Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Response of infilled frames with brickwalls to earthquake motions

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ABSTRACT: The results on an experiment of a frame filled with a brickwall, using the 6 DOF earthquake testing facility of the Laboratory for Earthquake Engineering, NTUA-Greece against real time earthquake motions are presented. The construction, the testing procedure and the conclusions are based on the experience of the authors from field observations after earthquakes on the seismic response of infilled frames with brickwalls. In order to simulate the constrained conditions of the brickwalls due to the external frame, a flexible steel frame with a mass at the top, was constructed and put over the brickwall and fixed on the platform. The gap between the top side of the brickwall and the external frame was filled with nonshrinkable grout. The specimen thus composed, was excited along the in plane and the out of plane directions of the brickwall, with various time histories at its base. The response of the specimen to the transversal to its plane direction was quite satisfactory and did not suffer any considerable damage, although it was excited at least with 20 times repetition of the destructive Kalamata earthuake. This is attributed to the fixing of the brickwall at its top with the external frame, to the contrary of the practice, according to which the resulting gap due to the shrinkage of the brickwall is not filled with grout.

1 INTRODUCTION

Brickwalls, used as infill panels of concrete frames, are one of the two most vulnerable elements of structures, when they are subjected to earthquakes. Many collapses of brickwalls have been reported after all recent greek eartquakes (Corinthos 1981, Kalamata 1986, Killini 1988), most of the times due to their out-of-plane dynamic response. It has been noticed that, in such cases, brickwalls become more vulnerable when a gap exists between their two faces. This gap exists for purposes of insulation of exterior walls and is usually filled with an insulating material. Due to this reason, no "collaboration" exists between the two faces of the brickwalls, so their ability to confront earthquakes is reduced.

The contribution of brickwall stiffness to the overall response of buildings is negligible for their out-of-plane direction, though it is drastic for their in plane direction. That's why it is a woldwide approved practice to exclude brickwalls from the out of their plane seismic analysis of buildings. But brickwalls themselves suffer a lot in such cases. That is why an experimental program has been carried out, at our Laboratory, in order to estimate the reasons for the collapses that have been reported. This program was funded by the greek Earthquake Planning and Protection Organization (EPPO).

2 TEST SET-UP AND INSTRUMENTATION

2.1 Description of the wall specimen

The whole set-up design was based on the outcomes of the theoretical research by Vougioukas, Veissakis & Carydis (1992), according to which, it would be difficult to achieve collapse conditions for the wall specimen along its transversal direction. To achieve as maximum response as possible, it was tried, by the proper design and construction of the external steel frame, to have coincidence of the natural period of the whole specimen (external frame and wall) to the natural period of the wall itself as a cantilever beam supported at top and bottom.

The wall was 3 meters long and 2.5 meters high. It consisted of a double brick panel of a thickness of 8 cm each with a void between panels for the accomodation of heat insulation, of a thickness of 5 cm. In the midheight of the wall a concrete bond beam of a thickness of 10 cm was constructed, binding the two faces of the wall, having thus a width of 21 cm. The bond beam was lightly reinforced with 4 bars Φ 8 mm and few stirrups Φ 6 mm per 25 cm. The wall was constructed on a metallic base and fixed with the use of cement mortar.

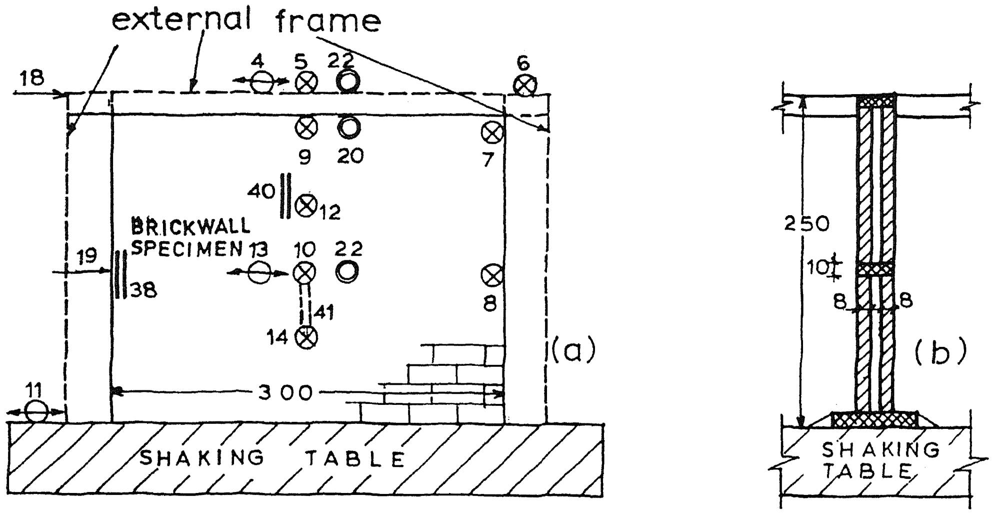
The metallic base was 3 meters long and 0.4 meters wide and was constructed from a metal flange having the shape of an inverted Π with a thickness of 0.5 cm, a flange of 1 cm and on top a flange with uneven surface of 0.3 cm thickness in order to ensure better friction between the wall and its base.

