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Dynamic Response of Historical Masonry Minaret under Seismic Excitation

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Abstract

In order to study the dynamic response of historical masonry structures, a scaled down brick masonry model constructed in civil engineering department at Baghdad University to simulate a part of a real case study, which is Alkifil historic minaret. Most of the previous researches about masonry structures try to understand the behavior of the masonry under seismic loading by experimental and numerical methods. In this paper, the masonry units (bricks) simulated in scale (S= 1/6) with the exact shape of the prototype bricks. Cementitious tile adhesive was selected to be the mortar for the modeling. The height of the model designed to be 1.5 m with a 0.5 m diameter. Detailed construction steps were presented in this paper. Experts built the model with high accuracy. A shaking table and other dynamic testing facilities were used at the University of Baghdad. The model was tested using the time-compressed El Centro 1940 NS earthquake at different amplitudes. The first ground motion of (PGA= 0.05g) which considered as weak ground motion was used to check the adequacy of the conventional behavior of the masonry model and the limit of the elastic behavior of the model during weak earthquakes. Moderate ground motion (PGA=0.15g) was performed to investigate the response of the model with minor to moderate damages. The severe ground motions were not appropriate to use in such circumstances because of the possibility to overturn the model. The experimental results showed very adequacy of the model to withstand the weak and moderate earth motion with no observed cracks.

Keywords: Masonry Structures; Minarets; Seismic Evaluation; Shaking Table.

1. Introduction

Masonry has been known as one of the oldest construction types and there is a high stock of masonry buildings around world including historical monuments which have being used for thousands of years or even up to now. It is estimated that more than 70% of the worldwide building inventory is masonry type. Availability of materials and workmanship, enough local knowledge of constitutes like a brick, stone, timber and mortar have made masonry construction an attractive choice for building owners. Masonry can be considered strong and durable for gravitational loads. However, due to the inherent structural deficiencies and material weakness of masonry, it has been proved that they are extremely vulnerable during earthquake events which resulted in a high number of casualties. Therefore, this type of building should be considered for retrofitting and strengthening against earthquake-induced loads. From a performance-based design viewpoint, the minimum requirements for life safety of the users of these buildings must be fulfilled. The first step for the retrofitting of this type of structure is a deep understanding of their structural characteristics, vulnerabilities, and dynamic response.

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Dynamic response of a structure can be caused by different loading conditions such as earthquake ground motion; wind pressure; wave action; blast; machine vibration; and traffic movement. Among these, earthquake motions and accidental blasts mainly cause inelastic response. Consequently, more research on nonlinear structural behavior has been carried out in relation to earthquake problems. The dynamic problems are different from static ones in the following points:

- Inertial Force (due to accelerated motion).
- Damping.
- Strain Rate Effect.
- Oscillation (Stress Reversals).

Dynamic characteristics up to failure cannot be identified solely through a dynamic test or a real structure for the following reasons:

- It is difficult to understand the behavior due to complex interactions of various parameters.
- It is expensive to build a structure, as a specimen, for destructive testing.
- The capacity of loading devices is insufficient to cause failure.

Historical masonry structures in Iraq should be preserved due to their high cultural significance, historical heritage and religious value. Several earthquakes have occurred in Iraq in recent years. Unfortunately, most of the historical masonry structures in Iraq suffered a partial collapse in the course of time due to aging, deterioration, fatigue, soil movements, etc. In fact, in every future earthquake, there is a high chance to lose a historical structure due to substantial damage or collapse. For this reason, it is very important and essential to protect and strengthen them against future earthquakes. Therefore, the protection needs to determine the dynamic response of the existing historical structures due to seismic activities. On the other hand, equilibrium between heritage and structural requirements will be a great challenge in the strengthening process. The main objectives of this study were to conduct experimental tests for the appropriate-scale historical structure model subjected to various seismic excitations.

2. Masonry Structures

Structures that are built from small units such as bricks, stones, concrete blocks, etc. are called masonry structures. These units are widely used in buildings until our days because of their simplicity in implementation. Unnumbered variation occurred on the masonry materials during time. Stone is probably the oldest units used in construction. Masonry is a diverse properties material consisting of units (such as stones, bricks, ashlars, blocks, and others) and joints of mortar (could be clay, lime-cement, bitumen, glue or others) [1].

Castori et al. (2017) Presents an analysis results of diagnostic executed on a specific monumental masonry building [2]. The restoration of existing masonry constructions is now a decisive problem for Europe. The suggestion of a new artificial performance consideration is presented and discussed by Sassu et al. (2017) [3].

3. Historical Buildings

The historical buildings are not just stones; it is the history of peoples and civilisations, the imprint of people in their lives. Therefore, it is important to pay attention to those architectural features that never stop telling the past of our souls and our steps on earth. Typically, for considering the building as historical ones, it must be at least 50 years old, must maintain high integrity, and must have some level of historic significance. Innovation in architecture is with no doubt extremely essential, though preserving and renovating the old buildings are also important since those old monuments are the reflection of our history, they help us to understand and respect people who lived in different eras with different behaviours and traditions

In the seismically active regions, the historical masonry buildings are severely damaged by earthquakes because these buildings had not been designed to withstand seismic impacts, at least not in the technical 'scientific' way from today's point of view.

Historic masonry constructions present strange features that make the classification of their structural behaviour not forthright [4]. Made in situ dynamic testing with full-scale to prove the best way to shed light upon the real performance of the unconventional systems.

4. Minaret

Minaret is a tower typically found neighbouring to most of the mosques buildings. Generally, a high spire with a conical- or onion-shaped crown, usually a standalone either building or taller than the attached support structure to it. The basic form of a minaret includes a base, cylindrical body shaft, balcony and upper part. Styles vary regionally and by era. Minarets provide a visual focal point and are traditionally used for the Muslim call to prayer (Adan). Minarets can be classified as historic buildings due to their age that exceeds hundreds of years and its cultural and religious value.

Historical structures are very important for showing the roots of country and must be passed on to future generations. Nohutcu (2019) made a study to achieve this goal. Seismic assessment for historical masonry minaret under different excitations is investigated in this study by using finite element models depended on ambient vibration data [5]. Demir et al. (2016) Presented a study to evaluate the seismic damage and the failure mechanism of the historical masonry minaret "Hafsa Sultan", which was constructed in 1522 [6]. Barış et al. (2017) made an assessment on an important historical masonry minaret built with bricks in Eastern Turkey (the minaret of Van Ulu Mosque). The minaret was affected by the October 23, 2011 (Mw = 7.2) and November 9, 2011 (Mw = 5.6) earthquakes [7].

