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Seismic Performance Evaluation of Phase Change Material-Based Energy Efficient Reinforced Hollow Concrete Block Masonry Building

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Abstract —*Majority of structures in Pakistan are masonry buildings because of their great heat and insulation properties, ease in construction etc. The insulation and heat resistance property of masonry buildings make it attractive now-a-days because of the emerging energy crises issue which compel civil engineers to think that seismic performance of building is not the only issue but also to find innovative techniques to make the buildings energy efficient. Since we need a structure which is energy efficient and earthquake resistant. For energy efficiency off course the choice is masonry buildings (heat insulation) but such type of structures are prone to earthquake because of its brittle behavior and lack of proper connections between various structural components. There were two parts of this research work one is determining the energy efficiency of phase change material utilized in masonry building which is performed by one of my companion Engr. Muhammad Ali [1]. He constructed two full scale rooms of same dimensions one was the PCM incorporated room and the other was a reference room for comparison. Special mechanism was designed which consist of providing steel box type pipes in the hollow cells of the blocks and will run throughout the height of walls and slab in which phase change material (vegetable ghee) was to be poured. Another aim of this research work is to seismically evaluate the performance of this type of masonry building in which steel pipes are used as casing for PCM which definitely reinforced the masonry building. For seismic performance a half scale model was constructed for shake table testing and focus was made on determining model's stiffness, strength, ductility and response modification factor.*

Key words*: Concrete block masonry; shake table test; phase change materials; energy efficiency; Seismic performance*

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I.INTRODUCTION

Masonry Buildings are the most attractive framework from the very beginning because of some of their desired properties (heat insulation, ease in construction etc.). Masonry is normally utilized for the walls of structures, bridge abutments etc. Brick is the most widely recognized kind of masonry and might be either weight-bearing or a facade. Block masonry is quickly picking up popularity as a practically identical material. concrete blocks, the greater part of which have empty centers, offer different potential outcomes in masonry development, by and large giving incredible compressive strength, and they are commonly most appropriate to structures with light transverse loading when the centers remain unfilled [2]. Masonry buildings may be reinforced masonry or unreinforced masonry buildings. The investigations made on the damages of unreinforced masonry buildings (URM) after a few quakes through the history have uncovered the high seismic weakness of this kind of construction [3],[4]. Usually total or fractional breakdown of unreinforced brick work structures happens during a seismic event because of low quality of construction materials and development innovation, absence of association between the convergence walls and among walls and floors and roofs [5]. Pakistan is a standout amongst the most seismically dynamic country on the planet, being crossed by a few noteworthy faults. Subsequently, earthquakes in Pakistan happen regularly and are destructive. Pakistan topographically covers both the Eurasian and Indian tectonic plates [6] hence this area is prone to severe seismic events, as the two plates collide. There is a background marked by serious quakes in Pakistan. The conspicuous precedent is the October 8, 2005, earthquake with an overwhelming size 7.6 quake struck the Kashmir area in the Himalaya. It spoils in excess of 80,000 individuals, harmed more than 100,000, and left 3 million destitute. Pakistan is a developing country and most of the buildings here are masonry buildings [7] because of their great heat and insulation properties, ease in construction, availability of low cost local materials and

