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Rubber Damping System of Industrialised Building System (IBS) Block Work House

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Abstract. The block work house with Industrialised Building System (IBS) is innovated to minimize the rate of casualties from earthquake disaster. In order to improve the ductility of IBS block work house, rubber dampers were used to resist dynamic motion of a structure under seismic event. Through the research, the seismic performance of the 1:5 down scaled IBS block work column was obtained. The objective of this research is to create a robust IBS column by improving the damping system. Time History Test on shake table was conducted for IBS column models to determine its structural behaviour under seismic loading. Three types of IBS column models with different rubber damper type and application were tested. The rubber damping properties for two different rubber types were also obtained. Sabah earthquake 2015 with the PGA of 0.126g was simulated for the time history shake table test. The dynamic parameters such as acceleration, response spectra, and displacement were evaluated. As the results of the study, it was found that the hard rubber has better damping properties than soft rubber. The rubber dampers that installed in xy-plane horizontally on the column system is effective as vibration isolator.

1. Introduction

Earthquake is the perceptible shaking of the Earth which resulting from the sudden energy release in the Earth's crust that creates seismic wave. Earthquake can be violent enough to destroy whole cities and cause casualties to human. Prior to the year of 1994, the number of fatalities due to collapse of buildings had been almost negligible in Japan. But for the Kobe Earthquake in 1995, over five thousand people were killed mostly due to collapse of wooden houses and steel welded structure that lack of ductility. The fatality data from Loma Prieta 1989 and Northridge 1994 events in United State included the collapse of transportation structures and buildings, which have becoming the major causes of deaths. The occurrence of an earthquake affects the number and circumstances of human casualties, daily activities and dislocations of residents should be considered in casualty estimation [1].

An urban earthquake has the potential to cause damage to structures and buildings which may be hazardous to humans. The recent years 2015 to 2018 earthquakes in Nepal, Japan and Ecuador had cause nearly 10,000 death and billions of currency damages. In order to prevent fatalities caused by collapse structures, the evaluations of the potential damage and properties of buildings must be taken into considerations, as well as the specific nature of the ground movements. The Sabah earthquake which occurred on 05 June 2015 was the strongest earthquake struck Malaysia since 1976. As the result of the earthquake, infrastructures such as 23 schools and Ranau Mosque was reported damages [2-3]. Hostels and rest house were damaged seriously and the areas surrounding suffered water supply disruption [4-5]. In this study, the PGA 0.126g in North-South (NS) direction was used for the simulation of time history test. The 0.126g NS direction earthquake motion has a slightly smaller PGA magnitude than 0.132g EW direction. However, the NS scenario was chosen due to its intense horizontal movements which may give larger dynamic effect to the models.

One of the construction methods that may take into consideration of earthquake structural design and construction industrialization is Industrialised Building System (IBS). The concept of the safe house or block house is innovated from safe room of hurricane shelter developed by Federal Emergency Management Agency (FEMA) in United States [6]. The IBS block house have a sufficient lateral stiffness and flexibility at joints between components that able to absorb the vibrations of earthquake. The new innovative IBS Blocks of Residential Building is shown in Figure 1 which the components can be assemble or disassemble quickly [7]. The damaged structural components can be replaced and repaired rapidly after the earthquake event. Hence, the aim of this research is to obtain the seismic performance of scaled 1:5 IBS block house column with the installation of rubber damping system.

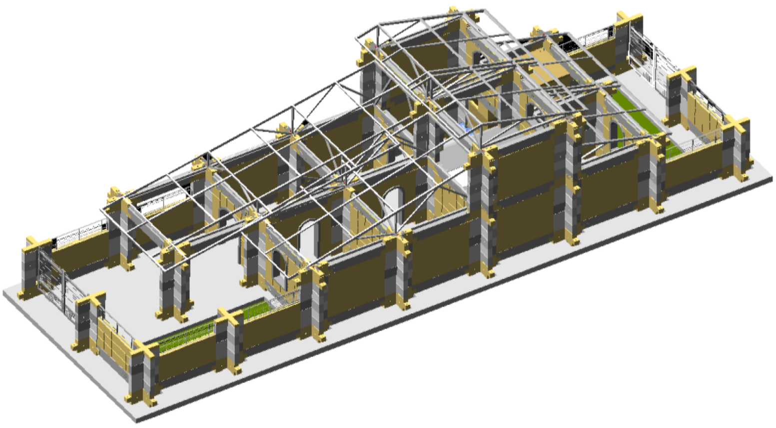


Figure 1. IBS Block Residential Building.