The metallic base was indispensable for the secure transportation of the wall and its positioning on the seismic table.

Finally, the base was bolted on the seismic table to secure a fixed base for the wall under excitation.

Tests were performed separately for the transversal and the longitudinal direction of the wall.

In order to secure the transfer of the excitation mass-inertia forces in the transversal and longitudinal direction of the wall, the upper surface of the specimen was connected to the excitation frame with the use of expanding cement (EMACO).



Legend: → or O Displacement transducers ═ strain gages All dimensions are in cm
↔⊖ or ⊗ Accelerometers

Figure 1. Front view and elevation of the specimen. Presentation of the instrumentation.

2.2 Description of the external frame

The metallic external frame had a ground plan of 3x3 m and consisted of 4 metallic columns L 200x200x20, 2.5 m high, situated at the corners.

The top of the columns were connected with peripheral beams of 3 m length having the same sections as the columns. The peripheral beams were supporting a grid of IPBE 160 beams carrying a weight of 5 tons.

The dimensioning of the frame was done with higher loads in order to avoid the appearance of any failure in the excitation frame during the tests.

The columns were fixed on the seismic table and the grid was bolted to the columns so that the connections would perform as hinges permitting the transfer of larger forces to the wall specimen, and coincidence of the natural periods of the bare frame with the brickwall, as it will be seen later.

In order to avoid oscillations transversal to the main excitation the frame was duly enhanced with diagonal bracings.

2.3 Instrumentation

- channels 18,19,20,22 shown on Figure 1 refer to displacement transducers. Channel 22 was alternatively used for measurements at the middle of the wall or at the top of the frame according to the requirements of each test
- channels 4-15 shown on Figure 1, refer to accelerometers
- also, five channels were devoted for strain gage measurements. Two of them did not function due to cracks of the brickwall. The remaining three numbered channels 38,40 and 41 are also shown on Figure 1. Strain gage 41 is on the opposite face of the wall.

3 EXPERIMENTAL RESULTS-EVALUATION

3.1 Strenth of brick units

The brick units were baked clay of dimensions 8 cm x 11 cm x 19 cm, with twelve holes along the major dimension of the unit of rectangular cross section 1.6 cm x 1.6 cm. The brick units were tested along each one of their principal axes for the determination of the respective strengths.

The results shown below are the mean values of the tests from three specimens. The loading speed was 1 kN/sec.

3.1.1 Along the dimension of 19 cm of the unit

Yield stress σ_y=22.5 MPa
Ultimate strength σ_u=38.0 Mpa

3.1.2 Along the dimension of 11 cm of the unit:

Yield stress σ_y=10.8 MPa
Ultimate strength σ_u=18.8 MPa

3.1.3 Along the dimension of 8 cm of the unit:

Yield stress σ_y=14.8 MPa
Ultimate strength σ_u=18.2 MPa

3.2 Pretest for the determination of the dynamic characteristics of the frame and the wall

The natural period and damping of the specimen had to be determined before the main series of tests in order to

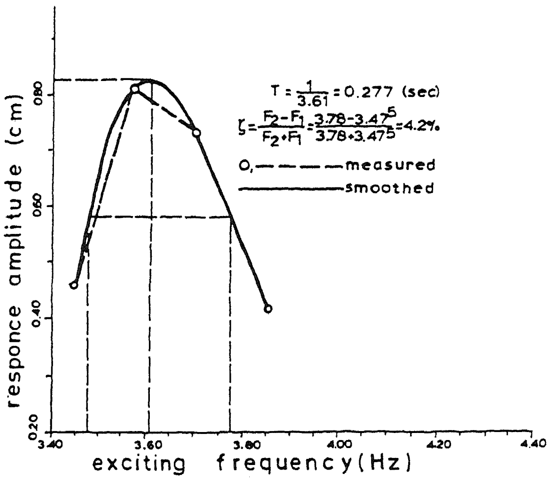


Figure 2. Determination of natural period and damping of the whole specimen.