Furthermore sensible resistance to fire. The insulation and heat resistance property of masonry buildings (especially hollow concrete block masonry buildings) make it attractive now-a-days because of the emerging energy crises issue. The energy crises issue compel civil engineers to think that seismic performance of building is not the only issue but also to find innovative techniques to make the buildings energy efficient. Energy efficiency of buildings is a need of the day because buildings drives 50% of the total consumed energy sources and same amount of CO_2 emission [8]. The petroleum products rule the world energy market, running out and present high costs, also its utilization is associated with the release of unsafe gases into the atmosphere. Therefore, the energy efficient use and the likelihood of the utilization of inexhaustible sources of energy are getting progressively significant. The energy efficiency of structures is currently one of the primary destinations of regional, national and worldwide energy policy. The utilization of materials, for example, hollow concrete blocks can increase the 'thermal mass' of a structure, offering high comfort in summer and winter and can be perfect for 'passive solar applications' [9]. The heat inertia of the masonry wall demonstrates its ability to store heat and emits progressively. The greater the heat inertia of the wall the better the limit of damping the outer temperature oscillations [10]. In summer, the heat insulation materials are widely utilized in buildings to diminish the heat stream into the building indoor space by using a compelling heat insulation to the thermal flow [11]. The significance of the insulation materials propels the heat transfer specialists to furthermore improve the present innovation of the insulation materials utilized in structures. The normally utilized insulation materials are fiberglass, cotton, and foams[12], [13]. In the course of the last few decades, the incorporation of the phase change material (PCM) into structure materials or components has been examined as a potential innovation for decreasing the cooling and warming burdens in buildings [14], [15], [16]. PCMs are natural or inorganic substances with low dissolving temperature also, high latent heat of fusion, for example, paraffin and salt. During the dissolving procedure, the specific heat of the PCM increase to multiple times to store huge amount of energy, and during the hardening procedure, the stored energy is discharged. Although use of PCM in building component or materials can make the building energy efficient but researchers also found that it reduces strength of the building materials (i.e. concrete) [17], [18]. It is true that the world is in need of energy efficient buildings but not at the cost of deteriorating its strength properties. Therefore, there were two parts of this research work one is determining the energy efficiency of phase change material used in building components which is performed by one of my companion Mr. Muhammad Ali [1]. He constructed two full scale rooms of same dimensions one was the PCM incorporated room and the other was a reference room for comparison. In order to incorporate PCM in building components without effecting the structural properties of building special mechanism was designed which consist of providing steel box type pipes in the hollow cells of the blocks and will run throughout the height of walls and slab in which phase change material (vegetable ghee) was to be poured. Another aim of this research work is to seismically evaluate the performance of this type of masonry building in which steel pipes are used as casing for PCM. For seismic performance a half scale model was constructed for shake table testing and focus was made on determining model′s stiffness, strength, ductility and response modification factor.

II.MATERIALS AND METHODS

2.1 Materials

The hollow blocks were casted of locally available material with mix ratio of 1:2:4 (cement: sand: Aggregate). The concrete used for the construction of the model was properly designed having a mix ratio of 1: 2.33: 2.72 (cement: sand: Aggregate) according to ACI method of mix design. The cement used in design of concrete was ordinary Portland cement (OPC) and a 1/2 inch (12.7 mm) down well graded coarse aggregate was used. The reinforcement used in the construction of the model was of grade 60 ksi. The steel pipes used as casing for incorporation of phase change material were of square shape 1inch x 1inch (25.4 mm x 25.4mm) made up of mild steel having thickness of 0.04 inch (1 mm).The mortar used in the construction of the model was made of OPC and locally available sand with a mix ratio of 1:5.

Table 1. Material properties

Materials	Test type	Test results (psi)	Remarks
Concrete blocks	Compressive	1935	28 days strength (1:2:4)
Mortar cubes	Compressive	1785	28 day strenght (1:5)
Steel pipe	Tensile (yield)	36170	
Steel	Tensile (yield)	65319	

2.2 Methods

2.2.1 Design of the Model Building

Due to limitations on shake table capacity and overhead crane the model building is a single story half scale model having dimensions of 1.83 m length x 1.52 m width x 1.6 m height. There was a window (0.76 m x 0.91 m) at the center and a door (0.61 m x 1.1 m) in a corner on two opposite walls while the two walls were without opening to represent a typical room in the locality. One purpose of the window provided in the opposite wall was also to reduce the flange effect on one side of the of the model building. The general layout is shown in Figure 1. The model represents a typical confined masonry building having columns at corners (101.6 mm x 101.6 mm) reinforced with four longitudinal 6.35 mm diameter bars and stirrups 3.2 diameter bar @ 76.2 mm c/c. Lintel beam (101.6 mm x 152.4 mm) reinforced with four longitudinal 9.5 dia bars and stirrups 3.2 mm diameter @ 76.2 mm c/c. The slab having thickness of 76.2 mm is reinforced with 6.35 mm diameter bars @ 101.6 mm c/c both ways. The model building was built on reinforced concrete foundation pad which serve several functions i.e. used for anchorage of the steel pipes used for incorporation of PCM and to connect the model to shake table through nuts and bolts. The foundation pad was designed for its own weight as well as for the weight of the model, to prevent excessive deformation during the transportation of the model to the shake table. The masonry units used in the construction of walls is a two cell hollow concrete block units which is also half scale having dimensions of 203.2 mm length x 101.6 mm thickness x 101.6 mm height shown in Figure 1.