1.1 Buckingham and Similitude Theory

Nowadays, down scaled models have been frequently used by many researchers to investigate the behaviour of the full-scale structure. Although there are always question with the down scaled model representation on the full-scale structure, many researchers believe that similitude theory may prove useful in investigating structural seismic performance and capacities through down scaled structural model. Similitude law and Buckingham's π Theorem is introduced to deduce the theoretical relation of variable describing a physical phenomenon, and provides dimensionally homogeneous equation involving the physical quantities. Hence, with the combination of Buckingham's π Theorem and similitude law, the prototype structure (p) full scale and the scaled model (m) can be distributed into simple equation $\pi_i^p = \pi_i^m$. Prototype and scaled model capacity are always influence scale factors S_i [8].

Scale factor S_i is defined as quantity in scaled model over quantity in prototype. The summary and useful quantified scale factors for engineering purpose are shown in Table 1. In structural material elasticity with scale factor S_e is equivalent to elasticity of $E_{prototype}$ over elasticity of E_{model} which defines the downscaled material strength effects [9]. The scale factor in acceleration domain $S_a = [(1/S^{1/2})(S/S^{1/2})]$ = *time multiplication with velocity dimension = 1.0* in constant gravitational environment [10]. Hence, the scaled coefficient for real time history earthquake signal is equal to 1.0. By carefully applying the respective scale factors, it is feasible to obtain structural behaviour and performance of scaled model which representing the full-scaled structures.

Table 1: Similitude relations for elastic model [10]

Parameter	Scale Factor	Parameter	Scale Factor
Dimension	S	Uniform distributed load (P_p)	S_e
(h_p = Height or t_p = Thickness)		Shear force (V_p)	S_eS^2
Area (A_p)	S^2	Moment (M) or Torque (T)	S_eS^2
Volume (V_p)	S^3	Stress (σ_p)	S_e
Linear displacement (U_p)	S	Velocity (V)	$S^{1/2}$
Moment of inertia (I_p)	S^4	Acceleration (a)	S_a or $S/S=1$
Frequency (f)	$S^{-1/2}$ or $(S/S_a)^{-1/2}$	Curvature (C)	$1/S$
Time (t)	$(S/S_a)^{1/2}$	Mass (M)	S_eS^2/S_a
Density (ρ_p)	S_e/S_aS	Stiffness (K)	S_eS
Point load (F_p)	S_eS^2	Spectral Acceleration (S_A)	$S_eS^2/ (S_eS^2/S_a)$
Line load (F_L)	S_eS		

1.2 Rubber Damping System

Rubber was chosen because of its ease of installation, energy storage capacity and ability to convert energy to heat when it is deflected. The elastic hysteresis properties of rubber provide energy dissipation and damping when a system is subjected to vibrational forces [11]. In this study, two types of rubber with different hardness shown in Figure 2 were tested. The effectiveness of xy-plane horizontal damper was discussed for two column models with rubber layer and a column model with rubber block. The structures with horizontal damping system can be possible as an alternative way than base isolation. Maintenance and ease of installation of damper horizontally on structures is much better than base isolation [12].

(a) Soft Rubber (b) Hard Rubber

Figure 2. Soft and hard rubber cylinder specimens.

As the vibration isolator in the system, the properties of rubber are important to be determined in detail. According to the standards and specifications on seismic isolator [13-15], two parameters of shear modulus, G and damping ratio, ζ are calculating from the hysteretic stress-strain diagram which obtained by testing the rubber specimen under cyclic shear loading. The shear modulus, G is defined as slope of the straight line connecting the points at the maximum shear strain in either direction,

$$G = \frac{\tau_1 - \tau_2}{2\gamma_a} \tag{1}$$

where γ_a is the shear strain amplitude. The equivalent damping ratio,

$$\zeta = \frac{EDC}{2\pi\, G\, {\gamma_a}^2} \tag{2}$$

where energy dissipated per cycle (EDC) is the area of the hysteresis loop [16].

