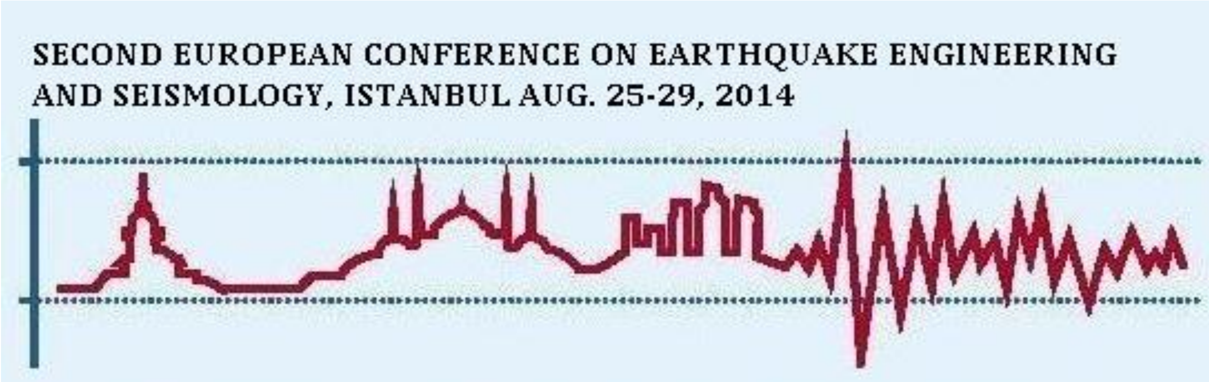

EXPERIMENTAL STUDY ON A SHAKING TABLE TEST OF A CONFINED MASONRY STRUCTURE

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ABSTRACT

Every large-scale earthquake causes widespread social damage and, most tragically, human casualties in developing countries. The main cause of human casualties is collapse of houses of common people, often called “non-engineered” houses because they are built with little or no intervention by engineers. In order to contribute to mitigate damages by developing feasible and affordable seismic design the authors implemented a shaking table test with a full scale specimen of a confined masonry structure, which is one of the most common non-engineered structures worldwide. The authors conducted analysis on observation and test results and draw two implications, 1) quality of construction works is one of the key issues for resilience, and 2) several vulnerable patterns were identified such as, separation of RC members and brick walls, out-of-plane failure of walls, shear failure of walls.

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INTRODUCTION

Every large-scale earthquake causes widespread social damage and, most tragically, human casualties. The main cause of human casualties is the collapse of houses of common people, often called “non-engineered” houses because they are built with little or no intervention by engineers. In spite of this critical situation, few researchers and engineers have paid attention to such houses. The report “Living with Risk: 2004 Version,” by the UNISDR (United Nations International Strategy for Disaster Reduction), clearly describes the situation: “It remains something of a paradox that the failures of non-engineered buildings that kill most people in earthquakes attract the least attention from the engineering profession.”

The authors have been involved in several projects on safer non-engineered houses, have conducted collaborative research and development, and proposed a comprehensive approach, which means inter-disciplinary, inter-sectoral and international, in a paper entitled “A Proposal for a Comprehensive Approach for Safer Non-engineered Houses” in November 2010 Issue of Asian Architecture and Building Engineering (JAABE). In the proposal, research on characteristics of structures like failure procedures and technical solution on feasible and affordable seismic designs are highlighted to be critical issues as well as dissemination of technical information and support for people and community to employ the seismic technology.

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In this context, the authors have been conducting series of basic tests like strength test of brick, mortar, and components like prisms and walls. They conducted shaking table tests as well to grasp behaviour of structures during shaking motion. The first experiment was on non-reinforced brick structure and the results were reported at 14th Word Conference on Earthquake Engineering 2008(14WCEE), International Seminar on Seismic Risk and Rehabilitation of Stone Masonry Housing in Azores 2008, Bulletin of Earthquake Engineering, Volume 10, 2012, published by the European Association for Earthquake Engineering and other occasions.

This paper reports results of the second shaking table experiments on a confined brick masonry structure. Confined masonry structures are one of most commonly employed structure types for non-engineered houses worldwide and often suffered severe damages from earthquakes such as shown in Figure 1.