5. Earthquakes

An earthquake is a sudden movement of the earth's surface. The movement of the earth's tectonic plates causes earthquakes. Earthquakes occur where the earth's plates meet along plate boundaries. For example, as two plates move towards each other, one can be pushed down under the other one into the mantle. If this plate is stuck, it causes a lot of pressure on surrounding rocks. When this pressure is released, it produces shock waves. These are called seismic waves. This is an earthquake. The waves spread out from the point where the earthquake started - the focus. More damage is done near the focus. The point on the earth's surface directly above the focus is the epicentre.

Asteris et al. (2014) presented a methodology for earthquake assessment or the resistant design of masonry structure systems. Three existing structures in different countries with different seismicity levels were analyzed as a case study. The methodology proved helpful to the analysis of existing masonry historical buildings. Moreover, it has been shown that the proposed approach offers a ranking method, which helps civil authorities to optimize a decision on choosing, among structures, which one present higher levels of vulnerability and are need is strengthening. In addition, it helps the practicing engineer to choose the optimal repairing scenario [8].

Bothara et al. (2009) made an experimental investigation of seismic performance of a two-storey brick masonry house with one room in each floor. The half scale building tested by shaking table to simulate earthquake ground motions in two direction, longitudinal and transverse direction. The building was subjected to different ground motions with graduated intensity increasing. After each ground motion, white-noise tests were made to assess the dynamic properties of the system [9].

Thamir et al. (2018) studied numerically the time-history responses of a square plan two-story reinforced concrete building, considering the elastic and inelastic behaviour of the materials. ABAQUS software was used in three-dimensional (3D) nonlinear dynamic analysis to predict the inelastic response of the buildings [10].

6. Research Methodology

Masonry material displays individual directional properties because of the mortar joints that play as planes of weakness [1]. Generally, the technique for numerical representation depends upon the level of accuracy and the level of simplicity preferred. The consideration of micro modelling is to describe the individual components of masonry, namely, units and mortar. There are two types of micro modelling approach, simplified and detailed micro modelling. Figure 1 illustrates the modelling strategies for masonry structures.

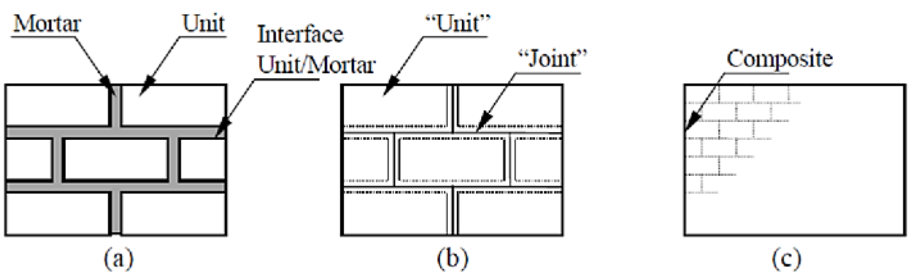


Figure 1. (a) detailed micro modelling. (b) simplified micro modelling. (c) macro modelling

6.1. Macro Modelling

In the macro modelling, masonry units, mortar, and the interface between unit-mortar are lumped in the continuum. This type of modelling does not differentiate between masonry units and mortar joints hence, deals with masonry as an anisotropic homogeneous continuum. Figure illustrates the macro modelling technique.

6.2. Simplified Micro Modelling

The usage of Simplified Micro Modelling (SMM) is that units are expanded and modelled by continuum elements while the mortar behaviour and unit-mortar interface is lumped into discontinuous elements.

6.3. Detailed Micro Modelling

The usage of Detailed Micro Modelling (DMM) approach is to represent masonry units and mortar by solid continuum elements and the interface between unit-mortar by contact discontinuous elements. In this research, the macro modelling techniques will be followed.

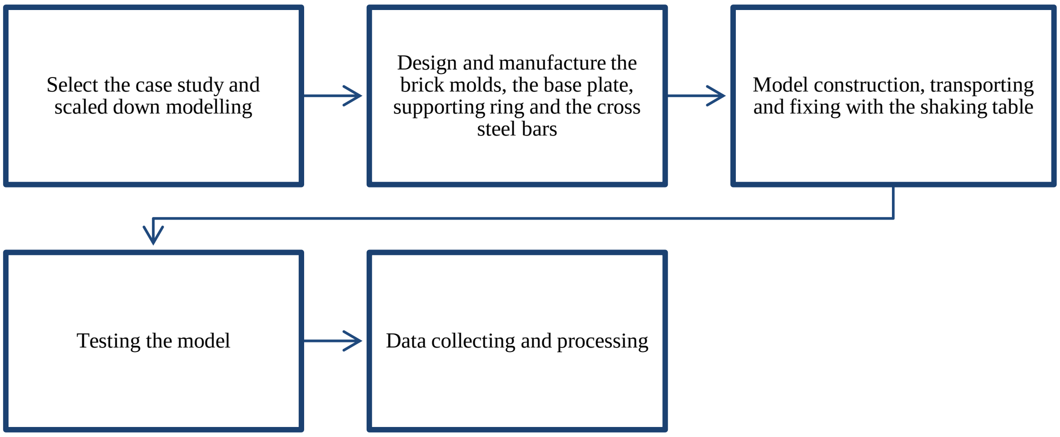


Figure 2. Research methodology

7. Structural Description of the prototype Minaret

Alkifil minaret is one of the Iraqi historic milestones. It was built in the fourteenth century (713 after migration) with a 25.16 m height. The minaret consists of five parts described briefly below:

- Base: The minaret has a base at 70 cm under the earth level with a 6.5 m height
- Body: the minaret body is a structure built from clay bricks with a 3.12 m diameter and 12.6 m height with slope 3.5 degree to the southwest
- Decorated balcony: it is a ring built from ornamented bricks.
- Neck: The minaret neck has a fluted end and reaches a circular basin.
- Stairs: the minaret has a spiral stair without a central column like other minarets. The stairs extend from the base to the circular basin.

The minaret had many cracks and damages because of aging factors; this is due to its age that exceeds 700 years. It was repaired many times during its life and the last reparation was at 2013 by Imen Sazeh Fadak, Iranian company [11].