2. Methodology

Structural specifications of 1:5 down scaled IBS column components are shown in Figure 3 [17]. Square blocks, rectangular blocks, T-blocks (small), T-blocks (big), L-blocks (small) and L-blocks (big) were used and assembled to construct a complete IBS column. The complete formation of a total 28 blocks formed a column with 780mm height and 240mm width as shown in Figure 3. There were four L-shape blocks placed on top of the column and four T-blocks were placed at the bottom of column.

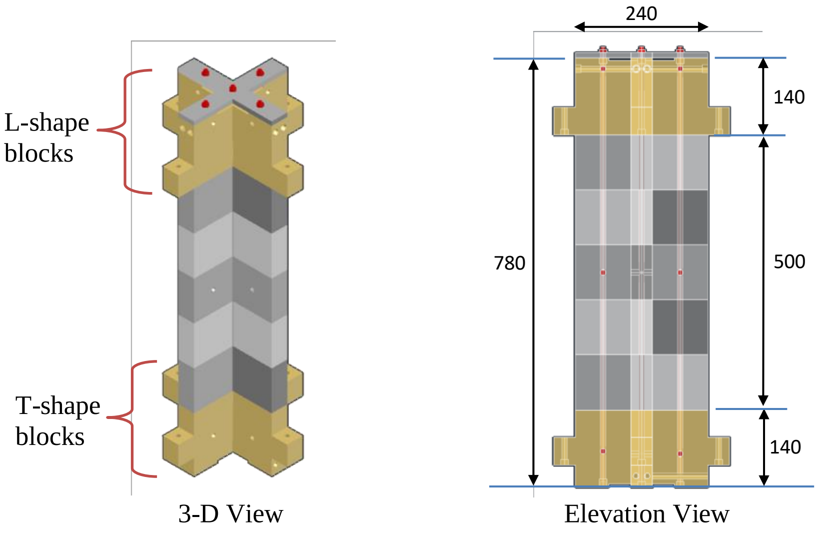
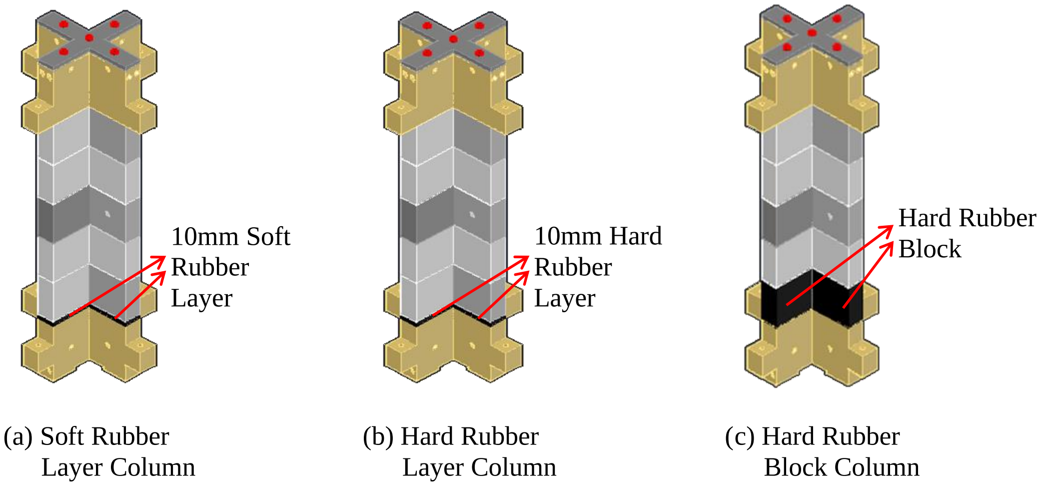


Figure 3. IBS block formation column in 3d view and elevation view.

2.1 Column Models Specifications

Three column models were built and tested in laboratory. The first and second column models were using rubber layer with 10mm thickness as xy-plane horizontal dampers. The rubber material used for the first model was the soft rubber type which is called Soft Rubber Layer Column, while hard rubber type was used for the second model which is called Hard Rubber Layer Column. The rubber layers were placed on the T-shape blocks and then the other concrete blocks were assembled on it. For the third model of column, the hard rubber dampers were applied in the mode of replacing the second bottom concrete blocks level with rubber block, which is called Hard Rubber Block Column. Figure 4 shows three column models with soft rubber layer, hard rubber layer and hard rubber block.



