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Shake table tests on typical stone masonry buildings used in the Himalayan Belt

Qaisar Ali[1], Akhtar Naeem Khan[1], Mohammad Ashraf[2], Awais Ahmed[3], Bashir Alam[2], Muhammad Fahim[3], Shahzad Rahman[1]

ABSTRACT

Stone rubble masonry structures are found in abundance in northern region of Pakistan and in the Himalayan belt. The construction techniques and structural features of these buildings are fairly uniform throughout the Himalayan belt, even though the area is inhabited by people from different cultures. Such structures are usually constructed using dry masonry or mud mortar, making them available to damage and collapse in earthquakes. Collapse of such structures featured prominently in the Kashmir Earthquake of October 08, 2005 that left about 80,000 people dead and around 3.5 million homeless. In order to study the seismic behavior of these structures, shake table tests on three reduced scale models were conducted. First, a basic model having two-wythe typical stone masonry walls without horizontal bands and vertical confining elements was tested on shake table. Subsequently, two additional models were tested that incorporated simple earthquake resistant features, such as, horizontal and vertical concrete bands. All the models were constructed on reduced scale of 1:3 and were subjected to actual acceleration record from past earthquakes. Some preliminary results of these tests are presented. Test data indicates that seismic performance of rubble stone masonry structures can be significantly improved with low cost modifications.

Introduction

Stone masonry buildings constitute a substantial portion of the total building stock of the northern areas of most South Asian countries such as Afghanistan, Pakistan, India, Nepal and Bhutan. Based on the combination of different systems of walls, roof and floors, a variety of stone masonry buildings exist in these countries. The main construction techniques and structural features of these buildings are however fairly uniform throughout the Himalayan belt, even though the area is inhabited by people from different cultures.

Two wythes random rubble stone masonry walls in dry or mud mortar with flat earthen or pitched GI sheet roof is the most common construction type in these areas, fig 1. The seismic performance of these buildings in the past earthquakes has shown extremely dismal results (Bothara K.J 2008). Such buildings are therefore considered as one of the most seismically vulnerable structures. Collapse of such structures featured prominently in the Kashmir Earthquake of October 08, 2005 that left about 80,000 people dead and around 3.5 million homeless (Ali Q and Muhammad T 2006).

[1] Professors, Department of Civil Engineering, NWFP UET Peshawar
[2] Assistant Professors, Department of Civil Engineering, NWFP UET Peshawar
[3] Lecturers, Department of Civil Engineering, NWFP UET Peshawar

Since stones are abundantly and easily available in these areas, they are bound to remain the natural choice of the people in the coming several years. Moreover under the prevailing economic conditions of the people, the chances of replacing stones by an alternate building material are very low.

Although different experts and agencies over the years have recommended a number of strengthening features to improve the seismic performance of stone masonry buildings (IAEE 1986; IS13828 1993 and Tomazevic M 1999), the most commonly preferred features are horizontal bands and/or vertical elements provided in RC or timber. These recommendations, by and large, are based on intuition, lessons learned from the past earthquakes, engineering judgment and/or limited research results derived from studying similar structures. A classic example of the use of horizontal and vertical timber elements for improving seismic performance of stone masonry buildings from one of the remotest northern areas of Pakistan, Gilgit, is shown in fig 2. History has shown that these features significantly improve the seismic performance of conventional random rubble stone masonry buildings (Ali Q and Naeem A 2007). The scientific quantification of good performance of these structures is however still lacking.

Though there exists enough experimental and numerical studies on unreinforced brick, block and dressed stones placed in cement sand mortar (Gulkan P.et.al (1979) ; Mann W 1982; Calvi G M 1996 ; Tomazevic M 1999 ; Ali Q (2006)), studies on random rubble stone masonry in dry or mud mortar are very limited (G. Vasconcelos et.al. 2006).

The present investigation discusses the results of three shake table tests conducted on stone masonry structures found in abundance in the Northern areas of Pakistan and in the Himalayan belt. First, a basic model having two wythes typical stone masonry walls without horizontal bands and vertical confining elements was tested on shake table. Subsequently, two additional models were tested that incorporated simple features, such as, horizontal and vertical concrete bands for improving their seismic performance. All the models were constructed on reduced scale of 1:3 and were subjected to actual acceleration record from past earthquakes.

