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IMPROVEMENT OF SEISMIC BEHAVIOR OF UNREINFORCED MASONRY STRUCTURES IN LOW SEISMICITY REGIONS BY CAPACITY DESIGN

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Abstract

In many cases the weak points of masonry structures during an earthquake are the corners of the walls. When the eccentricity of the normal force approaches half of the wall length, the size of the compression zone in unreinforced walls approaches zero, leading to infinite normal and shear stresses.
By a R/C bearing beam with ´Corner-Gaps´, a limitation of eccentricity can be ensured and the pinching of the compression zone can be avoided. Shaking-table tests at NTUA Athens have proven the effectiveness of the Corner-Gap-Element which enables the application of the Capacity Design philosophy.

Key Words

Masonry Corner-Gap Capacity Design

Intoduction

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.
With regard to these reasons and trying to find a low cost method to improve masonry structure behaviour made us to use an idea that we call Corner-Gap-Element. Corner-Gap-Element is a way to improve the deformation capacity of masonry walls [1, 4].

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The main idea is based on the weak point of masonry structures: the corner points of walls during an earthquake. Fig. 1 explains basic assumptions 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, restricts 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.

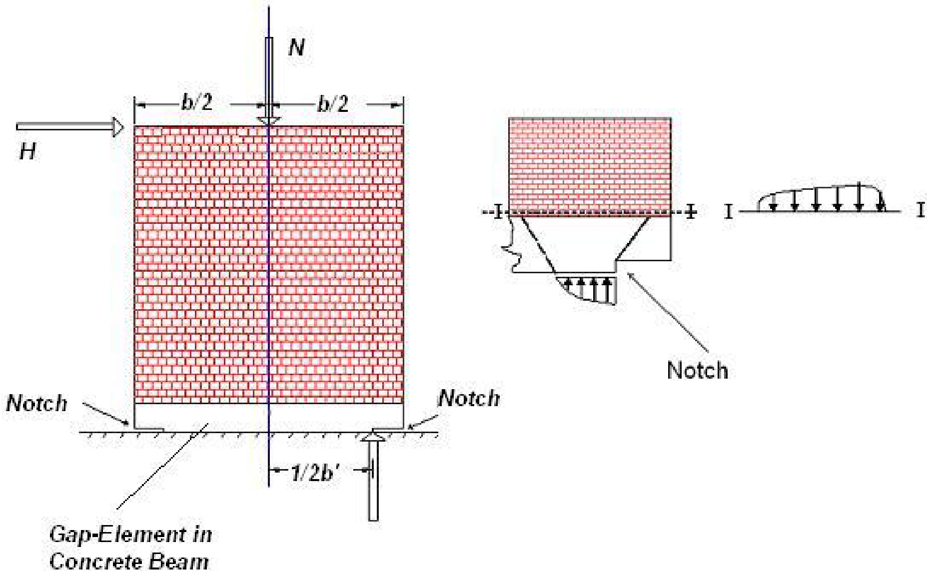


Fig. 1: Corner-Gap-Element in masonry wall

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

1.1 Experimental investigations - shaking-table tests at NTUA

The experimental investigations were performed in the Earthquake Laboratory of NTUA. Basic material like bricks and mortar-cement were transferred from Germany to Greece, to make compatible the specimens as well as German's structures. The experimental investigation included three specimens with various specifications, their details are available in table 1.

Table 1 Shaking Table Test – Specimens (unreinforced)

Number of Specimens	Type of Specimen	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 used units in three specimens are described above in table 1. For all specimens, no mortar has been used in the vertical joints like typical German buildings. The brick size was 497 x 238 x 175 mm³; 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.

- Structural Specifications:

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.