(a) Soft Rubber Layer Column
(b) Hard Rubber Layer Column
(c) Hard Rubber Block Column

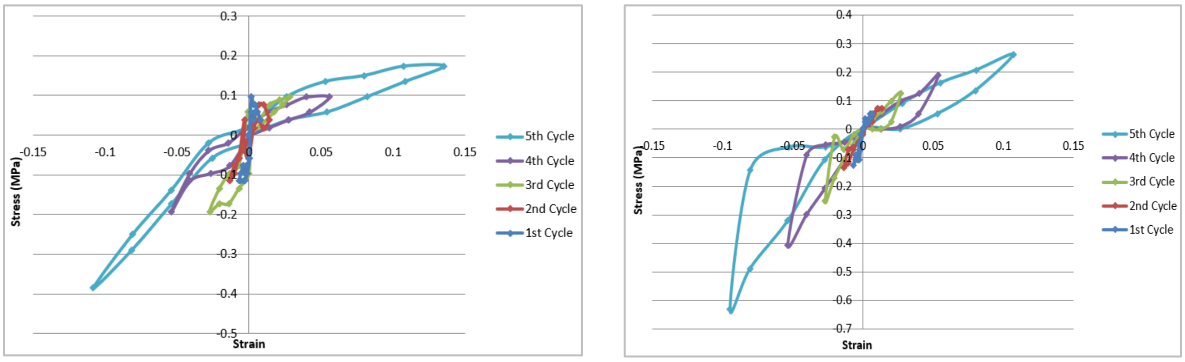
Figure 4. Three IBS column models with different damping system application.

2.2 Concrete Properties

Concrete grade C30 was used to cast all the reinforced concrete blocks. The concrete properties were obtained by conducting several material tests. Through compression test, the concrete strength for concrete mix at age 7 days was 22.43 N/mm², while the concrete strength for concrete mix at age 28 days is 32.46 N/mm². The concrete mix was tested with E-value test and its modulus of elasticity was recorded as 31.128 GPa with Poisson's Ratio of 0.206. The tensile strength of concrete was 3.516 N/mm^2 through the tensile splitting test.

2.3 Rubber Properties

Rubber is known as a good vibration isolator for industrial and engineering applications. The key to isolating vibration is to reduce the transmission between the components or supporting the structure. In order to determine the damping properties for two types of rubber used in this study, two cylinder samples of rubber are tested. Both soft and hard rubbers were prepared in cylinder form of 35mm diameter with a height of 90mm. The rubber samples were placed on the testing frame which allows for the simultaneous application of a static compression load and a dynamic lateral load applied on it. The maximum stroke of ±8mm with its lateral load relatively were recorded. Figure 5 shows the hysteresis stress-strain curve for soft and hard rubbers.



(a) Soft Rubber (b) Hard Rubber

Figure 5. Hysteresis stress-strain curve for (a) soft rubber and (b) hard rubber.

From the hysteresis stress-strain diagram, the shear modulus, *G* and the equivalent damping ratio, ζ were then calculated and computed in Table 1 for each cycle by using Eq. (1) and (2). From the table, the value of shear modulus, *G* is decreasing for both specimens from cycle to cycle. This is because with the increasing of pressure, the rigidity of the specimen decreases. The soft rubber has smaller shear modulus compared with hard rubber, which indicates the soft rubber is more flexible and easier to deform with smaller force. With the increase in the number of cycles, the stiffness of rubber is decreasing. This phenomenon is known as Mullins Effect [18-19]. From Table 2, the damping ratio for soft rubber is decreasing started at the 2nd cycle of loading, while the damping ratio for hard rubber is increasing from cycle to cycle. This shows that the damping behaviour in the soft rubber is rapidly decay compared to the hard rubber.

Table 2. Assessment of shear modulus, *g* and damping ratio, ζ for soft and hard rubber specimens

Soft Rubber Specimen	**1st Cycle**	**2nd Cycle**	**3rd Cycle**	**4th Cycle**	**5th Cycle**
G (MPa)	10.28	5.62	5.19	2.64	2.29
ζ	0.007	0.118	0.096	0.079	0.048
Hard Rubber Specimen	**1st Cycle**	**2nd Cycle**	**3rd Cycle**	**4th Cycle**	**5th Cycle**
G (Mpa)	13.36	7.68	7.01	5.54	4.42
ζ	0.018	0.034	0.079	0.083	0.077

2.4 Time History Experimental Setup

The time history test on shaking table is a realistic and clear showing of the response of a structure during an earthquake. The size of shaking table that used for time history test is 0.6m width with 2m length. The shake table is capable to sweep in one axis up to 100mm horizontally. The column model was set up on the shaking table before the vibration started. Periodic waves and random transient waves which represent the earthquake motions can be chosen as input motion of the shaking table that controlled by computer. Random transient shaking is used as strong motions that can simulate actual situation during an earthquake. Sabah earthquake 2015 with the PGA of 0.126g was selected as the input signal of the shaking table which shown in Figure 6.