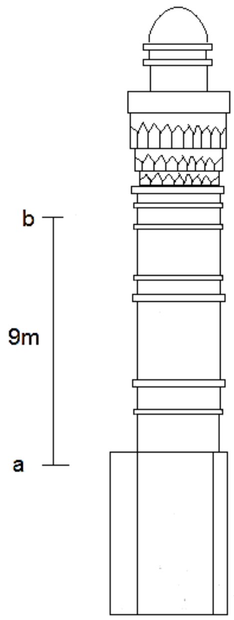


Figure 3. Alkifil historical masonry minaret

8. One-Sixth Scale down Model

The model was designed according to the similitude requirements provided in Table 1 [12]. Geometric dimensions of the model were obtained by directly scaling the prototype dimensions by the scale factor SL = 6. There were some reasons behind using the SL = 6. The first one was the small size of the scaled bricks that it was not able to be smaller and the other reason was the height of the laboratory where the model built. The height of the model was designed to be 1.5 m with a 0.5 m diameter. The model represented part of the minaret (from a - b) which was 9.0 m. (Figure 3)

Many limitations stand behind the part modeling of the minaret. The first was the scaling; the brick was difficult to be scaled over 1/6 scale. It will be too small and difficult to control the building procedure. After deciding the scale, the scaled height would be 6 m, which is not possible according to the laboratory height and uplifting circumstances. So that it was decided to simulate a part of the minaret. The body and small height of the base were chosen for simulation because the contact area between base and body and up of it is more likely affected area in seismic behavior. Moreover, the part above the body simulated as an added mass above the model (section 8.4).

Table 1. Similitude Requirements for the Model Structure (Harry Harris 1999)

Quantity	Symbol	Dimension	Scale factor
Geometry			
Linear Dimension	L	L	S_L
Displacement	δ	L	S_L
Frequency	ω	T^{-1}	${S_L}^{-1/2}$
Material properties			
Modulus of elasticity	E	FL^{-2}	S_E
Stress	σ	FL^{-2}	S_E
Strain	ε	-	1
Poisson's ratio	ν	-	1
Mass density	ρ	FL^4T^2	S_E/S_L
Energy	EN	FL	$S_ES_L^3$
Loading			
Force	Q	F	$S_ES_L^2$
Pressure	q	FL^{-2}	S_E
Gravitational acceleration	g	LT^{-2}	1
Acceleration	a	LT^{-2}	1
Velocity	v	LT^{-1}	${S_L}^{1/2}$
Time	t	T	${S_L}^{1/2}$

8.1. Brick Modelling

The first step for any modeling is preparing all materials that used in the model. The most important material in the present study was the bricks. There were some approaches to make the scaled down bricks:

- Cutting the original bricks to small pieces.
- Create bricks with small sizes from clay or any other materials

The first approach was very difficult because the brick is a brittle material that made it shatter during a cutting process that why the second approach was used.

Two molds were made from steel blocks with dimensions 50 × 50 cm and 1 cm thickness. Each one has two knobs to carry the mold. The first mold Figure 5(a) were cut with brick type 1 Figure 4 while the other mold Figure 5(b) were cut with brick type 2 Figure 4. Each mold produces 100 pieces of brick. In the usual case of making bricks, the wood used to make the molds, but in this study, the small size of the bricks make it difficult to extract from the mold unless it knocked on the ground that why the steel can withstand the knocking while the wood may break. In addition, the wood molds may be corrosion after time because of the repeat of using to produce a large number of bricks.

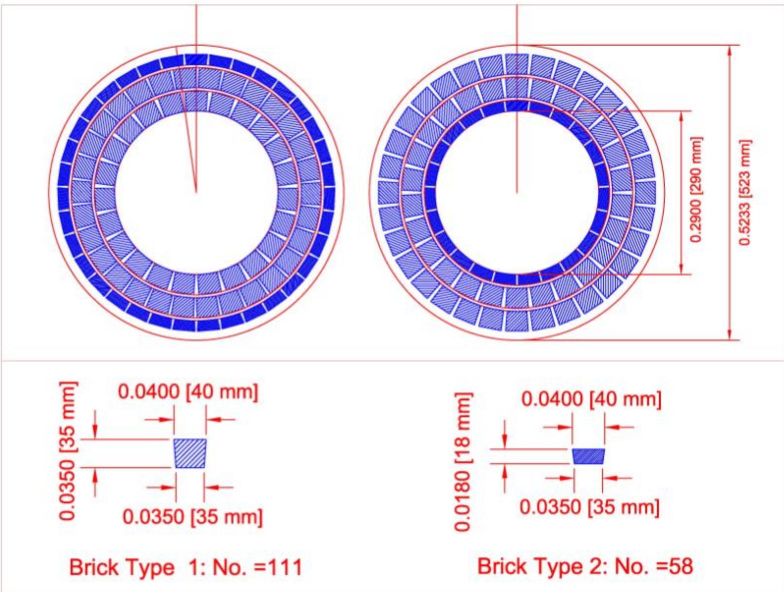


Figure 4. Scaled down brick dimensions

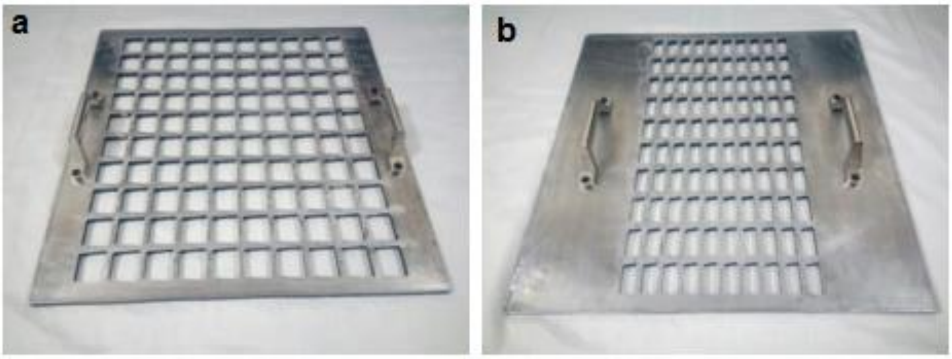


Figure 5. (a) The mold of brick type 1, (b) The mold of brick type 2

The prototype was built from clay bricks; therefore, clay was the most realistic material for brick modeling. The steps in making bricks were as follows:

- The first step in the brick modeling mechanism was making clay dough and let it fermented.
- The molds were dyed with grease to prevent clay dough from sticking in the molds.
- The clay dough was placed in the molds and then the molds lifted.
- The wet bricks were left at the sunrays for drying.

The above steps were repeated 100 times and 20,000 piece of bricks were made.

Figure 6. Scaled down bricks

8.2. The Model Mortar

The scaled down mortar thickness should be 3 mm. The usual mortars contain cement and aggregate is difficult to be in a 3 mm thickness it may separate from the brick layers after hardened. In addition, this modeling with small bricks and non-usual arrangement need time to build it in high accuracy and the usual mortar has quick harden time, so it is not appropriate. Therefore, a cementitious tile adhesive used as a mortar for the following reasons:

- Thin layers could be made in this material;
- Easy to use and apply;
- Slow hardening time.

To improve the 3 mm thickness of the mortar, a rounded wooden plate with 3 mm thickness were made for this reason. The worker put the plate on the layer of bricks and placed the mortar around the plate and parallel with its surface.