Results of seismic performance of typical stone masonry building and one with improvements are presented. Test data indicates that the seismic performance of rubble stone masonry structures can be significantly improved with low cost modifications

Models Description

Reduced scale stone masonry models were named as SM1, SM2 and SM3. All models were single story and single room. The size of the models was 5ftx4ft according to a scale factor of 3 for a prototype size of 15ftx12ft. Since the strength of stones and mud could not be reduced, simple model similitude principles were followed in reduced scale modeling. The complete attributes of these models are presented in table 1. SM1 was the basic model without any seismic features whereas SM2 and SM3 were models with proposed improvements.

The attributes of model SM1 were set to represent public buildings especially schools mostly used in the Northern areas of Pakistan. According to (ADP & WB 2005), 18000 school children died as a result of partial or total collapse of about 7669 school buildings in the Kashmir earthquake of October 08, 2005. These buildings are constructed in two wythes stone masonry walls using half dressed stones placed in cement sand mortar without horizontal bands and vertical elements. The stones are dressed on the bed and outer sides but all the other sides remain undressed. The roof in most cases is RC slab. Model SM1 was therefore constructed to contain most of the characteristics of these school buildings in order to investigate their seismic performance. Figure 3 shows details of the model.

Model SM2 was constructed using undressed stones placed in mud mortar. Vertical reinforced concrete elements were introduced in all four corners as confining elements to strengthen the masonry walls. The vertical elements were having a cross-sectional dimension of 15in x 15in and 5in x 5in in the prototype and model respectively. Each wall was erected in several steps and concrete was poured in the confining elements incrementally after completion of each portion of wall. No horizontal bands were present except at lintel level above the door and window in the front wall as shown in fig 4. The roof was flexible flat wooden roof with thick mud overlay instead of RC slab. The objective of this model was to represent a stone masonry building having undressed stones placed in mud mortar and reinforced concrete vertical elements at corners.

Model SM3 was constructed by making improvements in model SM2 with incorporation of horizontal bands at sill, lintel and roof level to study the effect of these elements on the seismic capacity of such buildings. Figure 5 shows detail of SM3.

Input excitation

One of the important aspects of shake table testing is to subject the models to a shaking, as nearly as possible, to the natural ground shaking caused by actual earthquakes. The input excitation should be such as to subject the model to most critical earthquake loading. Peak ground acceleration, duration, period and frequency are the parameters which determine the severity of an earthquake. Based on these conditions, two ground motion records were selected; one was 30 second record of the north-south component of El Centro 1940 record and the other was north-south component of Kobe 1995 record. In order to satisfy the similitude requirement of simple model, the time duration of the original records was compressed by a scale factor of 3.

Shake table test setup and methodology

The reduced scale models were tested in the Earthquake Engineering Center at the Department of Civil Engineering, NWFP University of Engineering & Technology Peshawar, Pakistan. The shaking was applied through a 5ft x 5ft one dimensional shake table. The model was constructed on a 5 inch thick concrete pad which was then mounted on the shake table and firmly secured with the help of bolts. The response of the model was captured through accelerometers and displacement transducers. All the gauges were connected to a data acquisition system and the data was recorded at a sampling frequency of 200Hz for a period approximately double of the duration of input excitation. All signals were processed for the base-line correction and noise removal by employing butter-worth band pass filter. However the displacement time histories were processed using a low pass filter.

The model SM1 was subjected to a shaking along the longer walls having openings. Two accelerometers, one at the top and other at the bottom and four displacement transceducers, two on the top and two at the bottom were connected to the model, fig 3.

The models SM2 and SM3 were mounted at an angle of 39^o to the direction of shaking in order to study both the in-plane and out of plane response. Two accelerometers, one at the top and other at the bottom of the model and three displacement transducers one at the bottom and two at the top were used to capture the response of the model, fig 4 and fig 5.

The models were subjected to ground motions by progressively increasing the amplitude of the earthquake shaking. At the end of each test run the models were carefully examined for any possible damage level.