To take care of similitude and scaling requirements both model and prototype were constructed of same materials (concrete and steel) which had similar density and stress properties but the pre-compression stress in model must be kept equal to the stress in prototype. in order to produce the desired level of vertical stress in the walls some additional mass must be placed on model which may be calculated using [19], [20] mass simulation model. The additional mass calculated was 1200 kg and was placed in the center of the roof of the model for equal distribution of stresses produced.

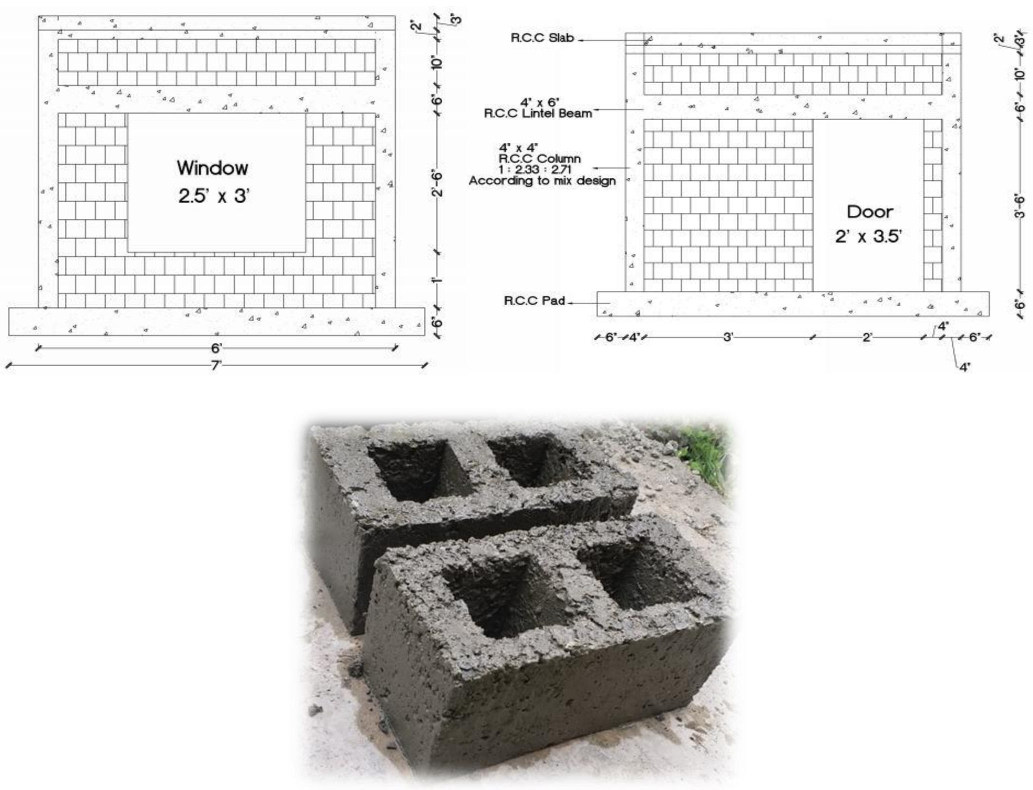


Figure 1. Configurations of the model building and hollow concrete blocks

2.2.2 Construction of the Model Building

The half scale model was constructed in a casting yard of University of Engineering and Technology Peshawar. First the steel pipes which was used as a casing for incorporation of PCM are welded with foundation pad reinforcement through a steel strip. The pipes are 18 gauge (1.02 mm thick) hollow steel square box type pipes having length of each side 25.4 mm. Pipes were also provided in the slab shown in Figure 2. Before concreting of foundation pad locations for shake table holes were fixed. The holes in the foundation pad was used for anchorage of the model with shake table. After concreting of foundation and gaining seven days strength construction of walls has been started. The bond adopted for the construction of walls are stretcher bond since the wall thickness was 101.6 mm shown in Figure 2. The mortar used for construction of walls have a mix ratio of 1:5 (cement: sand). The mortar thickness on average was kept 12 m.The model was plastered with the same mortar having a mix ratio of 1:5 and then white washed. The construction activities are shown in Figure 2.