8.3. Model Construction

The model was constructed the Strength of Material laboratory in the civil engineering department at Baghdad University. The dimension was 0.29 m inner diameter, 0.49 m outer diameter and 1.5 m height.

The model was constructed on high-strength steel base plate with strong hooks in corners necessary to lift and transport the model on the shaking table and fix with it. The model should be braced from the base to prevent overturning. A cylindrical mold with 20 cm height and 56 cm diameter were made from steel and connected with the base plate by four bolts to brace the model. The wall of the model was constructed according to the prototype design of the bricks. The plate has a 25 hole some of them used for bolts to fix the support ring with the plate and the plate with the shaking table and others for fixing the hooks to uplift the model (Figure 7).

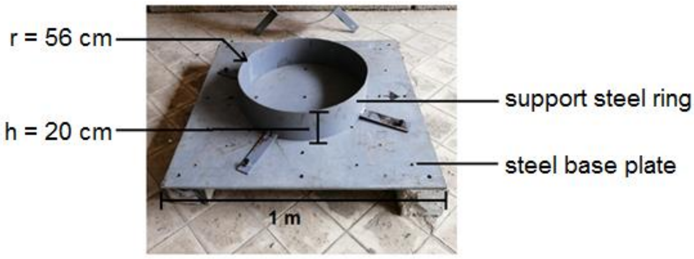


Figure 7. The steel base plate and the support ring

Two steel bars with a rectangular cross section take a cross shape were made with four holes one on each arm for hooks to carry the model during the uplifting procedure (Figure 8).

Figure 8. Steel bars with four hooks

Experts in high accuracy constructed the model. The inner and outer dimensions were checked after each layer (Figure 9). The alignment of the model were set carefully by using alignment-measuring instruments during the construction of the model. The construction took 21 hours to finish at a rate of 4.8 layers by hour.

The model were transported by a forklift near the shaking table and then uplifted by a lever and put down on the shaking table. The model was fixed with the table by 8 bolts to prevent slipping and overturning.

Figure 9. Checking the dimensions and the alignment during the model construction

8.4. Mass Simulation

For proper modeling of dynamic behavior, mass similitude of the model must be satisfied. Using the constant acceleration scaling and same material for the model, an additional mass must be applied to the model to compensate for the difference in the required and provided material densities (Baghdadi 2014). The added masses are computed as follows:

$$M_m = \frac{M_p}{S_L^2} - M_{om} \tag{1}$$

Where:

M_m Additional mass to be added to the model.

M_P Prototype dead load.

M_{om} Own weight of the model.

The prototype dead load mass (M_P) is 84926.5 kg and the model mass (M_{om}) is 340 kg. Therefore, the additional mass required can be calculated as follows:

$$M_m = \frac{84926.5}{36} - 340 = 2019\ Kg \tag{2}$$

The added mass required is 2019.1 kg, which is not appropriate with the work circumstances. So, the modeling was adopted according to the technical possibilities. The consequence of that is some distortion in the simulation of the nonlinear behavior of the model.

Additional weight in the form of 16 steel plates were made up for the weight deficiency for mass similitude, each plate has a 44 cm diameter and 2 cm thickness and weight 25 kg, the steel plates were fixed above the model so that the mass center of added mass coincides with a mass center of the model.

9. Shaking Table

The shake table is an indispensable testing facility for the development of earthquake-resistant techniques. A shaking table is a platform excited with servo- actuators to simulate different types of periodic and random motions, such as artificial earthquakes and other dynamic testing signals of interest in the laboratory. This is the only experimental technique for direct simulation of inertia forces, which can be used to simulate different types of motion such as recorded earthquake ground motions, sine sweep, etc. [13].

Shake table test results further enhance the understanding of the behavior of structures and the calibration of various numerical tools used for analysis. This facility can be utilized for verification of earthquake-resistant design of buildings, other structures, mechanical components, devices, etc.

The shaking table used in this study performed by Dr. Hayder Al Baghdadi in strength of material laboratory in civil engineering department at Baghdad University.

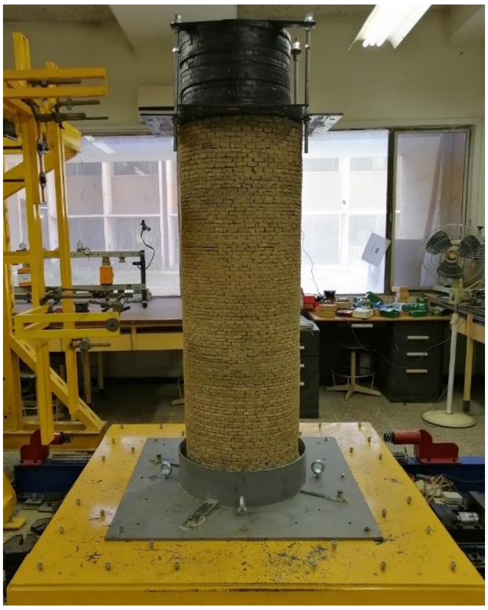


Figure 10. Model preparations for testing

10. Testing Procedure and Setup

The main objective of this testing was to experimentally investigate the historical masonry structures behavior under seismic excitation. According to that, the seismic shaking table tests were performed in two main phases:

Phase 1: Testing the model under low intensity level (0.05 g).

Phase 2: Testing the model under moderate intensity level (0.15 g).