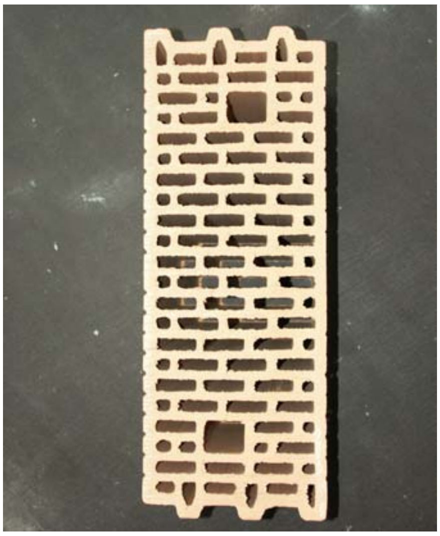


Fig. 2: Top view of used brick unit

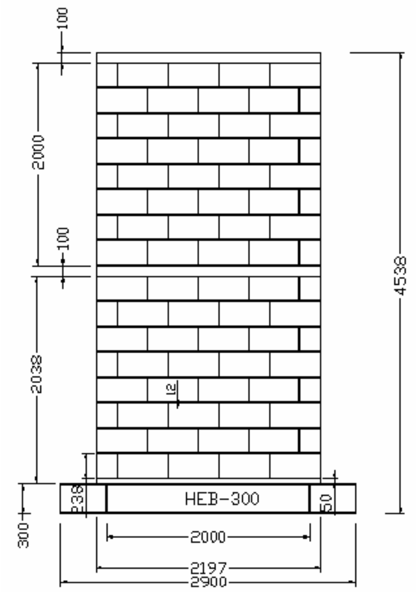


Fig. 3: Main wall of specimen #1

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 ρ = 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 and 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 mm^3. On the second floor the mass consisted of only five big steel plates with symmetric distribution with dimension 1000 x 1000 x 130 mm^3 (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)

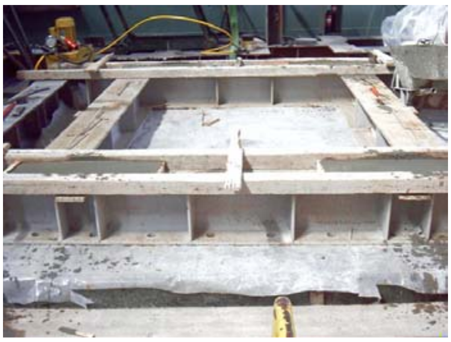
Engineering data of the specimens are summarized as follows:

- 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 and #3

Specimen #2 as specified in table 1 is a prototype specimen with Gap-Elements but the other specifications are corresponding related to the first one. Specimen #3 was the main specimen that tested with Corner-Gap-Element by attention to obtained experiences from specimen #2. Both specimen #2 and #3 had the same built-up procedures that are 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 the main wall in specimen #2 is shown). In the following the differences are described:

- Total weight (dead load + live load): 19,700 kg for specimen #2 and 18,200 kg for specimen #3
- Mortar: specimen #2 had normal mortar with 10-12 mm thickness and in specimen #3 used glue mortar with 2 mm thickness
- Height of the specimen: specimen #2 = 4.41 m and specimen #3 = 4.26 m
- Net length of support b´= 1.89 m
- Number of table excitation time histories: 11 for specimen #2 and 17 for specimen #3
- Rate of excitation (table acceleration): 0.588 – 5.89 m/sec² for specimen #2 and specimen #3 had 0.542 – 12.03 m/sec²
- Fundamental period: 0.170 sec for specimen #2 and for specimen #3 it decreased to 0.152 sec

- **Differences between specimen #2 and #3**

Due to experiences with specimen #2, some modifications have been implemented in specimen #3 as it is illustrated in fig. 8. For example the lateral walls are removed and vertical steel strip are put in between the Gap-Elements and the 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

- Experimental Observations

This section describes the observations of all three specimens during all steps of the tests. The table excitation followed a synthetic time history, which has been derived based on 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 of 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

- until 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 the main wall

- Specimen #3 observations

The following observations could be made:

- from 4 % g until 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.
- 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.
- 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. 10).

(a) (b)

Fig. 10: Failure of the second floor at 80 % g excitation (12.03 m/sec²) in Specimen #3

1.2 Evaluation of Experimental Data from shaking-table tests

Figs. 11 and 12 show different responses in the first and the third specimen. The Gap-Element confirmed the expected behaviour as a cheap and workable method in practice.