Figure 2. Construction procedure

III.SHAKE TABLE TESTING OF THE MODEL

The Department of Civil Engineering at UET Peshawar houses the Earthquake Engineering Facility, Pakistan's first and largest center for research and instruction in the fields of earthquake engineering and engineering seismology. Modern facilities are available at the Earthquake Engineering Center (EEC) for experimental and analytical investigations of various structures. At EEC there are two shake tables (shake table-1: small shake table, shake table-2: large shake table) the present model was tested on small shake table and it has the following properties (Dimensions: 1.5 m x 1.5 m, Type: Single Degree of Freedom / unidirectional, Peak Acceleration: 1.1g).

3.1 Instrumentation of the model

The model was instrumented with three Displacement Transducers and three Accelerometers at the floor and gable levels. These instruments were mounted on the specified locations to monitor and record the displacement or crack opening and accelerations respectively shown in Figure 3.

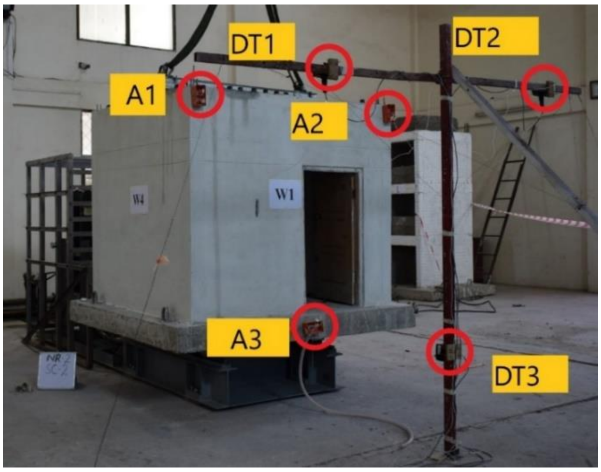


Figure 3. Instrumentation of the model

3.2 Test protocol

The model was subjected to a natural acceleration time history record of 1994 Northridge earthquake NR1 (Max acceleration 0.57g) as an input multiple excitations 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% and then subjected to its modified form NR2 (Max acceleration 1g) as an input multiple excitation 105% , 123%, 140%, 158%, and 175%. The peak ground acceleration for each run is shown in table 2.

Table 2. Input Excitation series and corresponding PGA

Test Run	PGA (g)	Test Run	PGA (g)
5%	0.028	80%	0.45
10%	0.057	90%	0.51
30%	0.17	100%	0.57
40%	0.23	105%	0.59
50%	0.28	123%	0.7
60%	0.34	140%	0.79
70%	0.39	175%	1

IV.RESULTS AND DISCUSSIONS

4.1 Damage pattern and test observations

Since the model was showing linear elastic behavior during the test therefore, there was no measurable damages observed. However, Small piece of plaster was spalled (due to rocking effect) at the base of south west column at 105% run. A leakage of PCM was observed at the base of east wall showing that the pipe is leaked or sheared during the test shown in Figure 4.

(a) (b)

Figure 4. (a) Spalling of plaster (b) Leakage of PCM

4.2 Amplification factors

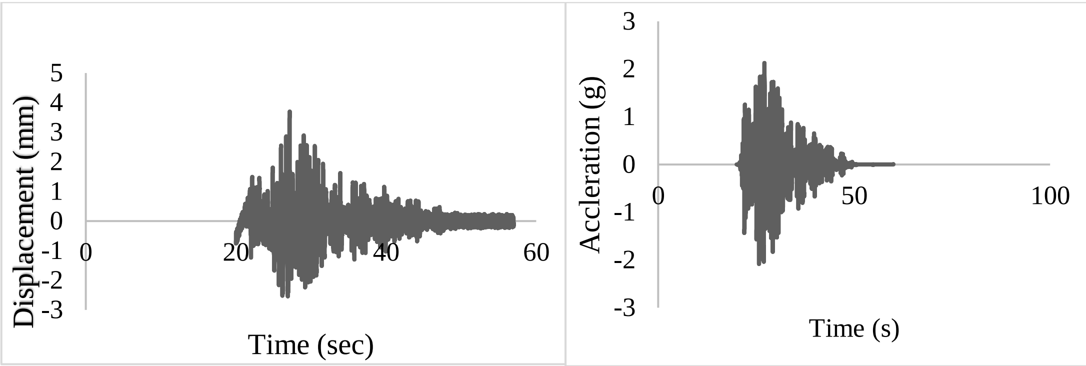
The amplification factors (Ratio of maximum acceleration at desired location to the maximum acceleration at the base) for each dominant run (input excitation) are listed in the table 3. From table 3 it is clear that the amplification factors are one or slightly greater than one for each excitation and that's why the model was showing linear elastic behavior.