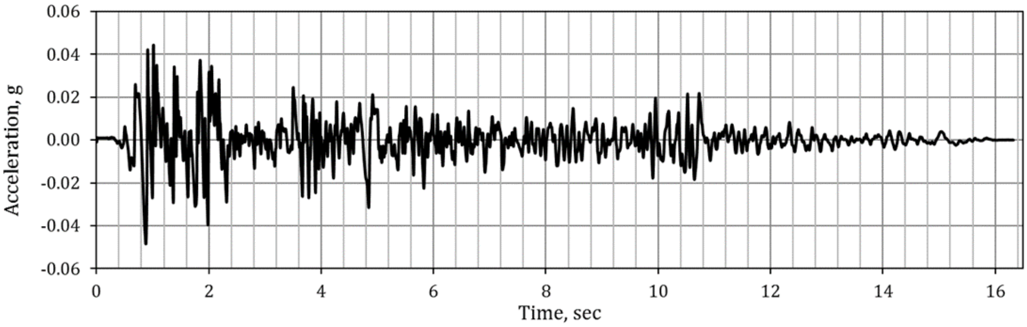


Figure 11. El Centro 0.05g

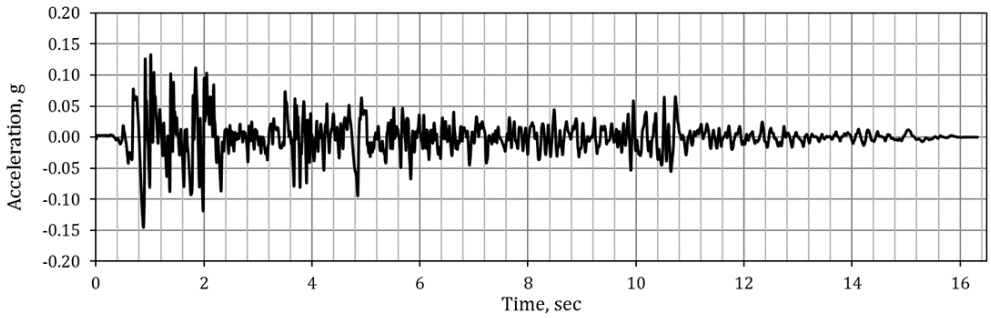


Figure 12. El Centro 0.15g

11. Data Collecting and Processing

NI DAQ (National Instruments Data Acquisition Card) collected the test data. The NI DAQ is used as a feedback-measuring device. Displacement signals are necessary for an input command to the table and integration of the acceleration time-history input is achieved through LabVIEW software. LabVIEW (short for Laboratory Virtual Instrument Engineering Workbench) is a system-design platform and development environment for a visual programming language from National Instruments.

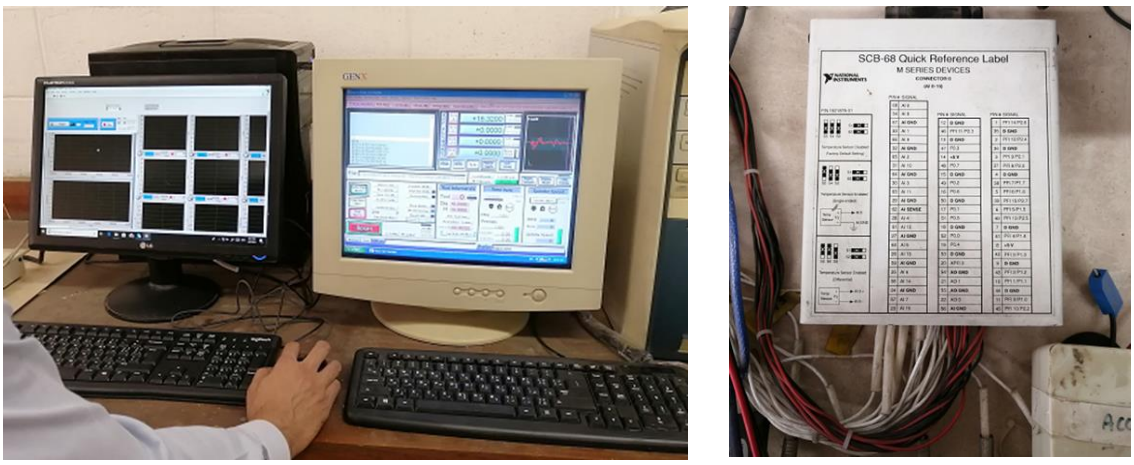


Figure 13. Processing the tests setup and installing the data collector

Two LVDTs set at top and mid of the model and connected to NI DAQ device to calculate the lateral displacements with time during the test. In addition, two accelerometers set at top and bottom of the model and connected directly by USB to the computer to calculate the acceleration with time.

Figure 14. The LVDT and accelerometer

12. Results

The displacement on top and mid points of the model and the acceleration at the base and the top were traced and recorded during each test. The results were processed and smoothed from the excess noise from the curves using DIAdem 2019 software. The results will be shown as follows:

- ***Results of 0.05 g Ground Motion***

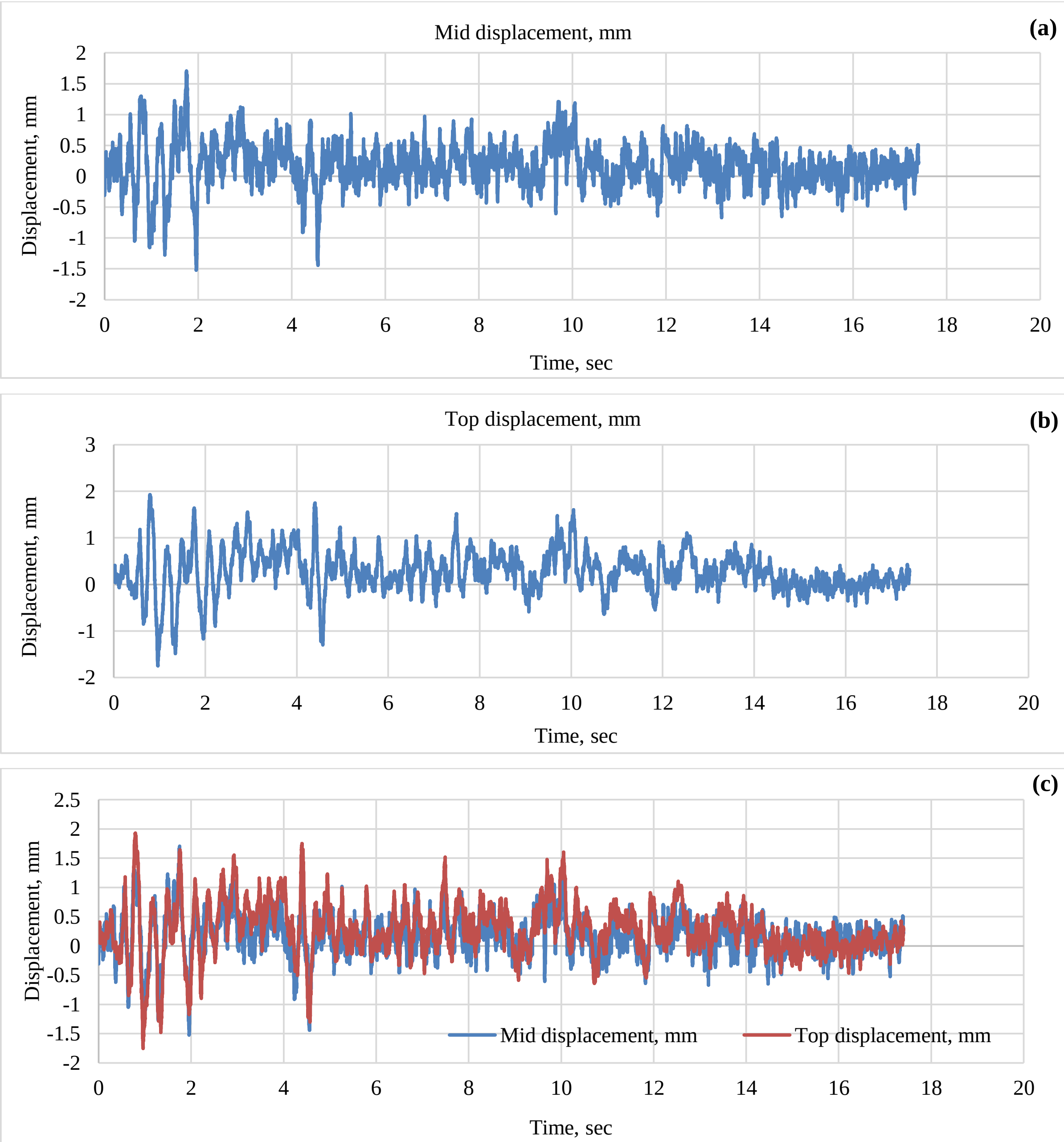


Figure 15. Displacement response of the model, El Centro 0.05g

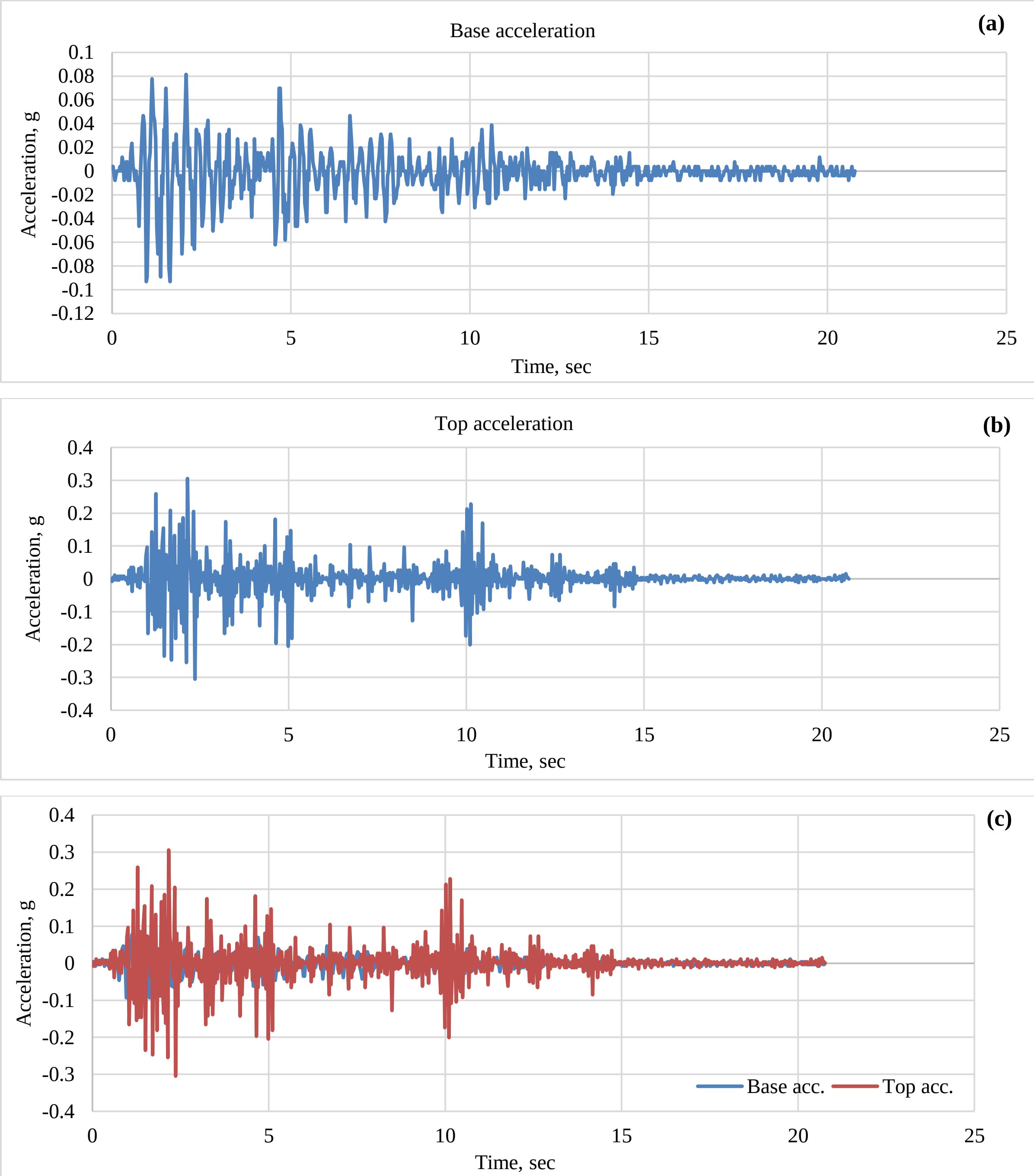
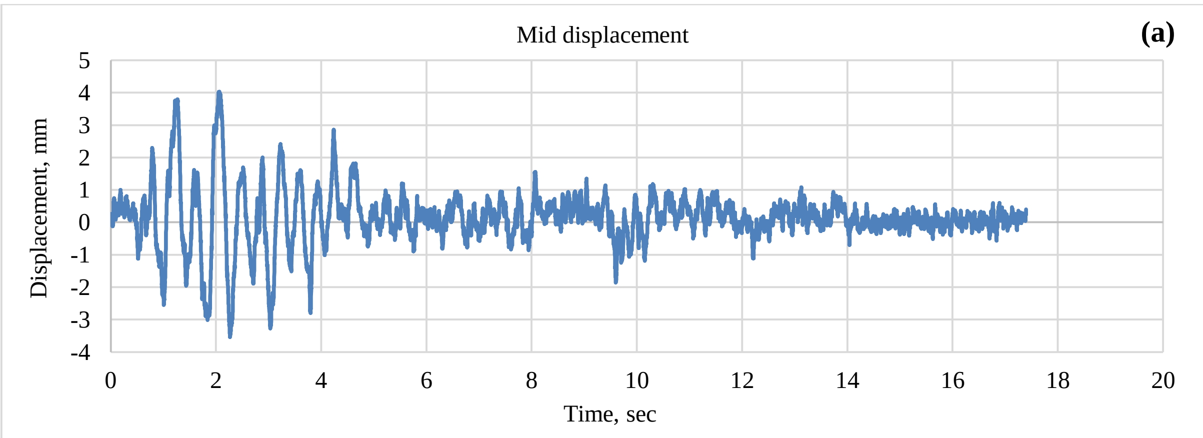