Figure 1 A confined brick masonry house severely damaged by 2004 Indian Ocean Earthquake and Tsunami in Banda Aceh, Indonesia

1. OUTLINE OF THE EXPERIMENT

1.1 Background and Purpose

Most of researches on non-engineered houses to date are based on field surveys on damaged buildings and remaining debris. Failure procedures and characteristics are just imagined based on observation on site and analysis. Under this situation the authors set the main purpose to reproduce and record behaviour during shaking motion and failure mechanism. For the purpose the authors tried to replicate a structure in a developing country by applying typical design, using bricks imported from a developing country, following practice of a developing country such as mixture ration of mortar and so on.

In order to record the behaviour the authors shot video image by 11 cameras from different directions, measured displacement at 37 points with LED lamps, and recorded acceleration at 10 points.

1.2 Specimen

The design of the specimen followed usual design in Indonesia applying stretcher bond (Figure 2). Section of reinforced concrete (RC) columns and beams is 120mm x 120mm so that surface of brick walls and RC members are in the same plane (Thickness of wall is 12cm). Bricks were imported from Pakistan. The specimen has square plan of 2830mm x 2830mm, and 2870mm in height. Total weight is estimated to be about 6,000kg. Design, materials and construction methods of each of parts are as follows,

1) Materials
    - Bricks

The front, right and left side walls are constructed with bricks imported from Pakistan (compression strength: 14.73MPa). The back side wall is with those made in Japan (compression strength: 32.36MPa). Quality of bricks made in Pakistan is not fully controlled judging from poorly dressed shape, non-monotonous colour, existence of bubbles inside and small average compression strength having wide range shown in Table 1.

- Mortar

The cement is made by a Japanese manufacturer. Mixture ratio of cement and sand is 1:8 following usual practice on site in Indonesia. Water-cement ratio is 2.0 and compression strength is 2.58MPa in average (Table 1).

Table 1 Compression strength tests

No of specimens	Bricks (MPa) Made in Pakistan	Bricks (MPa) Made in Japan	Joint mortar (MPa)
1	12.92	32.31	2.64
2	13.85	32.18	2.90
3	17.43	32.59	2.19
Average	14.73	32.36	2.58

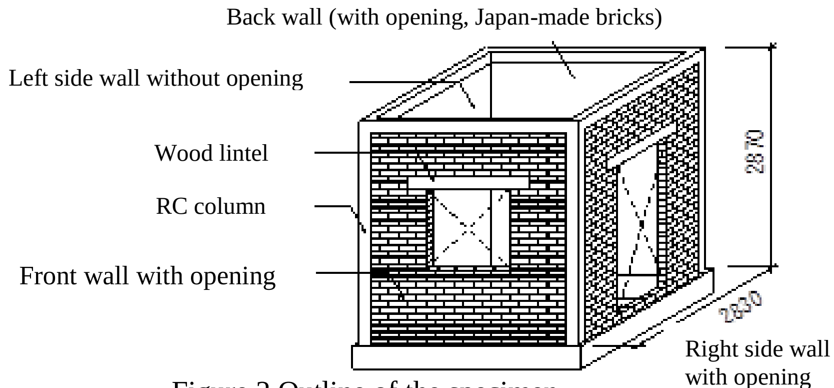


Figure 2 Outline of the specimen

2) Brick laying works
   The authors tried to make brick laying works similar to that of practice on site by employing by workers who have little experience of brick laying. Laying work followed usual way of 1) placing bed joint mortar for one brick on top end of brick wall, 2) laying one brick, 3) filling side joint mortar, 4) soaking of bricks was not applied. These works resulted in rather rough finishing shown in Figure 3. Thickness of joint mortar is 15mm for both bed and side.

Figure 3 Finishing of brick laying

Joint mortar is not completely filled, some are lacking and others are forcing out. Thickness of joint mortar is not even.

3) Lintels on opening
Wood lintels (H=150mm, W=120mm) were installed in each of opening.

4) Roof
Roof is not installed because it is usually not tightly fixed and has no structural effects to the whole structure.