Table 3. Amplification factors

Test Run	Base Acceleration	Top Acceleration	Amplification Factor
5%	0.04393	0.043965	1.000797
10%	0.07174	0.076845	1.07116
30%	0.13273	0.13518	1.018459
50%	0.26477	0.25896	0.978056
60%	0.32386	0.36798	1.136232
70%	0.36295	0.429295	1.182794
90%	0.52574	0.57041	1.084966
100%	0.54334	0.599765	1.103848
105%	2.01919	2.126055	1.052925
123%	1.54048	1.6207	1.052075
140%	0.85693	0.92517	1.079633

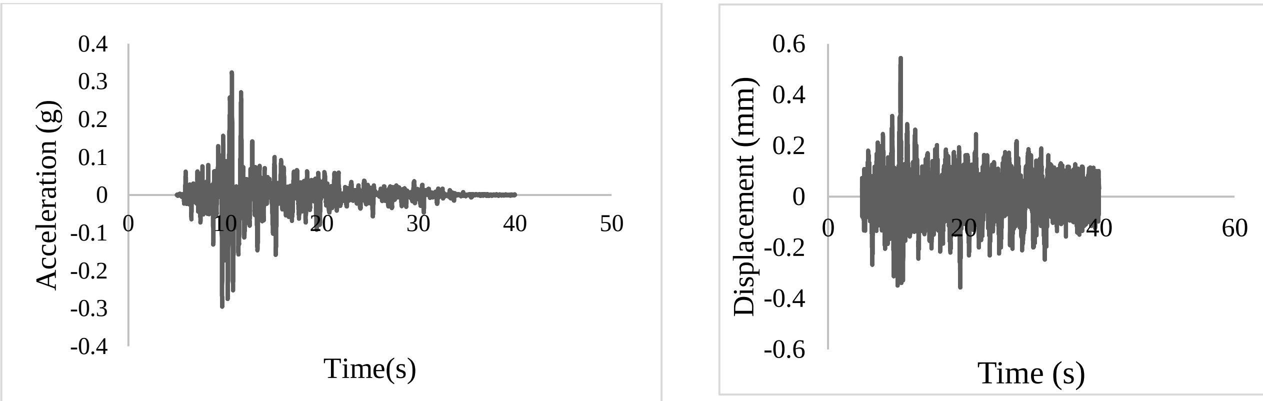
4.3 Response acceleration & its corresponding displacement

The below Figures (Fig 5, Fig 6, Fig 7 and Fig 8) represent response acceleration and its corresponding displacements for the prominent input excitation 60%, 105%, 123% and 140% respectively. In Fig 5 (a) the maximum response acceleration reaches up to 0.32g for which the maximum corresponding displacement in Fig 5 (b) is 0.53 mm. Similarly in Fig 6 (a) the peak response acceleration is 2.1g for which the corresponding displacement in Fig 6 (b) is 3.57 mm. In Fig 7 (a) the maximum response acceleration is 1.9g while the corresponding displacement in Fig 7 (b) is 2.9 mm similarly in Fig 8 (a) the peak response acceleration is 0.9g and the corresponding displacement in Fig 8 (b) is 1.34 mm. From all these Figures it is cleared that there is no measurable displacement even for a response acceleration of 2.1g that's why no measurable cracks were observed.



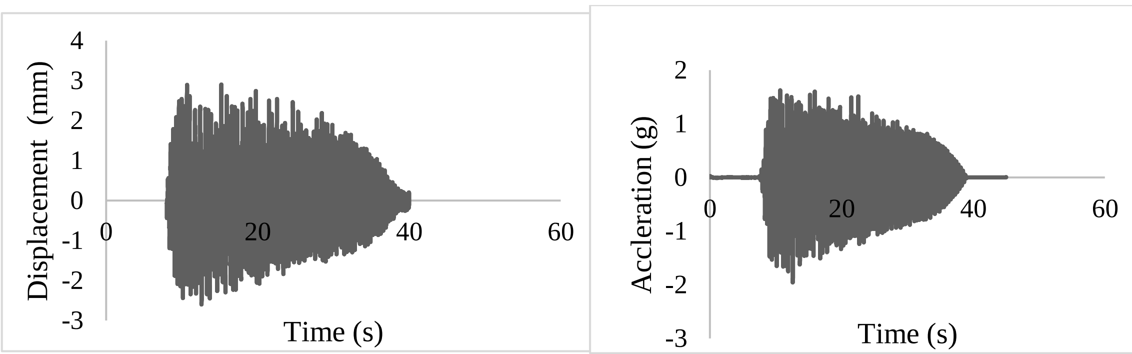
(a) (b)

