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SEISMIC BEHAVIOUR OF CAPACITY DESIGNED MASONRY WALLS IN LOW SEISMICITY REGIONS

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SUMMARY

Earthquakes are not restricted to national borders and every year they kill many people around the world. As we know the best way to minimize the effects of earthquakes is to improve our understanding of the phenomenon to complete and to follow the necessary regulations for the seismic design of structures. In this case, masonry structures are in different position because of the lack of sufficient knowledge in comparison with other structures, such as concrete structures, steel and timber. On the other hand, unreinforced masonry is used for most of the buildings in Germany, Belgium, the Netherlands and Austria.

Eurocode 8, which represents a new generation of structural design codes in Europe, defines requirements for the design of buildings against earthquake action. In Central and Western Europe, the new earthquake zones in connection with the corresponding design ground acceleration values will lead in many cases to earthquake actions, which are remarkable higher than defined by the design codes used up to now in Central Europe.

These reasons made us to find a new method to improve the behavior of masonry structures with low costs. The Corner-Gap-Element is a way to improve the deformation capacity of masonry walls [1, 4]. The main idea is based on the weak point of masonry structures: the corner points of walls during an earthquake. Fig. 1 explains the main idea of the Corner-Gap-Element and the way of loading of masonry walls that in most cases leads to a high exploitation of the shear capacity. Since the bending moments increase with shear forces, the eccentricity of the normal force in the critical cross section becomes significant. This in turn leads to a reduction of the size of the compression zone in unreinforced walls with high concentration of normal stresses and shear stresses. In order to overcome this problem, Corner-Gap-Elements, enabling the transfer of the capacity design concept to unreinforced masonry have been proposed. These elements, consisting of a bearing beam made of a sufficient strong material (such as reinforced concrete), ensure a limitation of eccentricity of the normal force and thus, restrict the pinching of the compression zone. The deformation can be concentrated in the joint below the bearing beam. The masonry itself is protected from high stresses as a potential cause of brittle failure. The experimental test results on the shaking table in the earthquake engineering laboratory of NTUA (National Technical University Athens) have confirmed the main idea.

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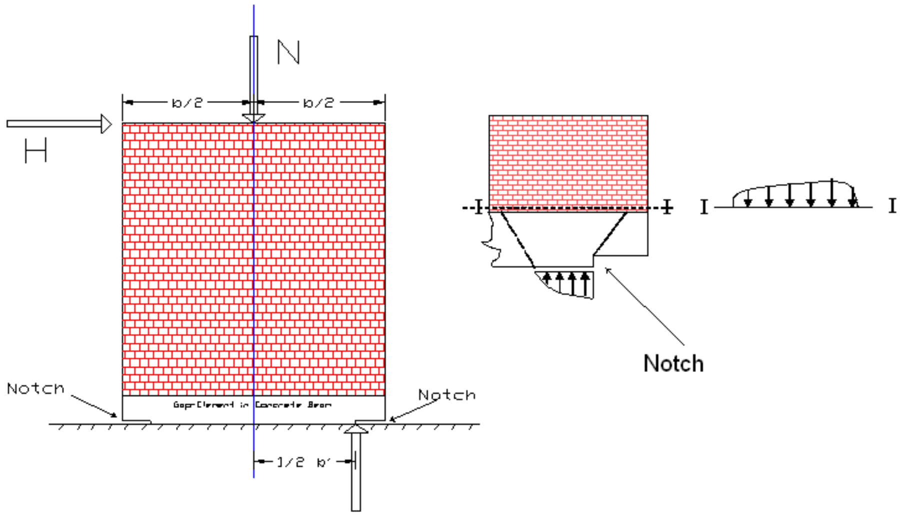


Fig. 1: Corner-Gap-Element in masonry wall

INTRODUCTION

In this contribution, the experimental tests at NTUA as well as the evaluation of the experimental data obtained there will be presented.

EXPERIMENTAL INVESTIGATIONS - SHAKING-TABLE TESTS AT NTUA

The experimental investigations were performed in the Earthquake Laboratory of NTUA. The bricks and some other basic material were transferred from Germany to Greece. The experimental investigation included three specimens with various specifications as described in table (I).