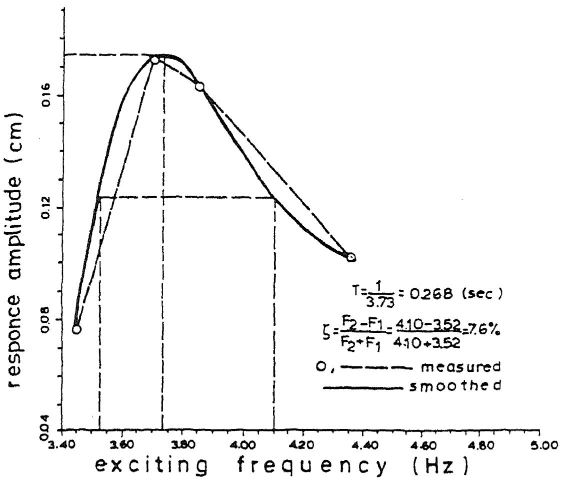


Figure 3. Determination of natural period and damping of the wall as a cantilever.

define the parameters of the main tests.

At the first phase of the pretests the two systems (of the wall and the frame) were tested uncoupled.

Initially, the wall was secured with ties on the seismic table in order to avoid its overturning during the excitation of the frame. Then the frame was excited with an acceleration of 0.05 g of steadily increasing frequency (sweeping). The excitation had a duration of 118 sec starting at 2Hz and ending at 5 Hz.

Eventually the ties were removed from the wall and an excitation of 0.025g with the same duration and frequency sweeping was used. The selected frequency bandwidth had been determined after simple theoretical calculations and estimations.

The above mentioned excitations were along the transversal direction of the wall.

The response of the frame and of the wall were recorded separately.

First, the records of the base displacement were substructed from those of the top in order to estimate the relative displacements. Eventually the relative displacements were analyzed with fast Fourier transforms and the natural period of the frame, was estimated as T=0.238 sec.

The transfer function between the base and the top of the frame accelerations was also estimated. The peak value of the function was at 4.8 Hz or a period of 0.208 sec.

Similar work was performed for the wall (transversal direction). After the removal of the ties the wall was excited with an excitation amplitude of 0.025 g. The transducers used were two for displacement, one at the middle and another at the top of the wall and two for acceleration at the same levels.

The fast Fourier analysis of the relative displacement at the top of the wall produced a natural period of the free wall of T=0.467 sec or 2.1 Hz.

The above value was verified from the transfer function of the relative displacement between the top and the middle of the wall. The transfer function presents also peaks at the periods T=0.29 sec, T=0.22 sec, and T=0.18 sec, as well as at T=0.46 sec.

3.3 Excitation with ramped sinusoidal motion-Determination of the natural period and damping of the whole specimen - Estimation of the overall response

After the performance of the pretests, the upper part of the wall was stiffly connected to the external frame with the use of expanding cement.

Then the system was excited with sinusoidal transversal acceleration ($a \times \sin(2\pi/T)$, $a=0.05$ g, T=0.2, 0.21, ..., 0.30 sec. The duration of the tests was 8 seconds (1 second initial ramp, 6 seconds of the main excitation, 1 second final ramp).

In Figure 2 the diagram of the maximum relative displacement of the top of the specimen to its base versus the exciting frequency is presented. Using least square approximation curve of second order for the best fit of the measured data at the region of maximum values, the natural period T=0.277 sec and the damping ratio $\zeta=4.2\%$ were determined. For the determination of damping the half power bandwidth method was applied.

In order to determine the natural period and damping of the wall as a cantilever beam of span 250 cm, supported at top and bottom, the following procedure was followed: from the signal measuring the displacement of the middle of the wall, half the relative signal measuring the displacement of the top was substructed. Its maximum values versus the exciting frequency are presented in Figure 3. Following the same as above procedure, but using a third order best fitting function a natural period of T=0.268 sec and damping ratio of $\zeta=7.6\%$ was determined.