Figure 16. Acceleration response of the model, El Centro 0.05 g

- ***Results of 0.15 g ground motion***



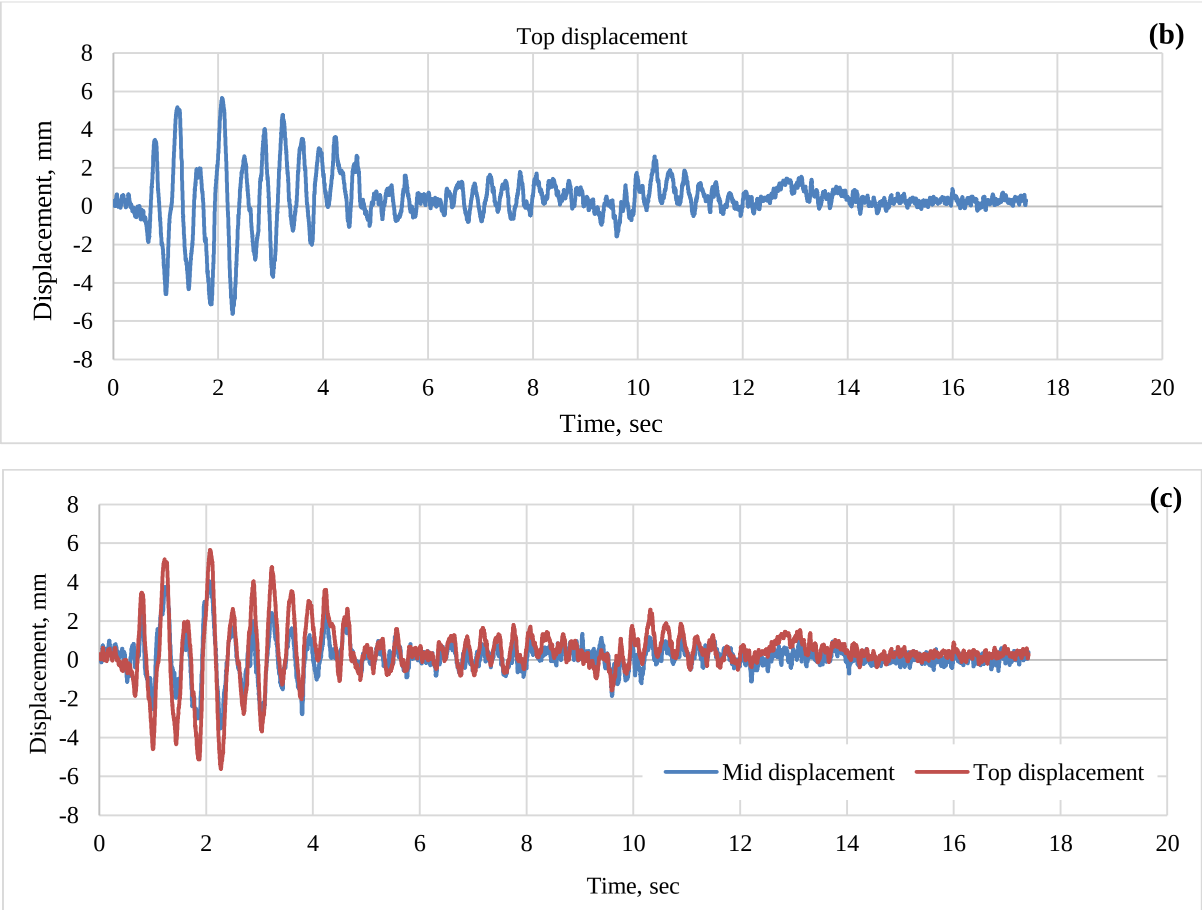
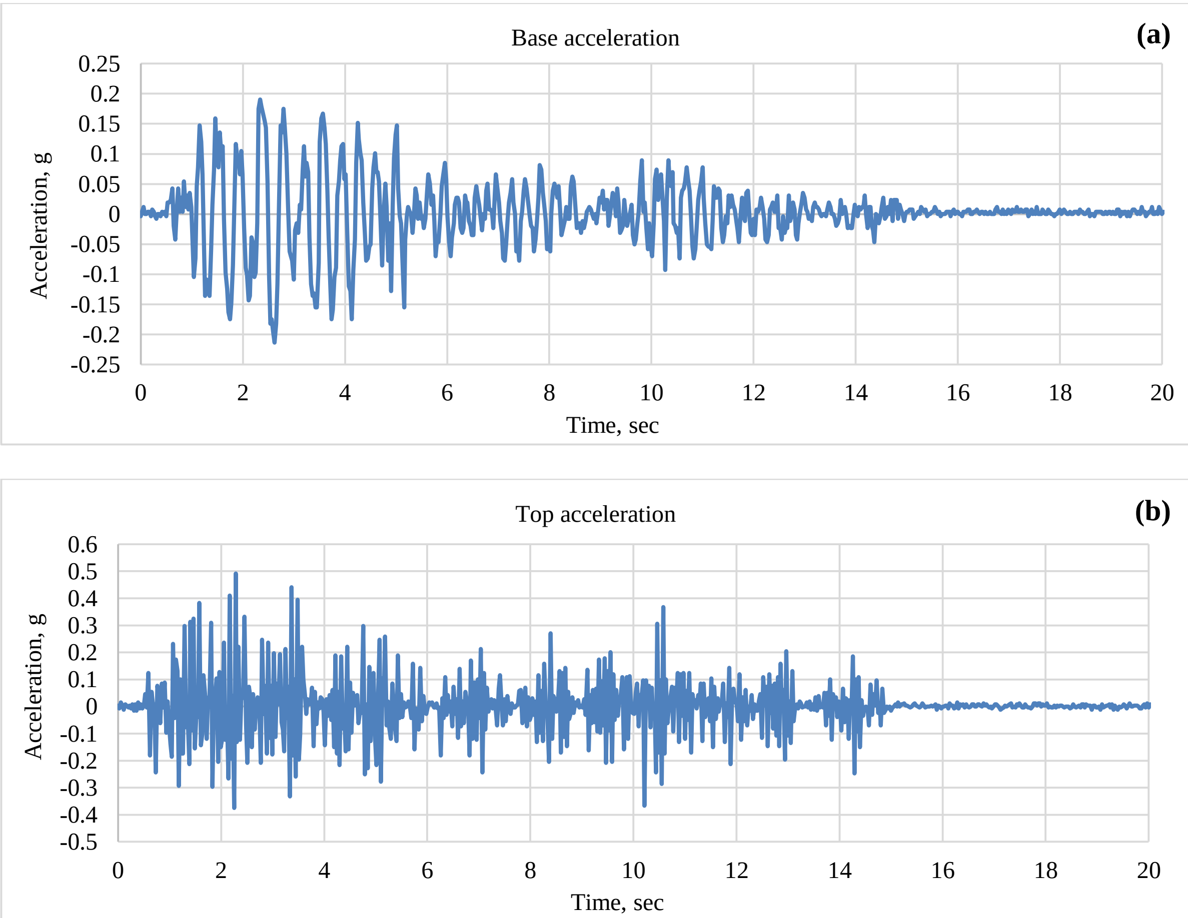