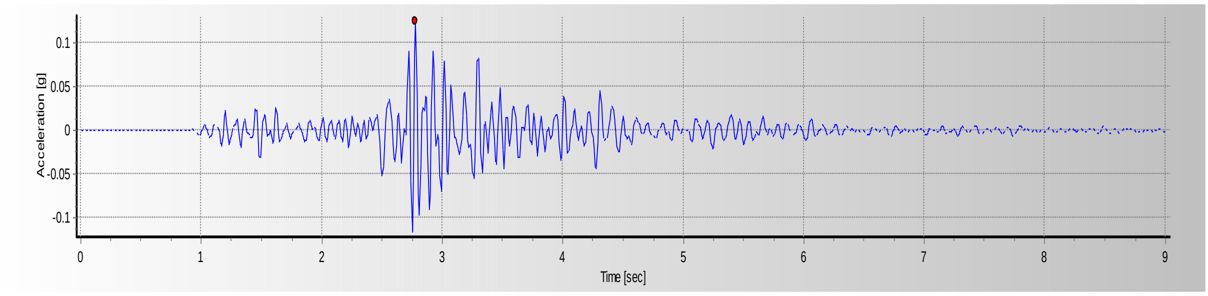


Figure 6. Seismic input signal PGA 0.126g.

Before the time history test started, the long steel bolts were inserted into the steel footing, and the footing were fixed properly on the shaking table. The bottom T-shape blocks were then inserted into the long bolts, followed by the rubber layer as shown in Figure 7 for soft rubber layer and Figure 8 for hard rubber layer. After inserting the rubber layer, the rest of concrete blocks were then continue assembled on the rubber layer according to its blocks arrangement to form a complete column system. From the Figures 7 and 8, the soft rubber layer was obviously squashed by the self-weight of column blocks above, while the hard rubber layer was still in shape. Figure 9 shows the setting up of third column model with hard rubber block.

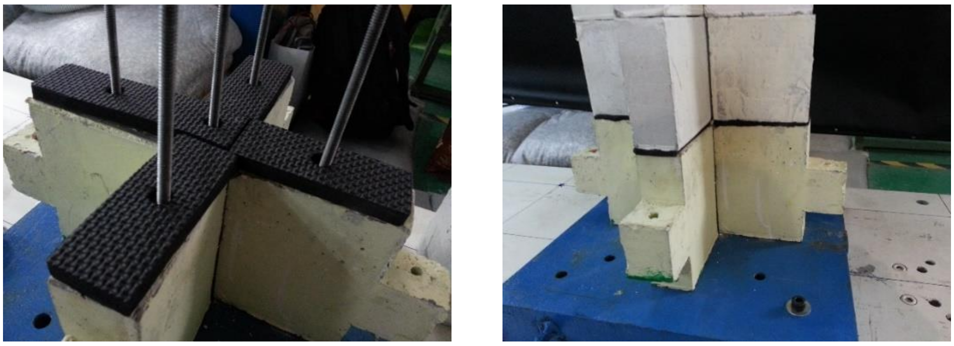


Figure 7. Setting up of soft rubber layer column on shaking table.

Figure 8. Setting up of hard rubber layer column on shaking table.

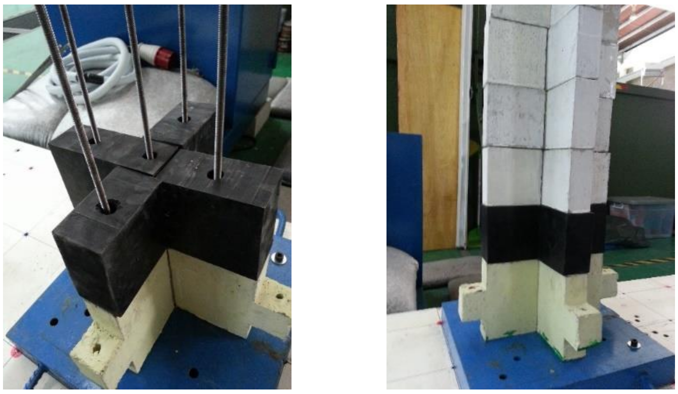


Figure 9. Setting up of hard rubber block column on shaking table.