In Figures 4 to 9 some time histories of interesting recordings are shown for the excitation of the whole system with the above specified ramped sinusoidal motion of period T=0.21 sec and acceleration a=0.05g. The time histories, presented, are between 10 sec and 18 sec, while the time span 0 sec to 10 sec was devoted for excitation with zero acceleration and zero displacement. This was done for reasons related to the control of the shaking table.

In Figures 10 to 16 the time histories at the same as the

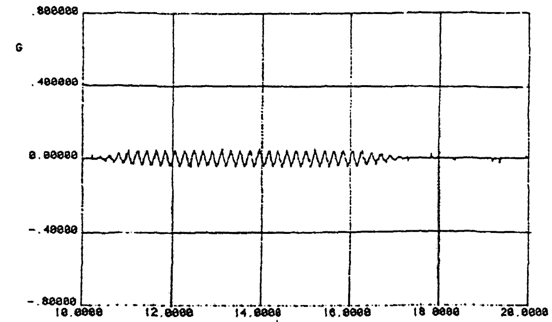


Fig.4. Time history of the achieved acceleration of the shaking table, for T=0.21 sec, a=0.05g

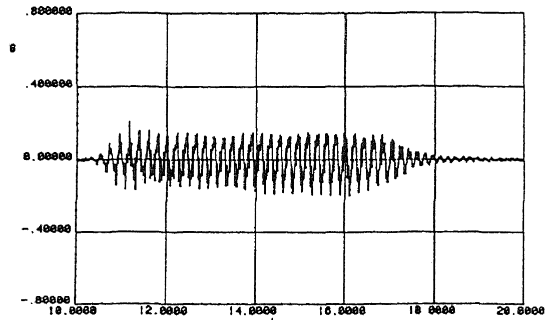


Fig.5. Time history of the total acceleration at the top of the wall, for T=0.21 sec, a=0.05 g. Maximum total acceleration 0.2 g.

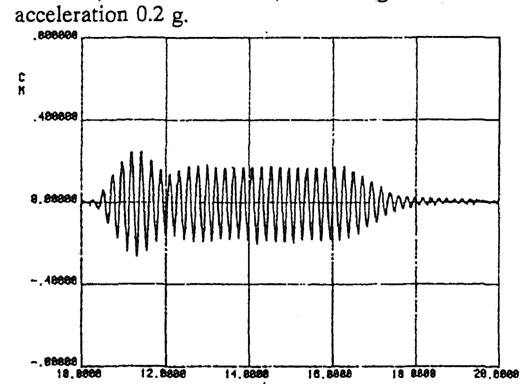


Fig.6. Time history of the relative to the base displacement at the top of the wall, for T=0.21 sec, a=0.05 g. Maximum relative displacement 2.5 mm.

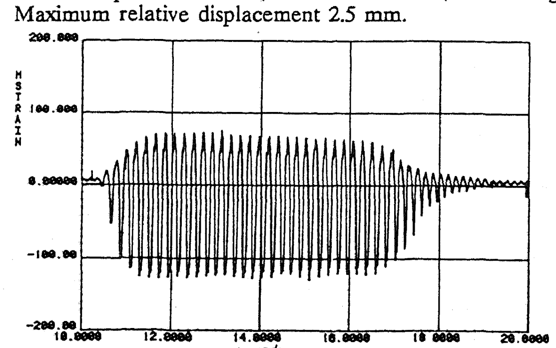


Fig.7. Time history of the strain at gage numbered 40 (see Figure 1), for T=0.21 sec, a=0.05 g. Maximum strain 12 x 10^{-6}

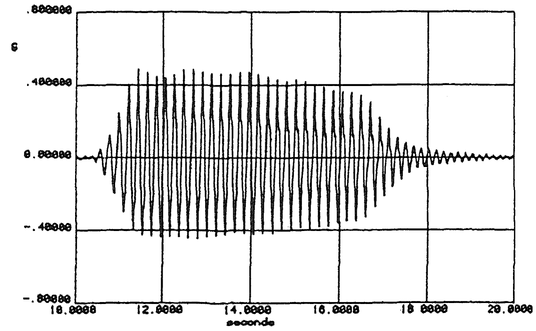


Fig.8. Time history of the total acceleration at the middle of the wall, for T=0.21 sec, a=0.05 g. Maximum total acceleration 0.45 g.