Figure 17. Displacement response of the model, El Centro 0.15 g



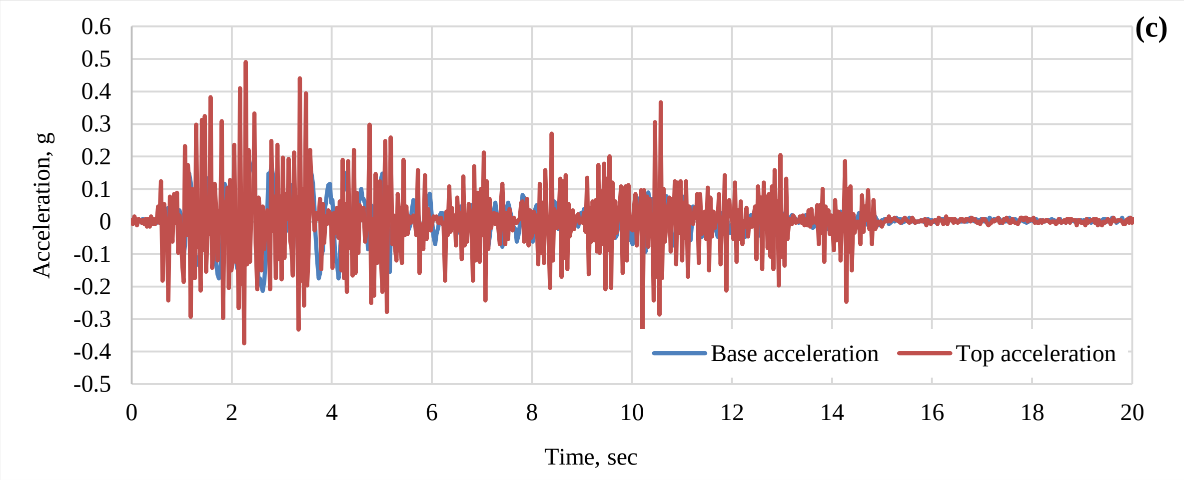


Figure 18. Acceleration response of the model, El Centro 0.15 g

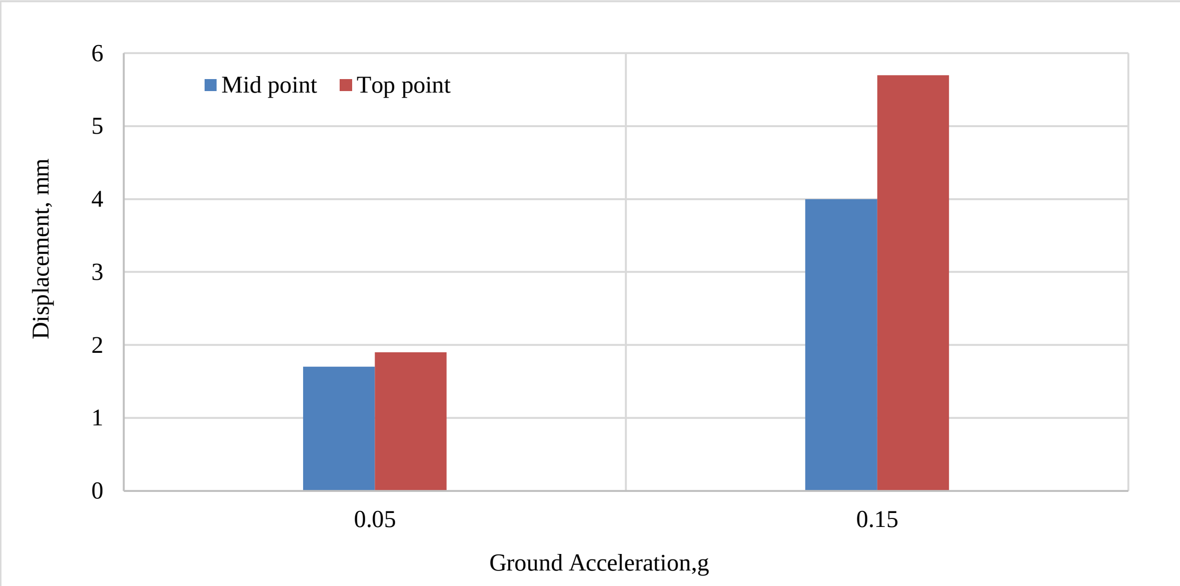


Figure 19. Variation of the Maximum Displacement with Ground Acceleration for the top and mid points in the model

- The experimental results showed very adequacy of the model to withstand the weak and moderate earth motion with no observed cracks.
- The maximum relative displacement at the top of the model subjected to El Centro 0.05 g was 1.9 mm while the maximum relative displacement at the midpoint of the model was 1.7 mm.
- For the excitation of El Centro 0.05 g, the increase in acceleration amplitudes between the upper and lower points of the model was by 73.3%.
- The maximum relative displacement at the top of the model subjected to El Centro 0.15 g was 5.7 mm while the maximum relative displacement at the midpoint of the model was 4 mm.
- For the excitation of El Centro 0.15 g, the increase in acceleration amplitudes between the upper and lower points was by 60%.
- The displacement at the mid-point of the model for intensity 0.15 g increased by 57.5% from the intensity 0.05g.
- The displacement at the top point of the model for intensity 0.15 g increased by 66.6% from the intensity 0.05g.

13. Conclusions

The shake table test of the model was a good experience to investigate the behavior of existing similar historical structures under earthquake action. Based on the experimental work results that have been achieved in this study, the following points can be concluded.

- For minor earthquakes, the potential resistance of such structures is adequate to resist the seismic forces with no damage.
- For moderate earthquakes, the model was very adequate to resistant the seismic forces with very minor cracks in the first quarter from the bottom. The reason behind this resistance is the increased in the rigidity with the deceased of the dimensions (scale down) and the distortion that occurred in the modelling because of the reduction in the added mass.
- The test results give an impression on the behaviour of the masonry structure under seismic loading that introduce a starting point for the researchers to start with in the further researches.
- The cylindrical shape of the model that represents the part of the minaret could be considered as a chimney subjected to ground motions. That gave the researchers the potential to start with its characteristics and move on in seismically evaluations of structures with the same properties in shape or material.

14. Conflicts of Interest

The authors declare no conflict of interest.

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