TABLE (I): SHAKING TABLE TEST – SPECIMENS (UNREINFORCED)

Number of Samples	Type of Sample	Horizontal Mortar	Vertical (perpendicular) Joints
1	Without Gap-Element	Normal (12 mm)	Non–Mortar
1	Gap-Element (prototype)	Normal (12 mm)	Non–Mortar
1	Gap-Element	Thin-Bed Mortar (2 mm)	Non–Mortar

SPECIMENS SPECIFICATIONS

- Brick Units:

The brick units in all of the specimens were of the same type as described in table (I). For all specimens, no mortar has been used in the vertical joints. The brick size was 497 x 238 x 175 mm^3, this is a typical kind of brick used in Germany by attention to thermal insulation and other parameters that are important for a country like Germany. Fig. 2 shows one of the used brick units.

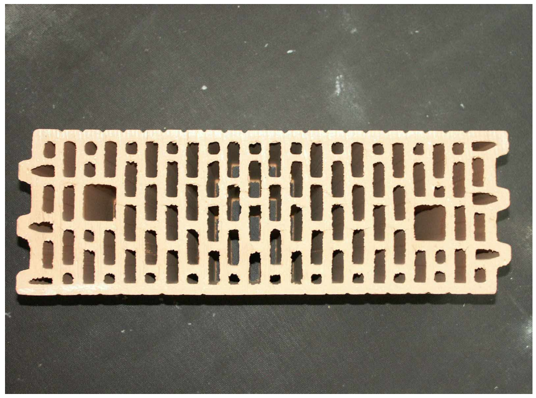


Fig. 2: Top view of brick unit used in all three specimens

- Structural Specification:

The first specimen should reflect the common way of constructing a masonry building. It was built with normal walls and normal mortar. Steel masses (5 tons each) on top of the slabs have been used to model live loads. A part of the total live load has been provided by using an increased slab thickness (18 cm instead of 10 cm). Specimen #1 had two stories with a total height of 4.40 m.

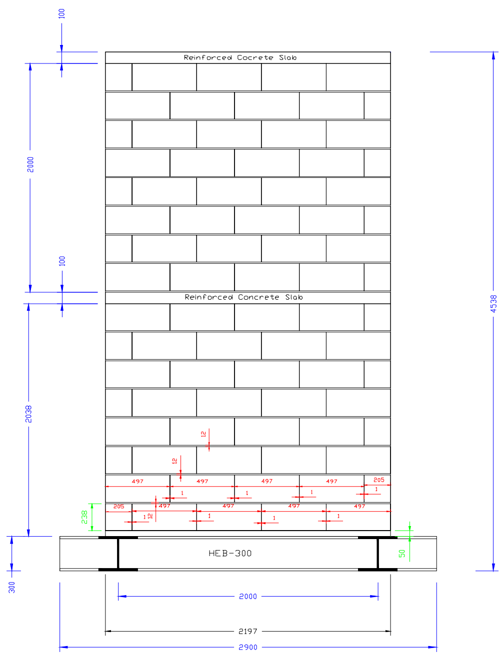


Fig. 3: Main wall of specimen #1

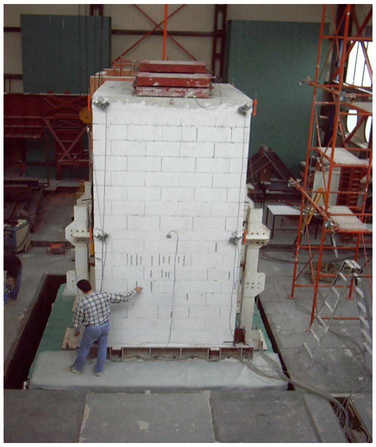
All three specimens have similar roofs with same dimensions and concrete materials. Dimensions of the roofs are 2710 x 2230 x 180 mm^3 and $\rho = 2400\ kg/m^3$.