Shake table test response

Observed damages

Reinforced concrete roof and the RC roof band in the model SM1 helped initially in maintaining the integrity of the walls by engaging all the walls to act like a box structure. A crack was observed nearly at a PGA value of 0.1g at the contact surface between the walls and RC roof band along the full perimeter. This ceased the functioning of box like structure of the model and made the walls more susceptible to damage by further shaking. The cracks initiated around the openings and at the corners and kept on widening with increased shaking. The propagation and widening of the cracks around the openings detached the walls, fig 6. Consequently out of plane walls started vibrating like a cantilever wall resulting in their collapse followed by collapse of in-plane walls and ultimately resulting in a rapid collapse of the overall structure. Figure 9 also shows that post crack behavior of the model SM1 is essentially of brittle nature. Various damage levels at different intensities of ground shaking along with base shear coefficient and story rotation are given in table 2.

Model SM2 showed slightly better behavior than model SM1. Presence of vertical columns at the corners increased the strength as well as the displacement capacity of the structure, fig 9. However the absence of horizontal bands in the model resulted in the termination of box like behavior of the model. Consequently the upper portion of the back wall collapsed nearly at a PGA value of 0.16g because lintel in the back wall was not continuously provided over the entire length of the wall but was provided only above the window opening as shown in figure 7. The collapse of this wall caused a rapid reduction in the capacity of the structure. Additionally, other walls also experienced damage in the upper quarter part essentially due to out of plane shaking, which caused further reduction in the overall capacity of the model. It is worth mentioning that the continuous lintel provided over the door and window in the front wall helped in maintaining the integrity of the wall, figure 7. The corner columns did not experience any damage even at high seismic demand. It was observed that providing columns alone without enough horizontal bands might not significantly improve the seismic capacity of the structure. Figure 9 and table 2 also demonstrate that there is not much difference between the overall seismic performance of the two models, SM1 and SM2, even though there is no vertical and/or horizontal bands except roof band in the model SM1.

The model SM3 showed considerably good performance in comparison to other two models, fig 9. The incorporation of vertical RC elements and horizontal RC bands helped to improve the structural response. In addition to introducing the box like structural behavior in the model, these elements divided the wall into small portions. The smaller these wall portions were the lesser was the damage caused, fig 8. Since the vertical elements at the door side in the front wall were curtailed at the lintel level and were not extended up to the roof of the model, the wall above the lintel level suffered moderate damage at a PGA of 0.27g, fig 8. Structural damage to the model SM3 at different levels of ground shaking intensity are given in table 2.

Table 3 illustrates different damage levels for the three tested models.

Base shear and response displacement relation

Response curve in the form of story drift vs. base shear coefficient for each model is presented in fig 9. The base shear is calculated by multiplying the maximum response acceleration at the story level with the story mass. Story mass is taken equal to sum of the mass of roof and half of the mass of walls. Story rotation is determined as the ratio of response displacement to the story height and the base shear coefficient is determined as the ratio of base shear to the total weight of model. Additionally, table 2 is presented to show different damage levels at peak ground acceleration (PGA) in order to compare the performance of the models at various PGA values. Figure 9 and table 2 clearly demonstrate that the seismic performance of model SM3 with proper vertical and horizontal RC elements is significantly better than the models SM1 and SM2.

Conclusions and recommendations

1. The performance of SM1 was the worst among the three tested models, even though the stones were placed in fairly rich cement sand mortar. This infers that half dressed stones placed in cement sand mortar without vertical and horizontal elements are seismically inferior to undressed stones placed in mud mortar with vertical and horizontal elements properly in place.
2. The vertical RC elements in the model SM2 without horizontal bands could not substantially improve the seismic performance of the model. Though vertical elements at the corner helped in increasing the overall capacity of structure up to some extent, they without horizontal bands could not confine the wall properly to prevent the collapse of especially out of plane walls in the upper parts of the structure.
3. The performance of model SM3 was excellent because the model did not suffer substantial damage at a PGA of 0.27g, whereas, the other two models suffered heavy damages at about the same PGA.
4. The horizontal bands at the sill and lintel level substantially enhance the capacity of the structure by introducing box effect in the structure.
5. More number of horizontal bands even though if they are as thin as 3 inch are proved to be more efficient than fewer and thick horizontal bands, e.g. 3 inch thick horizontal bands with two 3/ 8 inch longitudinal bars and 2/ 8 inch cross tie at 6 inch center to center provided at plinth, sill, lintel and roof level will enhance the capacity of the structure much more than commonly practiced two horizontal bands 6 or 9 inch deep with four 3/8

inch longitudinal bars and 2/8 inch stirrups at 6 inch center to center provided at plinth and lintel or lintel and roof.