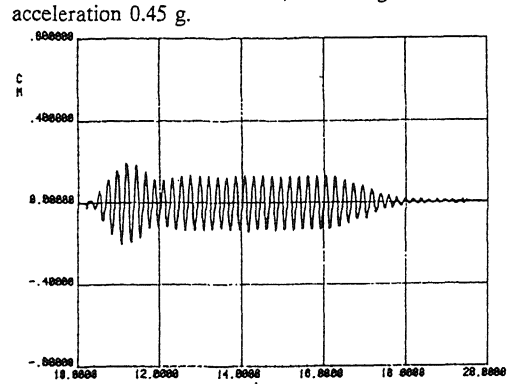


Fig.9. Time history of the relative displacement at the middle of the wall, for T=0.21 sec, a=0.05 g. Maximum relative displacement 2 mm.

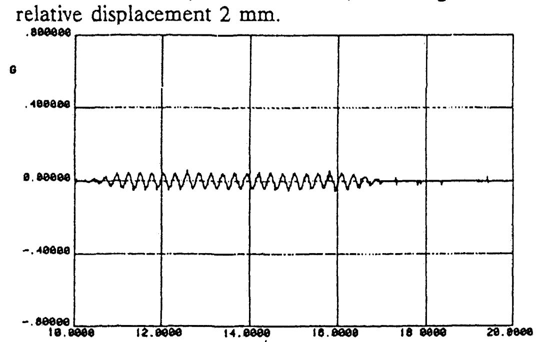


Fig.10. Time history of the achieved acceleration of the shaking table, for T=0.27 sec, a=0.05 g.

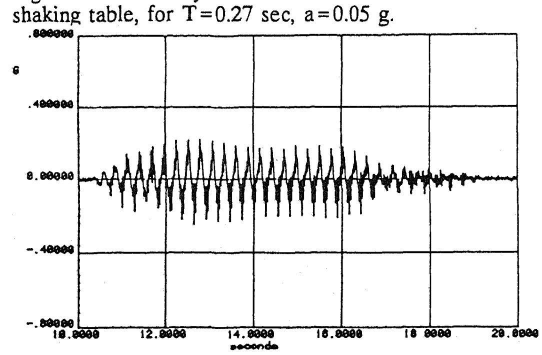


Fig.11. Time history of the total acceleration at the top of the wall, for T=0.27 sec, a=0.05 g. Maximum total acceleration 0.22 g.

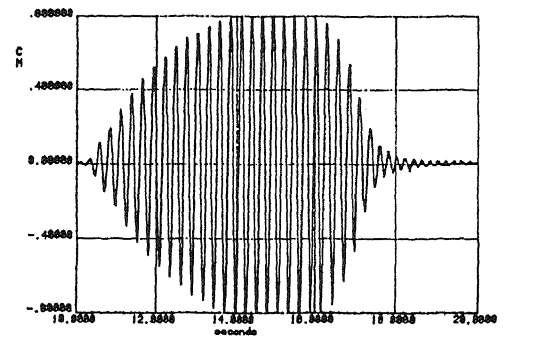


Fig.12. Time history of the relative to the base displacement at the top of the wall, for T=0.27 sec, a=0.05 g. Maximum relative displacement 8 mm.

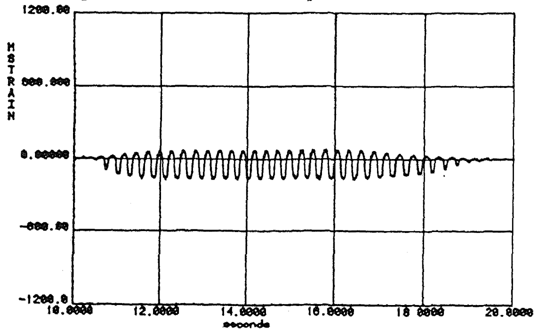


Fig.13. Time history of the strain at gage numbered 40 (see Figure 1), for T=0.27 sec, a=0.05 g. Maximum strain 162 x 10^{-6}

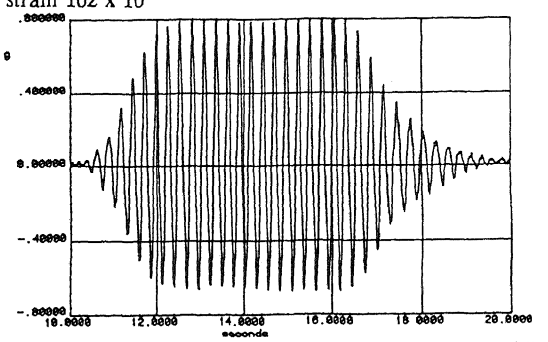


Fig.14. Time history of the total acceleration at the middle of the wall, for T=0.27 sec, a=0.05 g. Maximum total acceleration 0.8 g.