Transverse walls built in the middle of the structure were provided for lateral stability. To allow the deformation of the Corner-Gap-Element, no connection between main walls and transverse walls has been provided.

Fig. 4: Steel strip in lateral walls for prevention of out of plane failure

After finishing of each story, a prefabricated roof has been pasted with a special type of glue on the walls. The steel masses for live loads were put on each story in a symmetric position to avoid slippery, were fastened to the floor with long bolts. The first story's live load consisted of 200 pieces of steel in six rows with 980 x 330 x 10 mm³. On the second floor the mass consisted of only five big steel plates with symmetric distribution with dimension 1000 x 1000 x 130 mm³ (see fig. 5 showing live loads and their positions on the first and second floor).

(a)



(b)

Fig. 5: Live loads on the first and second floor

LVDT's were installed for recording displacements in vertical, horizontal and diagonal directions of the main and lateral walls. Accelerometers only recorded horizontal acceleration of roofs in two horizontal directions. Fig. 6 shows details of specimen #1.

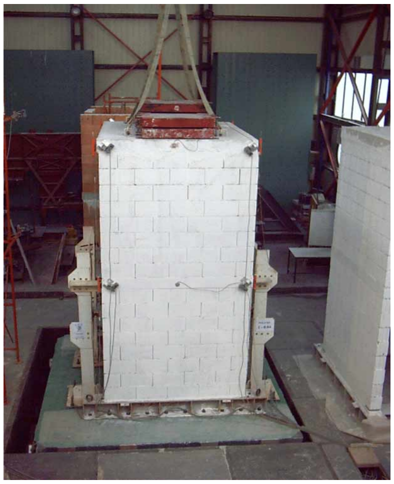


Fig. 6: Instrumentations on specimen #1 ready for testing (LVDTs & Accelerometers)

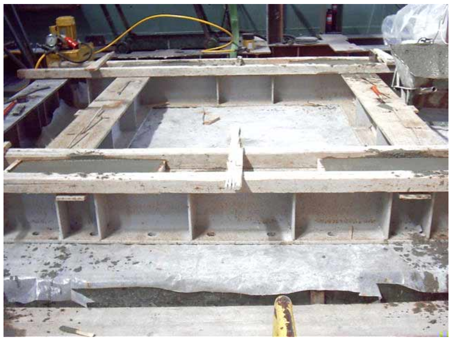
Engineering data of the specimens are summarized as follows:

- *Specimen #1*

- Total weight (dead load + live load): 19,200 kg
- Number of stories: two
- Brick size: 497 x 238 x 175 mm^3
- Live load: 5 t in every story, 10 t total live load
- Mortar: normal with 10-12 mm thickness
- Roofs: normal concrete with 2.71 x 2.23 x 0.180 m^3 and ρ = 2400 kg/m^3.
- Height of the specimen: 4.4 m
- Number of table excitation time histories: 11
- Rate of excitation (table acceleration):0.599 – 5.394 m/sec^2
- Structure fundamental period: 0.177 sec

- *Specimen #2*

Specimen #2 as specified in table (I) is a specimen with Gap-Elements, but the other specifications are corresponding to the first one. The Gap-Element building procedure is shown in fig. 7:



(a)

(b)

(c)

(d)

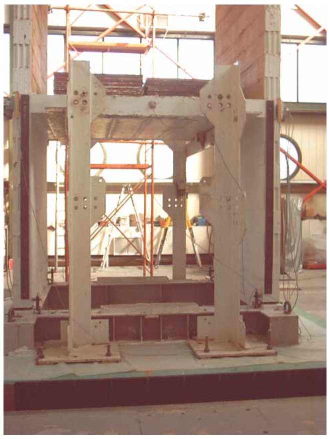
Fig. 7: Gap-Element building procedure

In order to allow a rocking movement of the base-beam with the Corner-Gap-Elements, the middle reinforcement should not have any intentional tensile connection to the steel foundation frame that was mounted on top of the shaking-table (see fig. 7-d, where one finished corner gap beam under construction of main wall in specimen #2 is shown).