1.3 Inputs of shaking motion

The shaking table experiment was conducted with a shaking table for one direction managed by the National Institute for Earth Science and Disaster Prevention (NIED) in Tsukuba City, Ibaraki Prefecture, Japan on July 4, 2008. Most of given shaking motion (Table 2) were based on a shaking motion of 2007 Pisco Earthquake recorded in Ica City (Figure 4) because the authors planned the next shaking table experiments in collaboration with Peruvian researchers in Peru applying the recorded shaking motion.

Scaling-down of time was employed in Input No. 1 – 4 in order to reduce deformation to meet to capacity of deformation of the shaking table. This resulted in very large acceleration of shaking motion.

Table 2 List of shaking motion inputs

Number	Type of input	Time scale	Max. deformation	Max. velocity	Max. acceleration	Intensity (JMA)	Intensity (MMI)	Failure of the specimen
1	ICA	0.1	10.1mm	19.7kine	793.0gal	5-	8	none
2	ICA	0.1	15.3mm	30.3kine	1,217.9gal	5+	8	none
3	ICA	0.1	30.6mm	57.2kine	2,271gal	6-	9	cracks in walls and columns
4	ICA	0.58	143.2mm	60.2kine	604.6gal	6-	9	cracks expanded
5	Kobe JMA	1.0	246.7mm	104.7kine	1,074.8gal	6+	9	collapse

*1 Type of input: ICA is a recorded shaking motion by Pisco Earthquake 2007 recorded in Ica city and Kobe JMA is by Hanshin-Awaji Earthquake 1995 at JMA Kobe Observatory Station.
*2 Time scale: Input No1 to No4 are given in scaled time. so as that deformation is smaller to be within the capacity of the shaking table. (Time scale 0.1 means time is reduced to be 0.1 times than the original record of shaking motion.)The scaled time made acceleration larger.
*3 Intensity is estimated based on a table for rapid estimating MMI by USGS, a table by Dr. Yoshimitsu Okada (National Research Institute for Earth Science and Disaster Prevention (NIED) , and formulas proposed by Dr. Fumio Yamazaki (Chiba University).

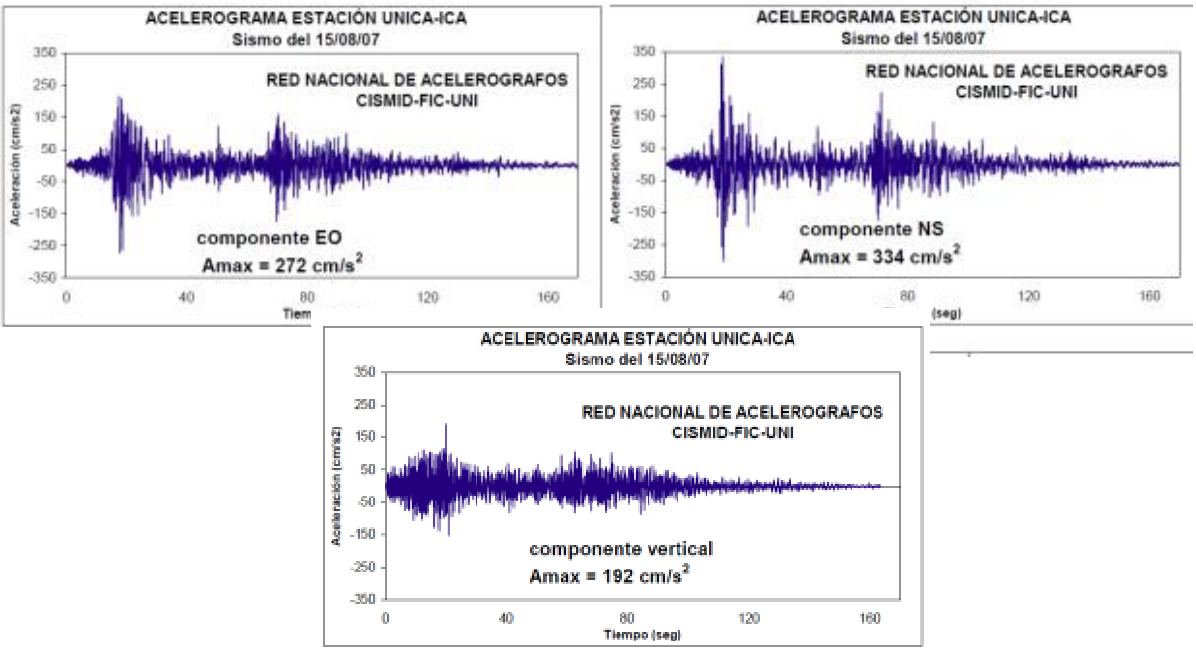


Figure 4 Recorded shaking motion (acceleration) of Pisco Earthquake 2007 in Ica City.
East-west component: upper left, North-south component: upper right, and vertical component: lower. Peak Ground Acceleration (PGA) is 334cm/s^2 in North-south component.