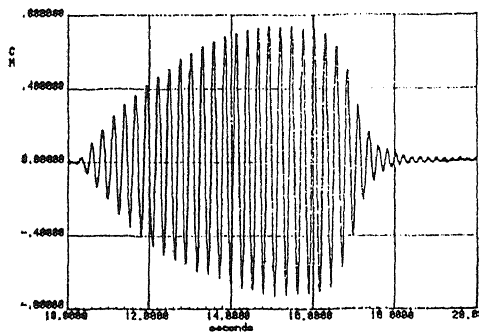


Fig.15. Time history of the relative displacement at the middle of the wall, for T=0.27 sec, a=0.05 g. Maximum relative displacement 7.4 mm.

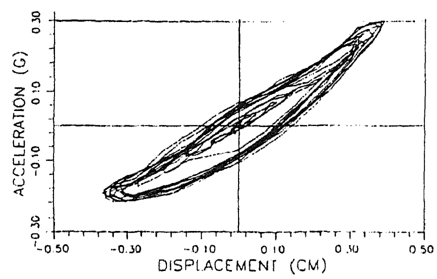


Fig.16. Acceleration versus displacement at the top of the specimen for excitation period T=0.23 sec.

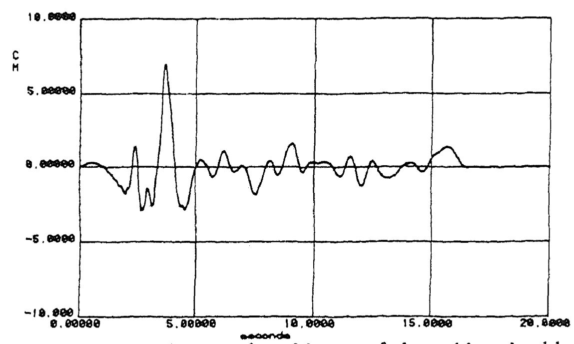


Fig.17. The Kalamata time history of the achieved table motion.

above mentioned points of the specimen are presented, corresponding to an excitation period T=0.27 sec, close to the natural periods of both the frame and of the wall as a cantilever.

In Figure 16 a diagram of acceleration versus displacement at the top of the specimen is shown for an excitation period T=0.23 sec.

The specimen was excited several times with ramped sinusoidal time histories that created considetable accelerations at the specimen. The specimen, and especially the wall behaved quite satisfactorily accomodating accelerations of the order of 0.8 to 1 g and relative displacements of the order of 6 to 8 mm at top or the middle of the wall without the creation of any considerable damage. Before the starting of the tests, horizontal cracks of small width appeared at both sides of the wall. These cracks were at one brick height above the base, at one brick height under and above the concrete bond beam at the middle height of the wall and at one brick height under the top end of the wall. The creation of these cracks was attributed to the shrinkage of theconcrete or cement at the respective levels. Nevertheless, these cracks did not affect the response of the wall against its transversal direction.

3.4 Real time seismic test

After the determination of the natural period and damping of the specimen, it was excited with the N-S component of