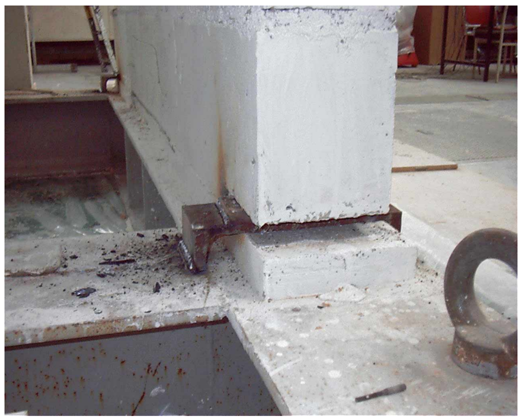
- Total weight (dead load + live load): 19,700 kg
- Number of stories: two
- Brick size: 497 x 238 x 175 mm^3
- Live load: 5 t in every story, 10 t total live load
- Mortar: normal with 10-12 mm thickness
- Roofs: normal concrete with 2.71 x 2.23 x 0.180 m^3
- Height of the specimen: 4.41 m
- Net length of support b´= 1.89 m
- Number of table excitation time histories: 11
- Rate of excitation (table acceleration):0.588 – 5.89 m/sec^2
- Fundamental period: 0.170 sec

- Specimen #3

By attention to experiences with specimen #2, some changes have been implemented in specimen #3 as is seen in fig. 8. For example removal of lateral walls and putting of vertical steel strips between Gap-Elements and first roof, fig. 8.



(a)



(b)

Fig. 8: Removal of all lateral walls and new type of sliding stopper for corner-gap beam, wall edges in first story reinforced with vertical steel strip

Engineering data for the third specimen are:

- Total weight (Dead load + live load): 18,200 kg
- Number of stories: Two
- Brick size: 497 x 238 x 175 mm^3
- Live load: 5 t in every story, 10 t total live load
- Mortar: Glue mortar with 2 mm thickness
- Roofs: Normal concrete with 2.71 x 2.23 x 0.180 m^3
- Height of the specimen: 4.26 m
- Net length of support b´= 1.89 m
- Number of table excitation time histories: 17
- Rate of excitation (table acceleration): 0.542 – 12.03 m/sec^2
- Fundamental period: 0.152 sec

Experimental Observations

This section describes the observations during all steps of the tests and for all three specimens. The table excitation followed a synthetic time history, which has been derived on the basis of a typical response spectrum as it would be applicable according to the draft of the German seismic design code DIN 4149 [2, 3]. To reflect the shallow sources for earthquakes in Central Europe, a short duration of time history has been selected. The time history took 5.12 sec. It has been applied several times with increasing intensity. It should be noted, that the acceleration values given here as nominal input data correspond to the ground acceleration on rocky soil. The maximum acceleration values should be 25 % higher according to a soil factor of S = 1.25. Actually, the real measured values differ from this factor. In most cases, somewhat higher values have been recorded.

- Specimen #1 Observations

- till 8 % (nominal input data) of g, no cracking or separation in the joints could be observed,
- when the excitation was increased until 20 % of g, the first cracks in the first layer of the main wall's bricks appeared,
- at 36 % g, ´jumping´ between the last layer of bricks below the first floor slab and one layer below could be noted. In this load step, severe damage of a corner brick in the first layer above foundation appeared (see fig. 9).

Fig. 9: Last test in specimen #1, shear failure cased collapse in first layer of main wall

- Specimen #2 Observations (prototype)

- at 12 % g excitation, only very small vertical movement could be observed, apparent by dusting of Gap-Elements.

- at 16 % g to 20 % g test continued without any special observation.
- at 24 % g excitation: uplift in mortar joint occurred in the main walls.
- at 28 % g uplift in the last area increased.
- at 32 % g first cracks in first brick layer of main wall observed.
- with 36 % g excitation, one of the main walls showed a step-like crack with horizontal displacement in joints as well as spreading of more cracks in corner brick.
- In the last attempt with 40 % g, (5.89 m/sec^2 recorded) both main walls showed big step-like failure about 3 cm because of shear effect.