6. The concrete having strength as low as 380 psi used in concrete elements both horizontal and vertical is proved to be enough in the given structural system.

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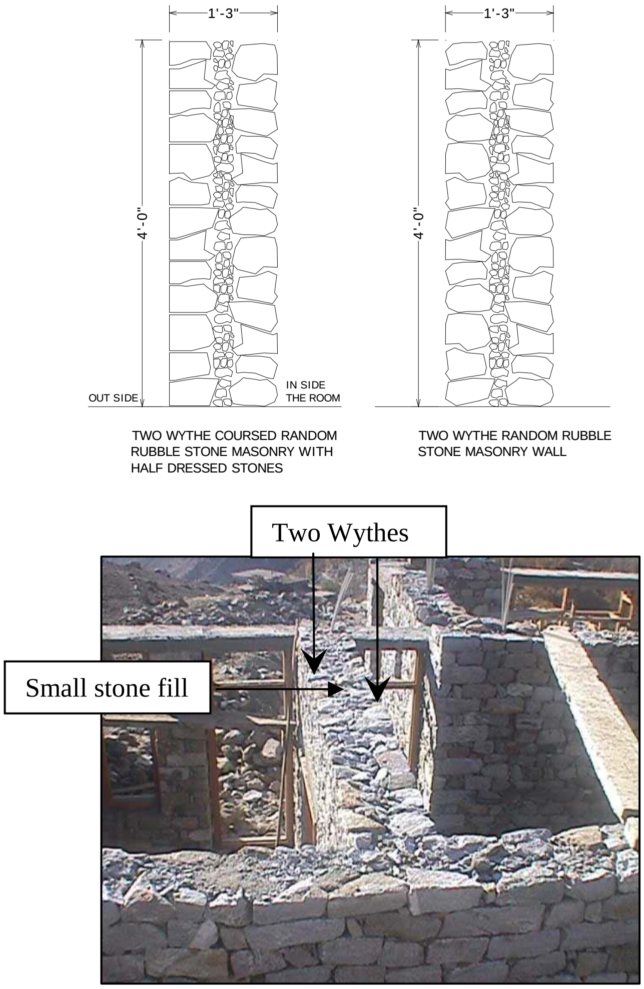