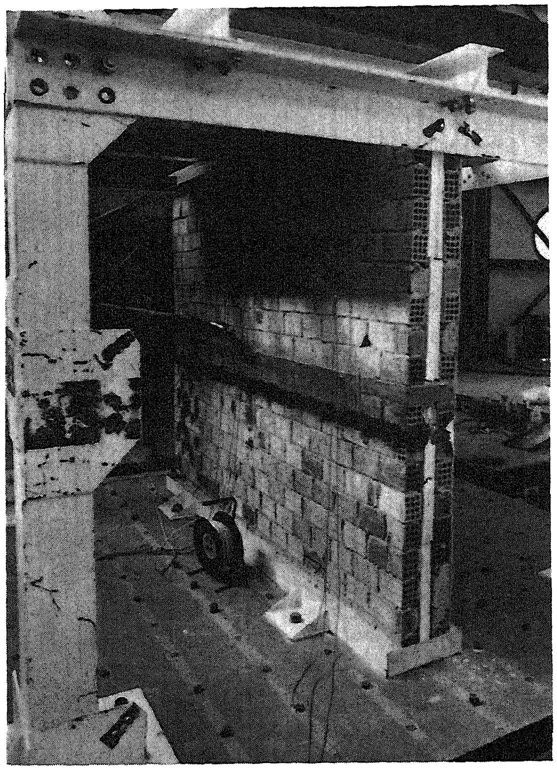


Fig.18. View of the test set-up after the excitation with twenty repetitions of the desctrutive Kalamata earthquake.

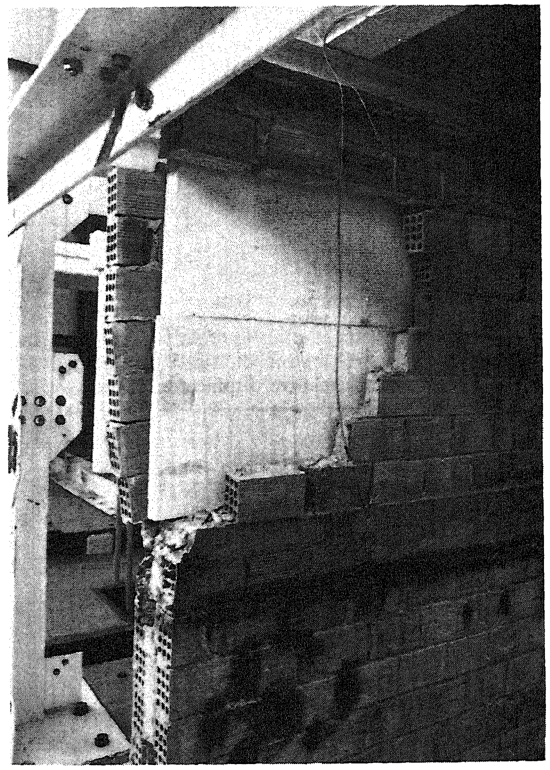


Fig.19. The upper corner of the wall after application of a strong sinusoidal excitation of 1 g along its longitudinal direction.

the very destructive Kalamata (1986) earthquake.

Time history of the achieved table motion for the Kalamata N-S component is shown in Figure 17.

Because many walls very similar to the specimen had collapsed during the real earthquake, nearly all instruments (accelerometers and displacement meters) were removed, so as not to be destroyed.

The specimen was excited 20 times in repetition with the Kalamata earthquake. Ten of them were with the full scale N-S component against the transversal direction of the wall. Five of them were with 20% increase of that component and five of them were with both full scale components of the earthquake. The specimen did not suffer any major damage, only the four initial horizontal cracks at each wall face became larger. As it was estimated, very large deformations were created at the middle height of the wall, of the order of 5 cm. Figure 18 presents the condition of the specimen at that stage.

Finally, the specimen was excited with a sinusoidal motion of maximum acceleration 1g and period $T=0.04$ sec along its longitudinal direction. After a few cycles the wall started deteriorating at its upper two corners. The damage was quite symmetrical. Figure 19 presents the collapse of the upper corner of the wall.

4 CONCLUSIONS

The specimen and especially the wall behaved very well against horizontal excitations transversal to its plane. The wall exhibited a very elastic response though it is composed of brittle materials. During the tests the wall was excited with about 20 repetitions of the very destructive Kalamata earthquake without presenting any considerable damage. The difference in the response from similar walls along their transveral direction in the city of Kalamata, that were damaged on a great percentage, almost totally, to the authors points of view, is due to the lack of fixing at the top of the brickwalls. In practice, a gap of about 0.5 cm to 1 cm is created due to shrinkage of the brickwall shortly (from observations, the shrinkage is almost completed within a week) after its construction. The wall at the laboratory was duly fixed at its top boundary to the frame with non shrinkable grout. Therefore, large vertical forces were created for any out of plane deformation of the wall, relative to the external frame. In practice, after about a week of the construction of the wall, the gap created from the shrinkage of the wall must be filled with non shrinkable grout.

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