a/T_1)^2)\text{-}0.5]\alpha \cdot S \tag{2}$$





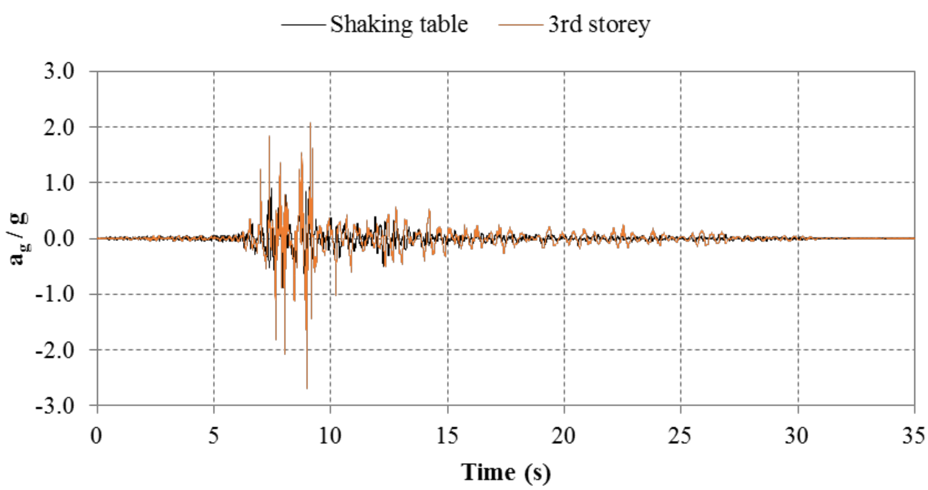


Fig. 5 – Acceleration of the walls with respect to accelerations of the shaking table at $a_g/g = 1.0$

where $\alpha=a_g/g = 1.0$; S=1.0 is the soil factor; z=0.52 m is the height of the non-structural element above the level of application of the seismic action (foundation); H=3.6 m is the building height measured from the foundation; $T_a \approx 0$ is the fundamental vibration period of the non-structural element; $T_1=C_t \cdot H^{3/4}=0.050 \cdot 3.6^{3/4}=0.13$ s is the fundamental vibration period of the building in the relevant direction.

From Eqs. (2) and (1) S_a and F_a are equal to 1.22 and 0.64 kN, respectively. By distributing the horizontal seismic force over the surface of the wall using the expression

$$q_a=F_a/(h_w \cdot l_w) \tag{3}$$

the value of the horizontal seismic pressure on the wall q_a=0.793 kN/m^2 is obtained. The lateral (out-of-plane) load effect due to arch action in a wall shall be less or equal to load resistance under an arch action. A condition $q_a \leq q_{lat}$ must be fulfilled, where q_{lat} is the lateral strength of the wall (analysis based on a three-pin arch) determined as

$$q_{lat}=f \cdot (t/h_w)^2 \tag{3}$$

where f=1530 kN/m^2 is the compressive strength of the wall (see Table 1), t=0.12 m is the thickness of the wall and h_w=1.04 m is the height of the wall.

From Eq. (3) the lateral strength q_{lat} is equal to 20 kN/m^2, thus higher than q_a=0.793 kN/m^2, which indicates the safety of the wall with respect to out-of-plane seismic action.

In compliance with [7] resistance models based on full vertical arching action, although they are typically applied to elements subjected to non-seismic actions (i.e. wind loads), and they may be considered appropriate only for undamaged infills.

6. Conclusions

Masonry is often used as an infill fully integrated with the surrounding frame and therefore has to be considered as structural element. The infill is built after the upper frame member and the top of the infill is usually not structurally connected to the structure above. Due to structural interaction with the frame, the infill and the frame will have equal drift deformations. If infill is made of brittle materials such as clay block masonry, in strong earthquakes the response of such a structure will be strongly influenced by the damage sustained by the infill.

Reinforced concrete frame structure infilled with masonry walls was built in a scale 1/2.5 and tested on shaking table under sequence of earthquake excitations. Observed were masonry walls placed in the central transverse bay that were exposed to the out-of-plane excitation which had door opening in the ground floor and window openings in the first and the second floor. The most vulnerable to earthquake damage was the ground floor masonry wall with the door opening. The damage occurred was the separation of the top row of masonry units in contact with the frame (see Fig. 4) at earthquake excitation of highest $a_g/g = 1.0$. At $a_g/g = 1.2$ the top row of the wall was demolished and the loss of the entire wall was imminent. In other storeys the separation of the wall from the frame was noticeable, however haven't showed significant crack growth in further excitation sequences. The tests revealed, that simplified method implied by the code (analysis based on a three-pin arch) incorrectly estimated their resistance since different failure mechanisms occurred and accelerations measured on the wall were higher up to three times in comparison with those of the shaking table (see Fig. 5). Position of the failed infilled masonry wall with opening and its failure mechanisms were opposite to the current perceptions for out-of-plane infilled walls behaviour.

In order to improve the out-of-plane behaviour of the framed-walls with opening vertical confining elements around opening should be built and structurally connected to the structure above and below. In such a way infill will be fully integrated with the surrounding frame and therefore composite framed-masonry structure with more predictable and reliable behaviour.

7. Acknowledgements

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