Figure 1: Typical Stone masonry building with two Wythes

Figure 2 : Use of horizontal and vertical timber elements in stone masonry

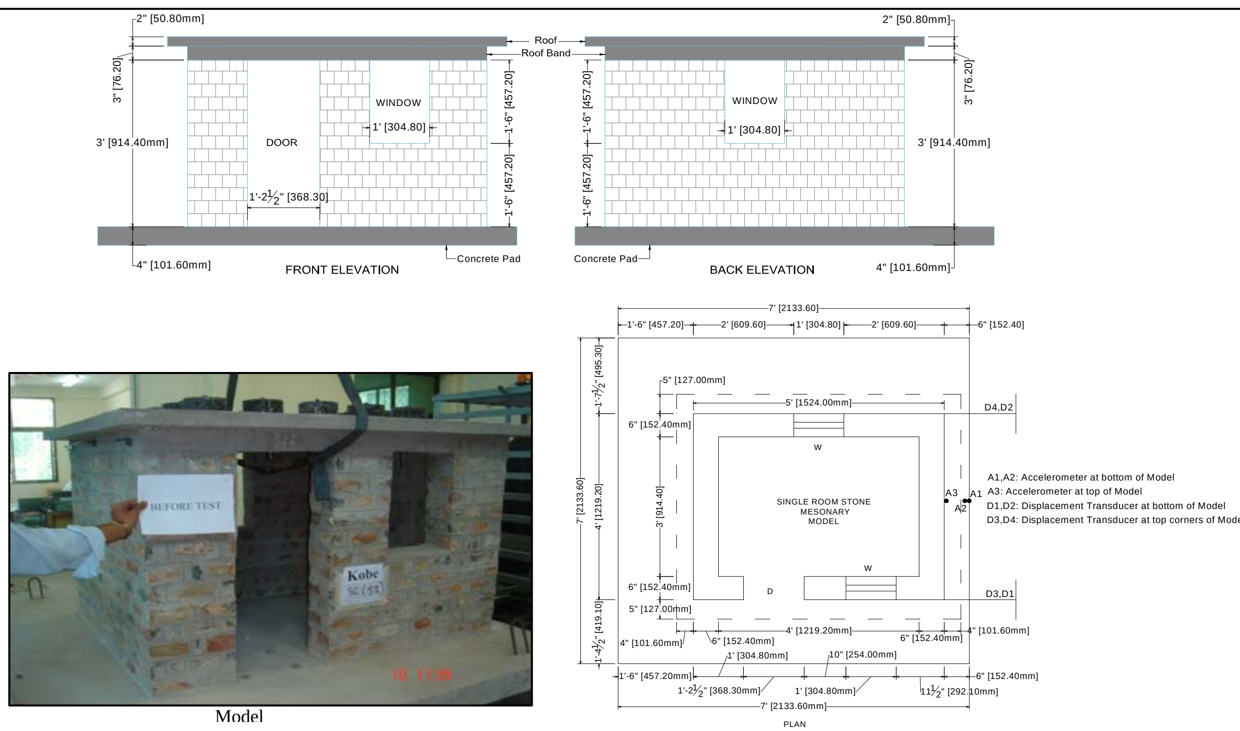
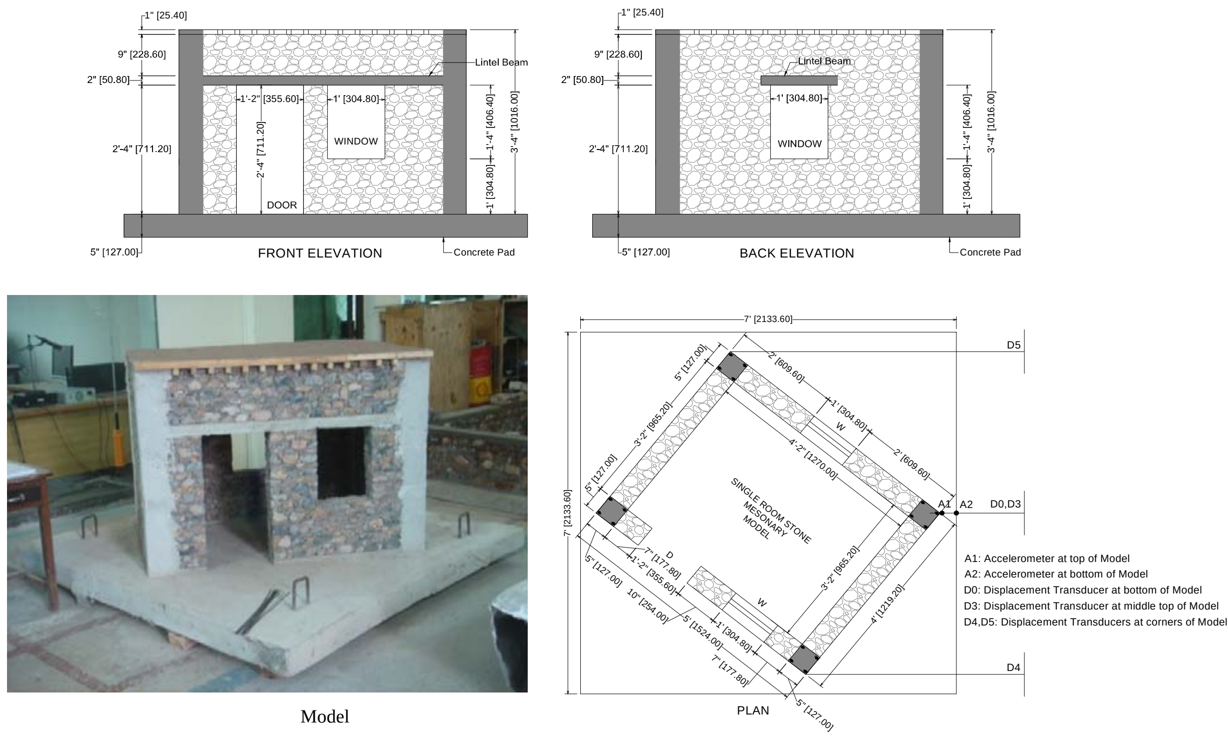
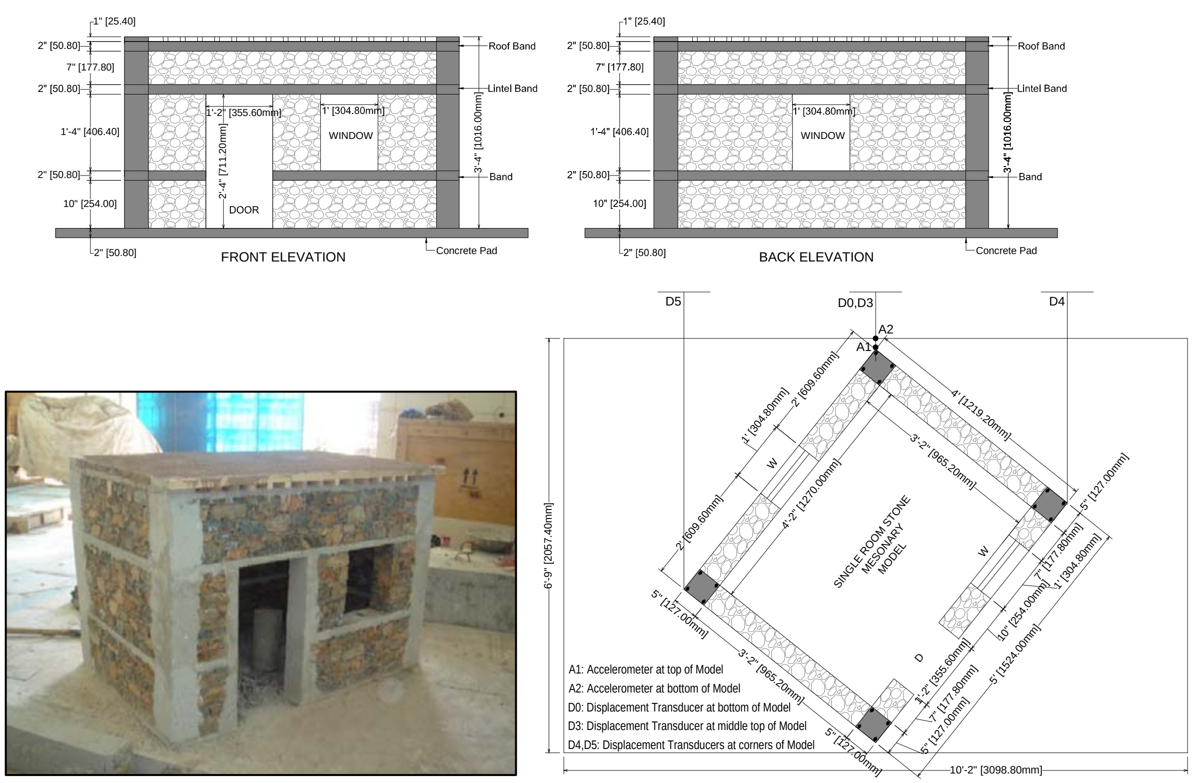