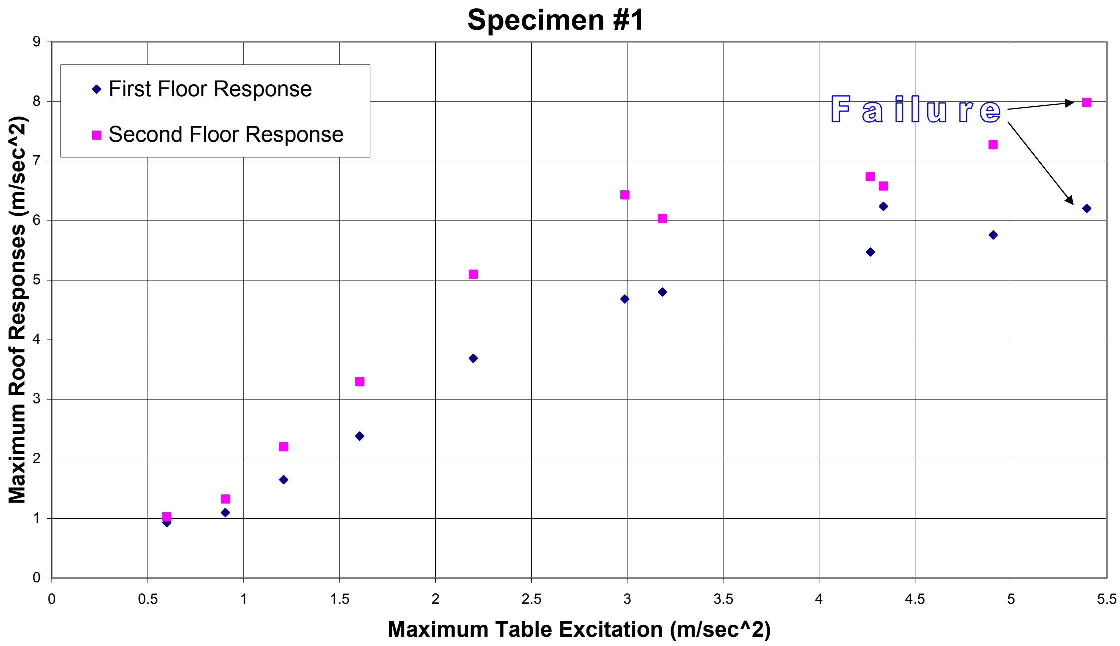


Fig. 11: Maximum table excitation vs. maximum floor responses specimen #1

The first specimen collapsed at 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. 12).

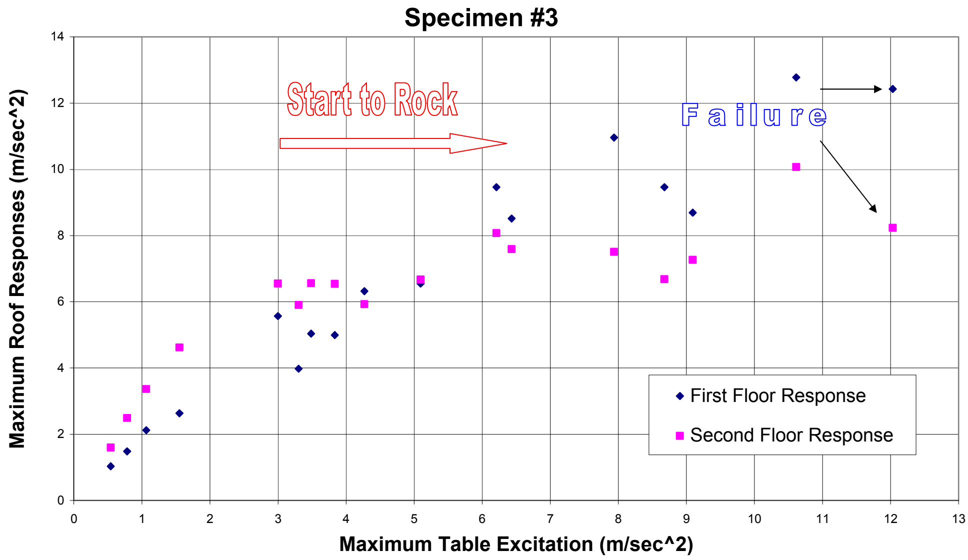


Fig. 12: Maximum table excitation vs. maximum floor responses specimen #3

The overturning moment versus the relative second roof displacement is depicted in Figure 13. 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].