2. RESULTS OF THE EXPERIMENT AND ANALYSIS

2.1 Overview of the result

As shown in Table 2, no failure occurred by Input No.1 and No.2. Therefore an input with very large acceleration (2,271gal) and velocity (57.2kine) was given in order to make the specimen cracked (Input No.3). This means the specimen has considerably high seismic strength as it endured with shaking motion of MMI 8 two times without any damage even though the authors tried to make the specimen similar to actual structures by employing workers with limited experience and following usual brick laying method. We found enormous cases of total collapse occurred in affected areas by large scale earthquakes. Shaking motion of the area is often assumed to be moderate because it did not make furniture toppled such as shown in Figure 5. This implies actual buildings in developing countries are very vulnerable judging from Descriptive table of Modified Mercalli Intensity Scale by USGS (Figure 6). As is seen in the result of the shaking table test, the specimen behaved almost in accordance with Descriptive table as it got cracked by the first MMI 9 shaking, endured another MMI 9 shaking, and finally collapsed by the third MMI 9 shaking.

Figure 5 Furniture withstood in totally collapsed school buildings in Bantul, Yogyakarta Special Province, Indonesia, which experienced the strongest shaking motion by the Central Java Earthquake 2006

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

MMI 7or higher : some furniture may fall down
MMI 10 or higher : vulnerable buildings may collapse such as stone masonry

Figure 6 Descriptive table of Modified Mercalli Intensity Scale (USGS)

2.2 Early stage of failure procedures (Input No.3 and No.4)

Figure 7 shows damages caused by Input No.3. Cracks occurred in the front wall in diagonal direction from corners of the opening and separation between the walls (front and left side) and adjacent RC column occurred as well. A failure was observed in the RC column. Cause of the failure is analysed to be a defect at a joint between concrete placing (Figure 8).

By the next shaking motion (Input No.4), the damage grew as follows,

1) end of the left wall separated from the column became free end and deformed largely during shaking motion,
2) end of the front wall separated from the column also deformed largely,
3) the cracks in the front wall expanded,
4) the failure of the RC column grew and some debris fell down from the point.

However it escaped from collapse and withstood during the shaking motion.

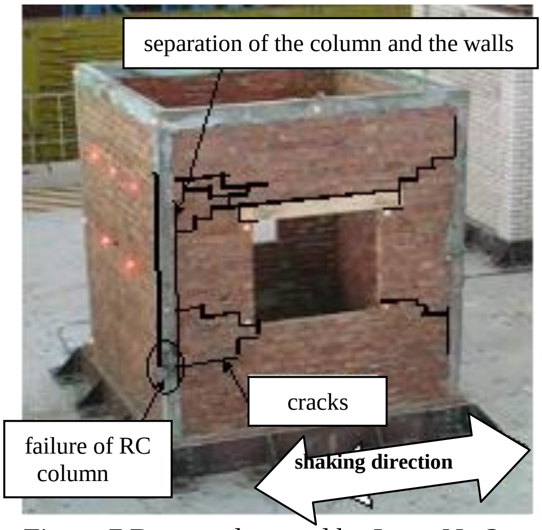


Figure 7 Damaged caused by Input No.3

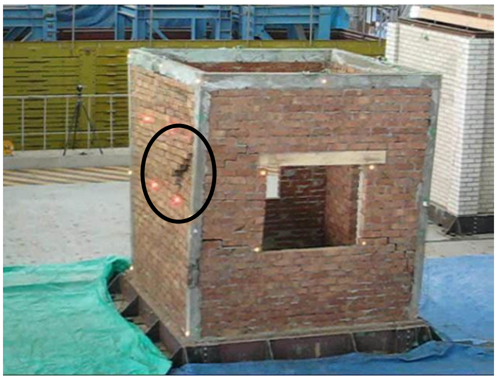


Figure 8 The column between the front and left side wall (left) and detail of joint of concrete placing (right)