Figure 5. (a) Response acceleration (b) Corresponding Displacement



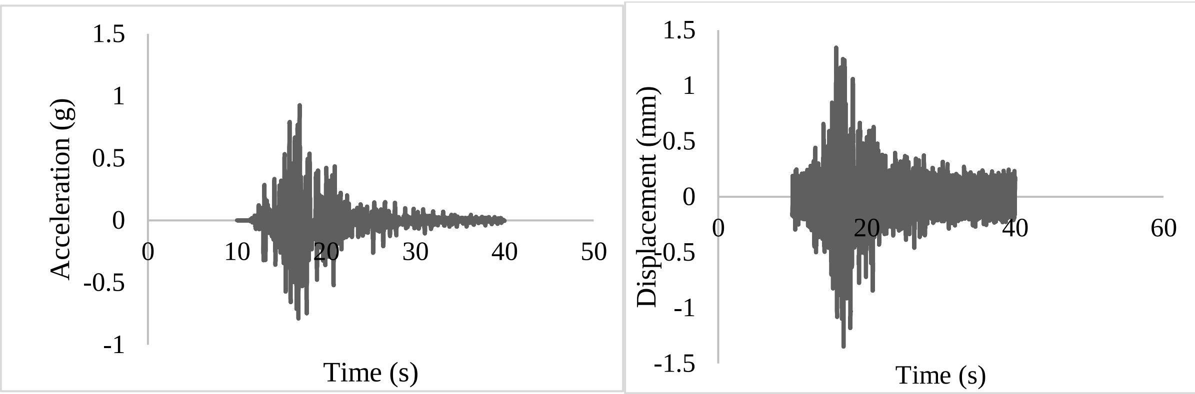
(a) (b)

Figure 6. (a) Response acceleration (b) Corresponding displacement



(a) (b)

Figure 7. (a) Response acceleration (b) Corresponding displacement



(a) (b)

Figure 8. (a) Response acceleration (b) Corresponding displacement

4.4 Capacity Curve

The model was shacked up to the maximum capacity (1.1g) of small shake table of EEC UET Peshawar for natural acceleration time history record of 1994 Northridge earthquake and was showing linear elastic behavior for which the capacity curve is shown in the Figure 9. In order to draw the capacity curve first we need to determine base shear coefficient and story drift. For base shear coefficient first determine base shear force which is obtained by multiplying the model top acceleration with the mass of the model above half window level plus the additional mass and then divide by total model mass to obtained base shear coefficient (BSC). Similarly to obtained story drift divide the displacement of top of the model by the model height. The capacity curve also reveals that no stiffness degradation has been seen throughout the test.

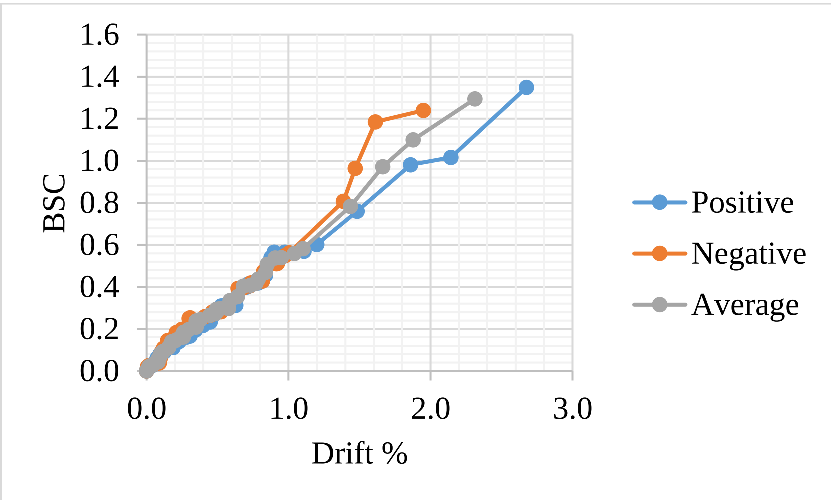


Figure 9: Capacity curve

4.5 Calculation of model stiffness

The stiffness of the model may be calculated from trending line when base shear is plotted against displacement shown in Figure 10. The stiffness of the model is 21.4 kN/mm