Figure 3 : Reduced scale model SM1 and its instrumentation detail for shake table test



Model

Figure 4 : Reduced scale model SM2 and its instrumentation detail for shake



Model SM3

Figure 5 : Reduced scale model SM3 and its instrumentation detail

Back Wall

Figure 6: Damages to the front and back walls of model SM1 (PGA = 0.19 g)

Front Wall

Back Wall

Figure 7: Damages to the front and back wall of the model SM2 (PGA = 0.16g)

Front Wall

Back Wall

Figure 8: Damages to the front and back wall of the model SM3 (PGA = 0.27g)

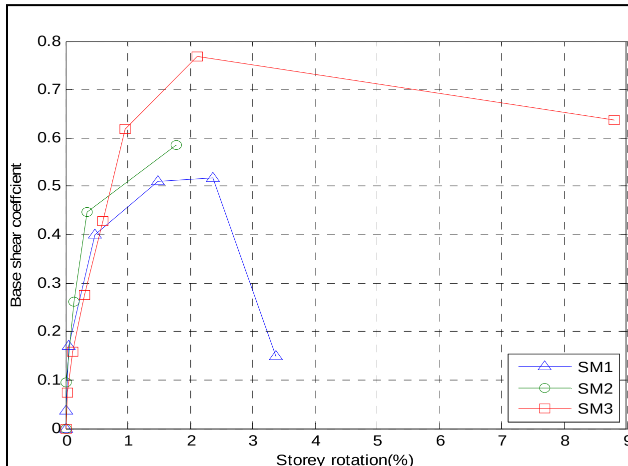


Figure 9: Seismic response envelop curves for models SM1, SM2 and SM3

Table 1: Model parameters

Parameter	SM1		SM2		SM3	
	Prototype	**Model**	**Prototype**	**Model**	**Prototype**	**Model**
Stone masonry	Coursed random rubble	Coursed random rubble	Un-coursed random rubble	Un-coursed random rubble	Un-coursed random rubble	Un-coursed random rubble
Stones	Half Dressed	Half Dressed	Undressed	Undressed	Undressed	Undressed
Mortar	Cement sand having compressive strength of 600 psi	Cement sand having compressive strength of 550 psi	Mud	Mud	Mud	Mud
Concrete	400 psi	380 psi	400 psi	380 psi	400 psi	380 psi
Vertical elements	No vertical elements	No vertical elements	Only at corners; 15″ x 15″ with 4,3/8″ bars and 1/8″ stirrups @ 6″ on center	Only at corners; 5″ x 5″ with 4,1/8″ bars and 1/24″ stirrups @ 2″ on center	Only at corners; 15″ x 15″ with 4,3/8″ bars and 1/8″ stirrups @ 6″ on center	Only at corners; 5″ x 5″ with 4,1/8″ bars and 1/24″ stirrups @ 2″ on center
Horizontal bands	Continuous roof band. 6″ thick horizontal band with 4,3/8″ bars and 1/8″ stirrups @ 6″ on center	Continuous roof band. 2″ thick horizontal band with 4,1/8″ bars and 1/24″ stirrups @ 2″ on center	Only above openings; 6// thick horizontal band with 4,3/8// bars and 1/8// stirrups @ 6// on center	Only above openings 2// thick horizontal band with 4,1/8// bars and 1/24// stirrups @ 2// on center	At sill, lintel and roof level. 3// thick horizontal band with 2, 3/8// bars and 1/8// cross-tie. @ 6// on center	At sill, lintel and roof level. 1// thick horizontal band with 2, 1/8// bars and 1/24// cross-tie @ 2// on center
Roof	RC slab	RC slab	Flexible Flat Wooden Roof with 6 inch thick mud overlay	Flexible Flat Wooden Roof with 2 inch thick mud overlay	Flexible Flat Wooden Roof with 6 inch thick mud overlay	Flexible Flat Wooden Roof with 2 inch thick mud overlay
Opening sizes	D:3.5′ x 9′ W: 3′ x 4.5′	D: 1′-2″x3′ W: 1′x1′-6″	D:3.5′ x 7′ W: 3′ x 4′	D: 1′-2″x2′-4″ W: 1′x1′-4″	D:3.5′ x 7′ W: 3′ x 4′	D: 1′-2″x2′-4″ W: 1′x1′-4″

Table 2: Peak ground acceleration(PGA), Base shear coefficient and story drift corresponding to different damage levels

Damage levels	SM1			SM2			SM3		
	PGA(g)	Base shear coefficient	Story rotation (%)	PGA(g)	Base shear coefficient	Story rotation (%)	PGA(g)	Base shear coefficient	Story rotation (%)
Minor	0.09	0.17	0.05	0.11	0.26	0.13	0.16	0.43	0.60
Moderate	0.19	0.40	0.48	0.16	0.44	0.35	0.27	0.62	0.96
Major	0.22	0.51	1.49	0.26	0.58	1.77	0.59	0.77	2.12
Collapse	0.41	0.15	2.65	-	-	-	0.84	0.64	8.81

Table 3: Illustration of different damage levels

Damage levels	SM1	SM2	SM3
Minor	Separation of roof band and slab from walls	Initiation of stone falling	Few stones falling from the upper portion of front wall
Moderate	Cracks initiation and propagation around openings and at the corners	Partial stone falling from upper part of walls	Further stone falling from front wall essentially due to out of plane motion
Major	Widening of cracks and falling of stones from out of plane walls	Substantial stone falling accompanied by partial collapse of roof	Substantial damage to all walls
Collapse	Collapse of structure	Collapse of walls, columns remain intact	Complete collapse along with RC columns