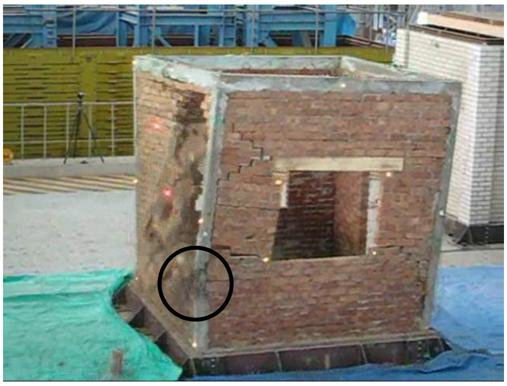
2.3 Collapsing procedures (Input No.5)

Total collapse of the specimen occurred by Input No.5 shown in Figure 9. The procedures can be described as follows,

1) The left side wall, which already lost support/connection with the adjacent column, deformed beyond its limit and started collapse (out-of-plane failure) (Figure 9-1)
2) The adjacent column collapsed triggered by the damaged point by Input No.3 and started to fall down (Figure 9-2)
3) Falling down of the upper part of column pulled the beam on the top of the front wall and caused buckling of left part of the front wall to outside (Figure 9-3)
4) The upper part of the column fell down largely (Figure 9-4, 9-5)
5) The beams on the front and left side walls were pulled down by the falling column and collapsed totally as well as the walls (Figure 9-6)
6) The two beams fell down to the ground (Figure 9-7)
7) Remaining right side wall started to fall down triggered by collapse of the front wall and the beam above the wall (Figure 9-8)



9-1 First collapse of walls occurred in the left side wall

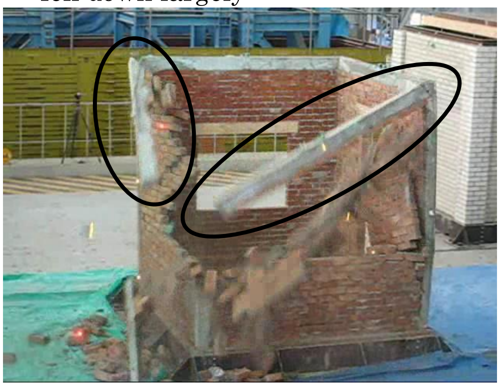


9-2 The adjacent RC column started to collapse

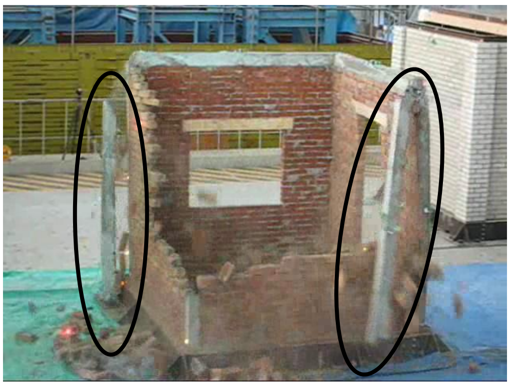
9-3 Collapse of the front wall started

9-4 The upper part of adjacent RC column fell down largely

9-5 Falling down of upper part of an RC column



9-6 Collapse of two walls with beams above



9-7 Falling down of two beams

9-8 Falling down of right side wall

Figure 9 Total procedures of collapse of the confined brick masonry specimen

2.4 Analysis on collapsing procedure of the structure

The total collapse started from separation of RC columns and walls, which allowed large deformation of the side end of the left wall and leaded to out-of-plane collapse. Then failure and falling down of RC column occurred, which caused the collapse of the front wall by buckling to outside. The cause of the failure of the column is due to the defect of concrete placing as mentioned before. If there were no defects in the column, it is expected that failure of the column might not have occurred and RC frame remained just like the building in Figure 1. This implies defects of RC members could cause serious damages to total structures.

In comparison with the front wall and back side wall (constructed with Japan-made bricks), the back side wall remained standing until final stage of shaking experiment. There could be two possible reason for the difference of performance of the two walls as, 1) no defects in RC columns adjacent to the back wall, 2) the back side wall of Japan-made bricks were strong and do not suffer shear cracks like the front wall. This needs further investigation.