During the time history test, a general purpose accelerometer sensor is required to record data of accelerations from the shaking table and from the different height of column. 3-axis self-recording digital accelerometers were used at the sample rates of 50 Hz. Accelerometers were attached on the column to observe amplification and resonance effects of the column along the test. From the data recorded by accelerometers, the time history of output acceleration and the time history of response displacement of the models were plotted. Figure 10 shows the experimental set up of column model on shake table for time history test. Accelerometers A1, A11, A2, A12 and A3 were sequentially attached to the target position from the bottom to the top of the column. The points A1, A2 and A3 are the position at the bottom T-block, middle and top L-block of column. While points A11 and A12 are the rectangular blocks that direct inserted to the middle bolts.

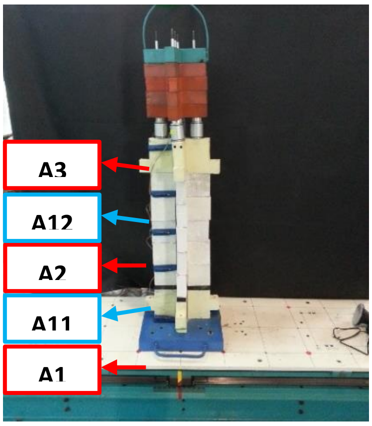


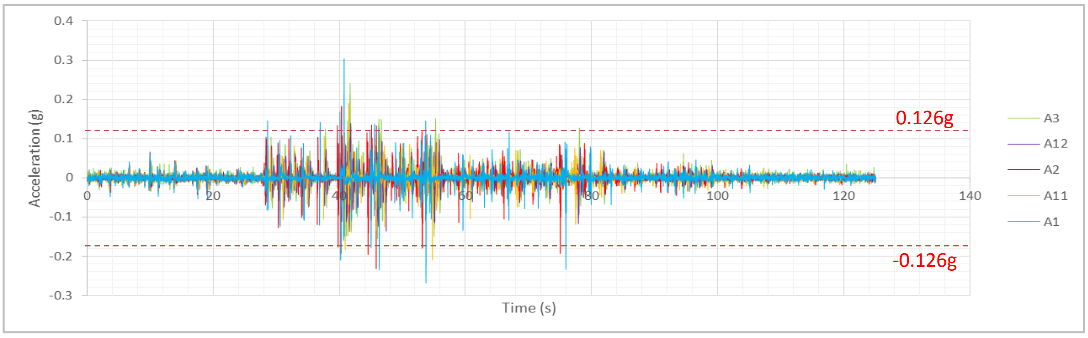
Figure 10. Experimental set up of column on shaking table.

3. Results and Discussion

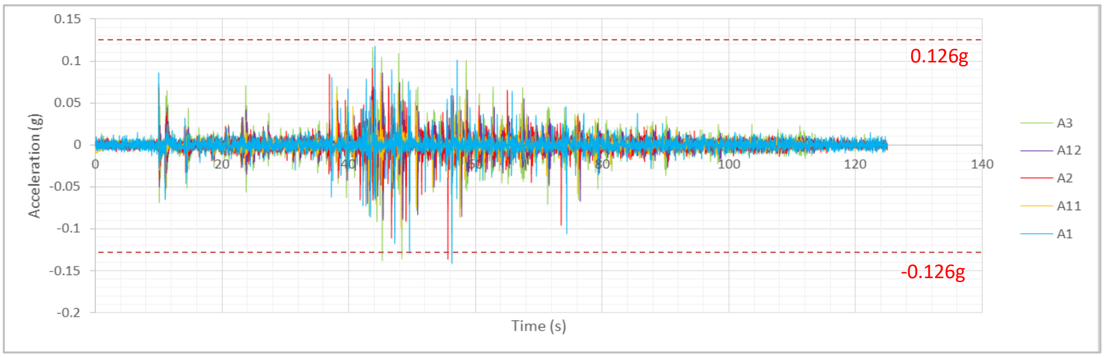
The material properties tests and time history test on column models were done to further evaluate the effectiveness of xy-plane horizontal dampers in the column system under earthquake excitation. The parameters such as acceleration, displacement and response spectra were obtained from the experimental results. The results are showing the changes of different parameters for the three tested column model types.