- Specimen #3 observations

Specimen #3 had some important changes:

- Lower total weight in comparison with previous specimens (because of removed lateral walls).
- Changing the shear system in Gap-Element as described in fig. 8-b.
- Put new steel strip between Gap-Elements and first floor fig. 8-a.

The following observations could be made:

- at 4 % g till 10 % g everything was like specimens #1 and #2.
- at 12 % g, some vertical movement has been observed in the Gap-Elements (dust in the air near the notches of Gap-Elements). No cracks could be observed.
- at 16% g, remarkable joint opening below Corner-Gap-Element.
- 20 % g; some small cracks, 2 layers below first floor slab
- 28 % g: remarkable uplift
- 44 % g: in this stage a little horizontal slip occurred below in Gap-Elements because of the torsion effect.
- Increased input until 64 % g without further significant observations. Anchor bolt of steel strip came out in one of the Corner-Gap-Elements. All bolts were fastened again afterwards.
- At 72 % g, the rear main wall on the second floor showed step-like crack with horizontal movement (fig. 10).
- Failure of back wall on the second story occurred at nominal input of 80 % g (measured max. table acceleration 12.03 m/s², see figs. 11 and 12).

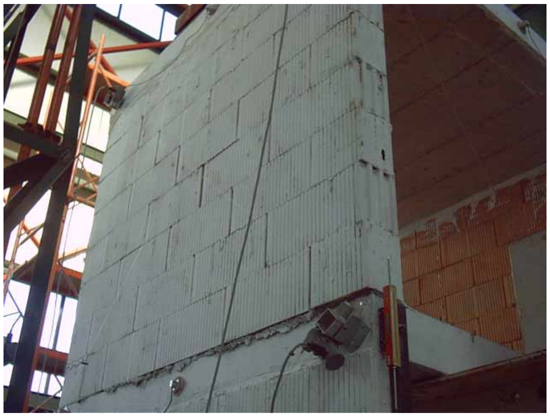


Fig. 10: Step-like diagonal crack through joints at 72 % g excitation

(a) (b)

Fig. 11: Failure of the second floor at 80 % g excitation (12.03 m/sec²) in Specimen #3

Fig. 12: Big horizontal movement in second floor's main wall (12 cm)

EVALUATION OF EXPERIMENTAL DATA FROM SHAKING-TABLE TESTS

Figs. 13 and 14 show the different responses for the first and the third specimen. Gap-Element confirmed the expected behavior as cheap and workable method in practice.