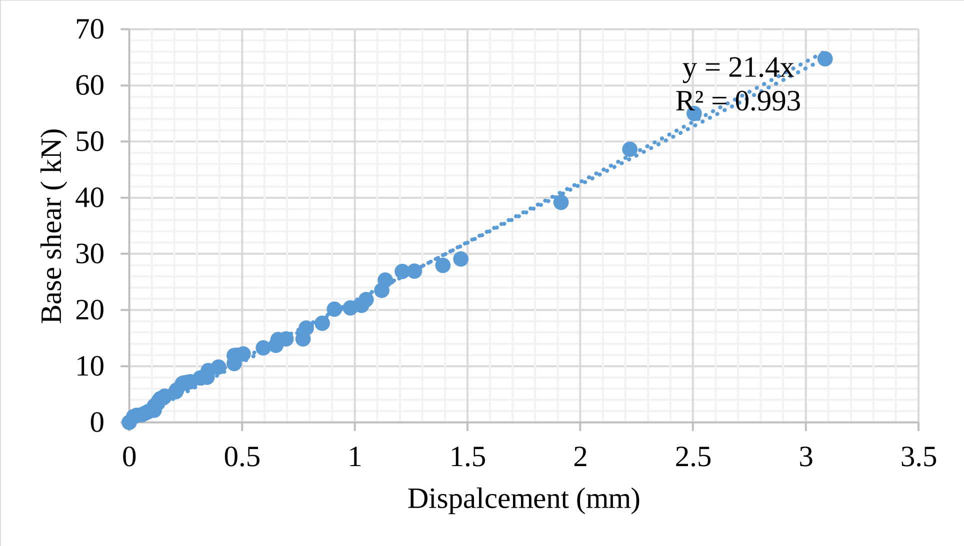


Figure 10: Base shear displacement plot

4.6 Calculation of response modification factor

The response modification factor can be calculated by using the following equation

*Response modification factor (R) = Rµ * Rs*

Where;

Rµ = Ductility factor

Rs = Over strength factor

Over strength factor (Rs) = Vy / Vd

Vy = maximum recorded base shear force since the model didn't reach yield limit in the test

Vd = design base shear which is calculated for Zone 3 using static lateral force procedure

Vy = 64.7 kN

Vd can be calculated by Static Lateral Force Procedure explained in UBC-97.
Vd = 18.63 kN (calculations based on zone 4)

Over strength factor Rs = 64.7/18.63 = 3.47

Ductility factor (R) = 1 (For Time period (T) < 0.2 Ru =1 Newmark and Hall 1982)

Time period of the model T = 2*π* Square root of (M/K)

M = mass of model

K = stiffness of model

By putting values the time period T = 0.07 sec

Ductility factor (Rµ) = 1 (For T < 0.2 Ru =1 Newmark and Hall 1982)

*Response modification factor (R) = Rµ * Rs* = 1*3.47 = 3.47

The response modification factor for reinforced masonry buildings in UBC97/BCP-SP 2007 is 4.5. Since the model did not reach its yield limit due to limitation on shake table capacity. The response modification factor of the model is approximately equal to 3.5 which nearly comparable to the one specified by UBC97/BCP-SP 2007 for the current loading state.

4.7 Calculation of displacement ductility

As the model didn't reach to its yield point we cannot determine displacement ductility

V.CONCLUSIONS

Since the model was very heavily reinforced with steel pipes for the incorporation of phase change materials which made it very stiff and therefore no measurable damages were observed during the shake table test. However a Small piece of plaster was spalled (due to rocking effect) at the base of south west column at 105% run. Moreover, a leakage of PCM was observed at the base of east wall showing that the pipe is leaked or sheared during the test but the since the model was behaving like rigid body motion this leakage may be due to drilling of holes in the foundation pad of the model for nuts and bolts to tie the model to the base of shake table.

By looking at the amplification factors and hysteresis curves it has been concluded the model was very much reinforced by introducing the steel pipes in the walls of the model for incorporation of PCM which made the model very stiff and thus was showing linear elastic behavior even operating the shake table at its full capacity.

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