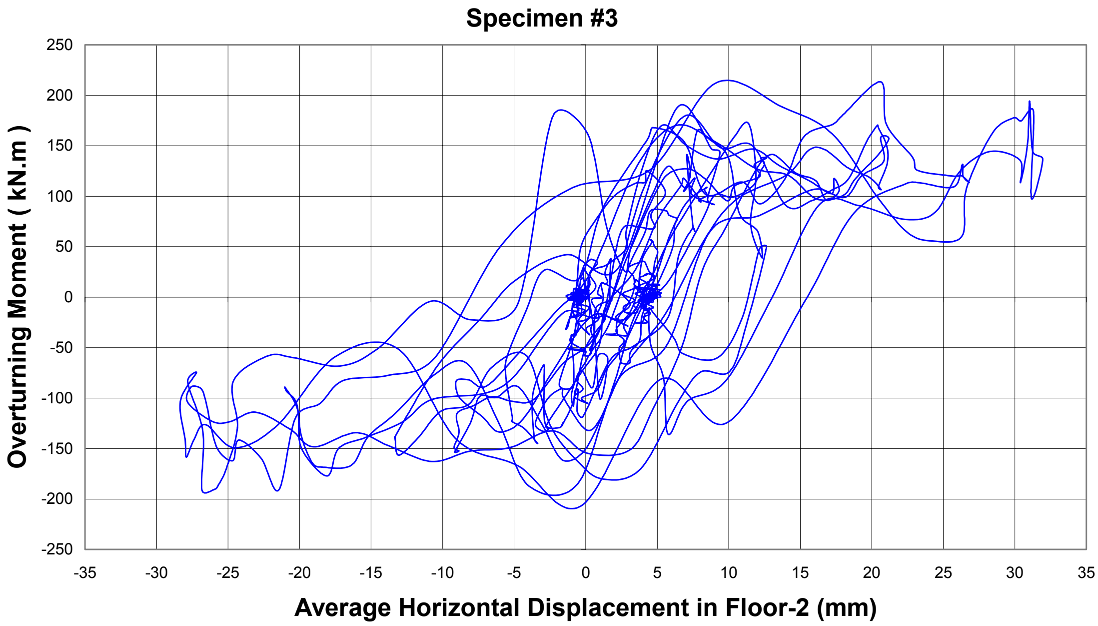


Fig. 13: Overturning moment in specimen #3, maximum table excitation 9.093 m/sec^2

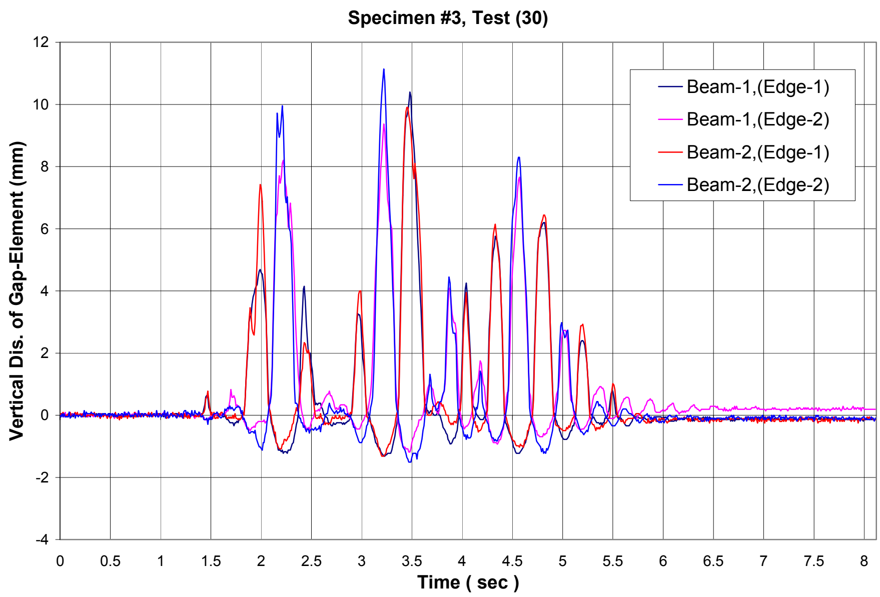


Fig. 14: Vertical opening (jumping) of Gap-Elements for specimen #3, maximum table excitation 9.093 m/sec^2

Conclusion

The use of Corner-Gap-Elements could help very much to obtain a cheap and effective method for building unreinforced masonry structures that are safe against earthquakes. More investigations are needed to complete the understanding of 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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