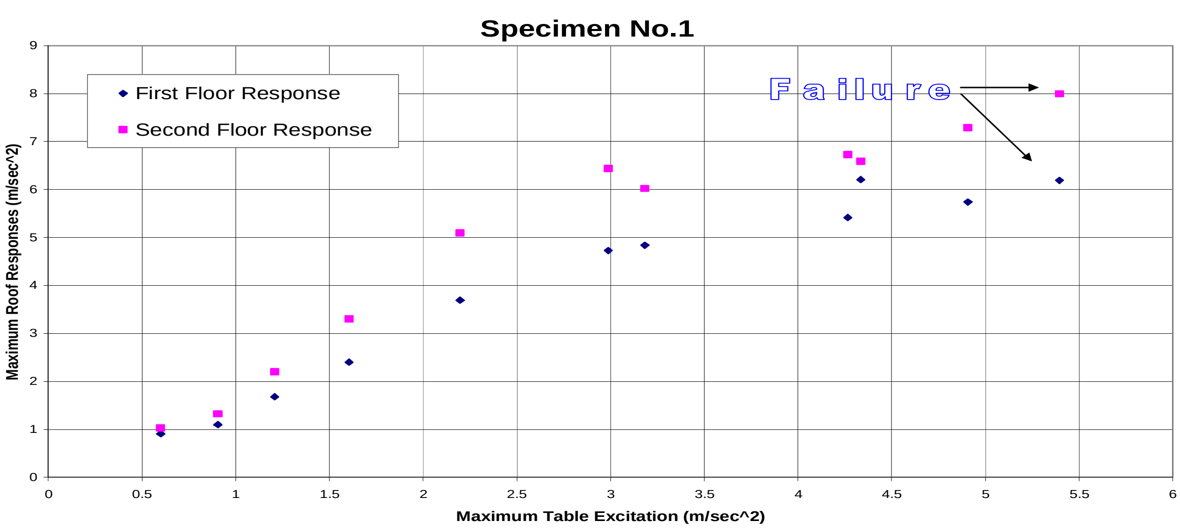


Fig. 13: Maximum table excitation vs. maximum floor responses specimen #1

The first specimen collapsed of about 5.4 m/sec² of maximum excitation and the failure was near the foundation in first floor's main walls. In the third specimen, failure happened in the second story. The inspection of the third specimen after the last test showed no noticeable damage in the first story. It is remarkable to see that the maximum acceleration of the roof of the first story becomes bigger than the maximum acceleration of the upper roof (fig. 14).

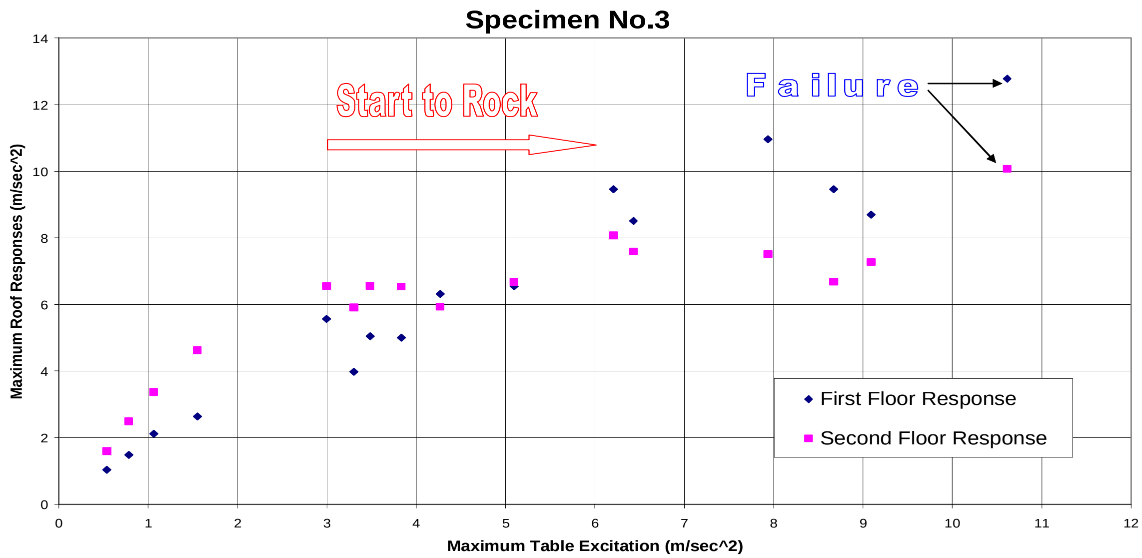


Fig. 14: Maximum table excitation vs. maximum floor responses specimen #3

Fig. 15 shows the uplift movement at the center of the top roof. This uplift motion is introduced by the rocking mechanism of the whole structure.