Shear cracks in in-plane walls (the front wall) appeared in the first stage of damage by Input No.3. In this experiment, the front wall withstood during shaking of Input No.4 in spite of large shear cracks and rocking motion of segmented walls. (Collapse of the front wall seemed to be triggered by the failure of adjacent column.) This behaviour of the wall might be in different way if the shaking motion was not one-direction shaking. It is assumed the wall may collapse even when there were no failures of columns just like the building in Figure 1.

2.5 Analysis of failure of brick walls

The left picture of Figure 10 shows debris of the specimen. Several bricks were still connected together by joint mortar. On the contrary debris of actual buildings damaged by earthquakes was usually separated into pieces like in the right picture of Figure 10. It is usually observed people start collecting reusable building materials like bricks, roof tiles from the debris in developing countries shown in Figure 11. Bricks could be reusable because joint mortar could be removed easily without breaking bricks. It implies bonding strength of mortar is not so strong. It is assumed weak bonding of mortar is one of the reasons of vulnerability of masonry walls in developing countries.

The authors observed joint mortar stuck to surfaces with carved seals of trade mark of bricks in most of cases, which seems to have stronger bonding than flat surfaces. They also observed most of failures occurred in joint mortar and bricks themselves rarely got broken.

The back side wall of Japanese bricks withstood until the final Input of No.5. In contrast the front wall collapsed. Both are similar in setting in in-plane direction and having opening. Further joint mortar was same quality. Only significant difference is quality of bricks but there were little observation of breaking of bricks. Possible reason of cause of difference in performance of the two walls could be different bonding strength by surface condition of bricks, tidiness of shapes which defines evenness of joint mortar. This issue needs further exploration.

Figure 10 Debris of the specimen for the shaking table experiments (left) and debris of housing destroyed by Central Java Earthquake 2006 in Bantul, Yogyakarta Special Province, Indonesia (right)


Figure 11 People immediately started to collect reusable material such as bricks, roof tiles from debris (left) and some were sold on road sides (right) in Bantul, Yogyakarta Special Province, Indonesia, soon after Central Java Earthquake 2006

3. Implication from the experiment and proposal for the next steps

3.1 Implication from the experiment

The specimen withstood MMI 8 shaking motion two times without cracks, and MMI 9 two times with cracks. As is shown in Figure 5 and 6, many buildings in developing countries suffer heavily damage from shaking motion MMI 7 or smaller. The main cause of the difference seems to be quality of construction works such as brick laying works, concrete placing works. The defect of concrete placing in Figure 8, which caused total collapse of the structure, is a typical case.

Several vulnerable patterns were identified like separation of RC members and brick walls, out-of-plane failure of walls, shear failure of in-plane walls. Improved designs to prevent/mitigate these patters are expected to increase resilience of structures.

3.2 Tasks for the next steps

1) Reproduction of more precise/real procedures

The shaking table experiment in this paper is by one direction shaking motion. Natural earthquake shaking motion is three directional including vertical. In order to reproduce more precise/real procedures, experiments with shaking motion of two or three directions are preferable. Experiments with one direction shaking table on specimens set not parallel to shaking direction are significant as well, as the specimens are to be exposed to shaking motion both in- plane and out-of-plane at the same time.

2) Creation of improves designs

The several vulnerable patterns of failures are identified. Based on these, creation of designs to effectively prevent/mitigate the vulnerable failure is recommended. The designs should be verified not only technically, but also from view point of economical affordability, feasibility on construction site, and acceptability to local construction workers.

4. CONCLUSION

The authors conducted the shaking table experiment to reproduce behaviour including collapsing procedures of the confined brick masonry construction, recorded, and analysed it. They identified vulnerable patterns of collapse like separation of RC members and brick walls, out-of-plane failure of walls, and shear failure of walls. It is recommended to reproduce more precise/real procedures by shaking table test in which specimens are exposed to two directions at the same time. Then creation of designs to prevent/mitigate the effects of the patterns is necessary. And those could be verified and examined for practical application on site. Through all these procedures, mitigation of damages by earthquakes should be achieved.

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