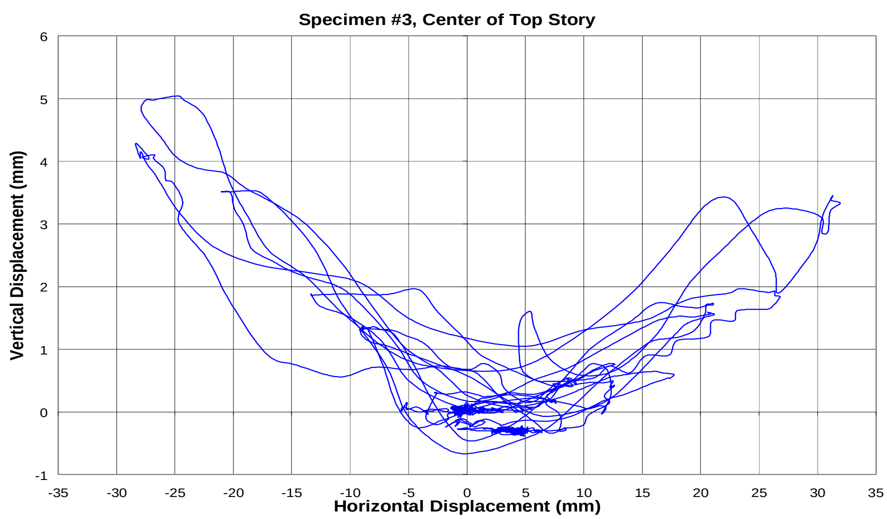


Fig. 15: Second roof vertical displacement vs. average horizontal displacement for the top story in specimen #3, maximum table excitation 9.093 m/sec²

Fig. 16 shows the torsional rotations of the roof plates. After 3.5 seconds, a significant remaining rotation can be seen from the plots.

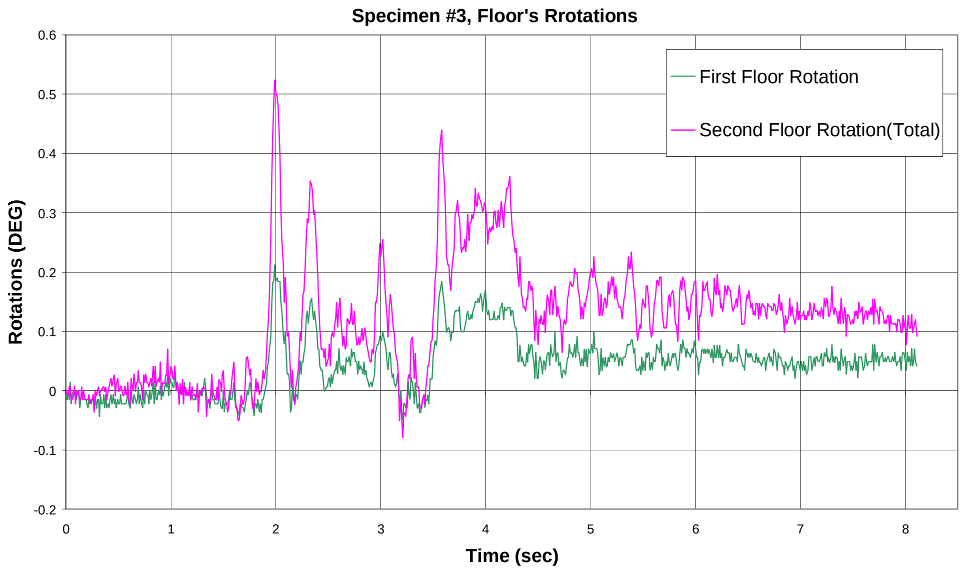


Fig. 16: Roof's rotation in Specimen #3, maximum table excitation 9.093 m/sec^2

The overturning moment versus the relative second roof displacement is depicted in Figure 17. The overturning moment has been computed under inclusion of rotational inertia effects of roofs and walls. It can be seen that the moment practically does not exceed a limit of 150 to 200 kNm. This value is almost identical with the maximum possible moment derived from the maximum possible eccentricity of the vertical loads, which is limited by the Corner-Gap-Element:

$$\max M \leq N \cdot \frac{b'}{2} = 182\,kN \cdot \frac{1.86m}{2} = 169\,kNm$$

This simple calculation does not consider the dynamic normal force arising from the vertical accelerations [5].

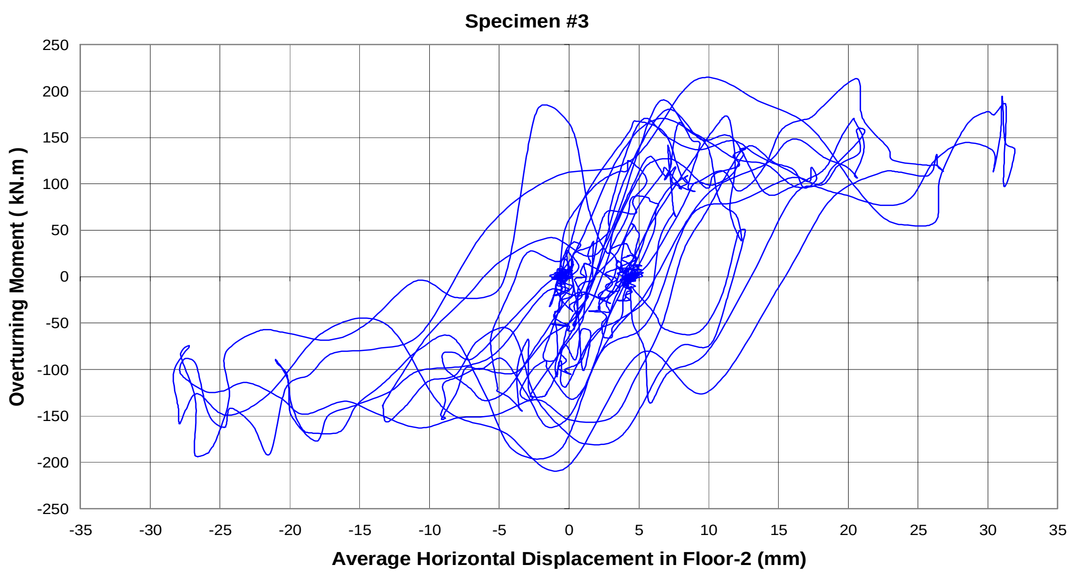


Fig. 17: Overturning moment in specimen #3, maximum table excitation 9.093 m/sec^2

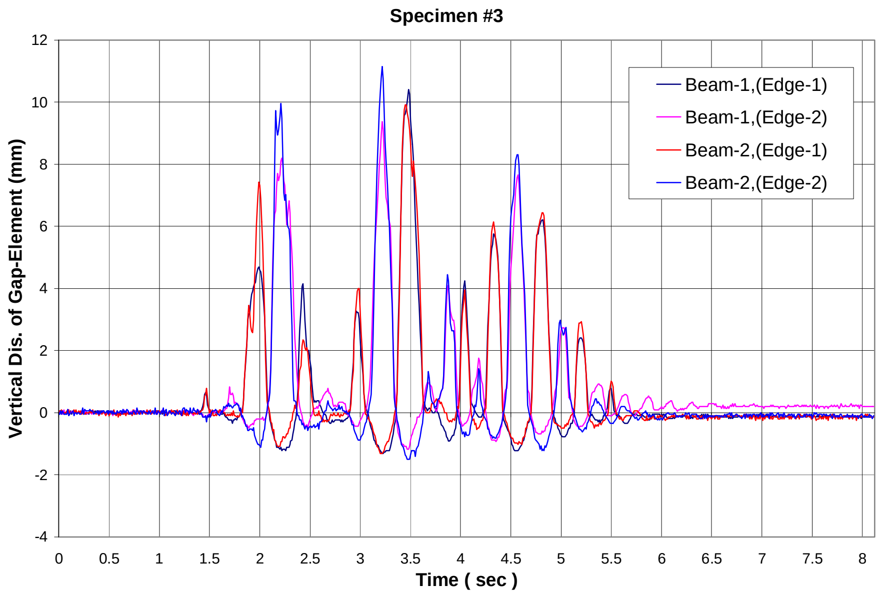


Fig. 18: Vertical opening (jumping) of Gap-Elements for specimen #3, maximum table excitation 9.093 m/sec^2

Fig. 18 illustrates the responses of the Gap-Elements. Both edges of the beams show the intended behaviour. The use of Corner-Gap-Elements could help very much to obtain a cheap and effective method for building structures that are safe against earthquakes. More investigations are needed in order to complete understanding the mechanisms acting in such structures and to develop practical design rules, enabling the application of the capacity design philosophy also for masonry structures.

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