3.1 Time History Acceleration

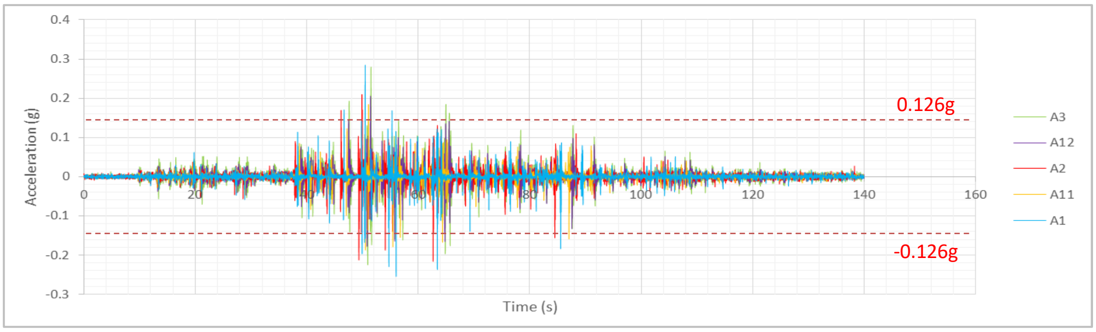
The PGA 0.126g was used as seismic input signal for the purpose of simulate the real time history of Sabah earthquake 2015. The recorded accelerations at the five positions of column were compiled in a same graph for showing the trend of the column model response to the seismic motion. The response of accelerations was plotted as Time History Acceleration Graph in Figure 11.



(a) Soft Rubber Layer Column



(b) Hard Rubber Layer Column



(c) Hard Rubber Block Column

Figure 11. Time History Acceleration of (a) Soft Rubber Layer Column, (b) Hard Rubber Layer Column, and (c) Hard Rubber Block Column

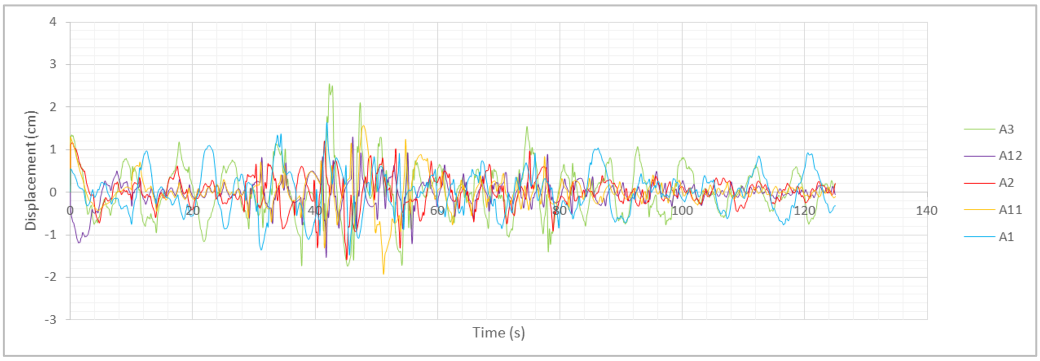
Values of the maximum acceleration with its corresponding time that acquired from time history graph are shown in Table 3. Based on the values, the seismic response of Hard Rubber Layer Column demonstrated smallest acceleration response in overall as compared to another two column models. The smaller acceleration response is due to the hard rubber layer has high resistance in seismic loading which reduce the oscillation of the whole column system. From Figure 11, it shows that the acceleration response of Soft Rubber Layer Column and Hard Rubber Block are similar. By comparing the values of maximum acceleration for the both column models, the Hard Rubber Block Column has smaller acceleration at the bottom level of A1 (-6%) and A11, however its acceleration values at position A2 (11%), A12 and A3 (15%) are getting larger compared to Soft Rubber Layer Column. Although the hard rubber has better damping properties than soft rubber, when the application is direct replacing the concrete block with rubber block, the stiffness of the whole column system has been reduced. This is because the density of hard rubber block which is 1750 kg/m^3 is lower than concrete block with designed density of 2380 kg/m^3.

Table 3. Time of maximum acceleration and maximum acceleration at targeted position of column models

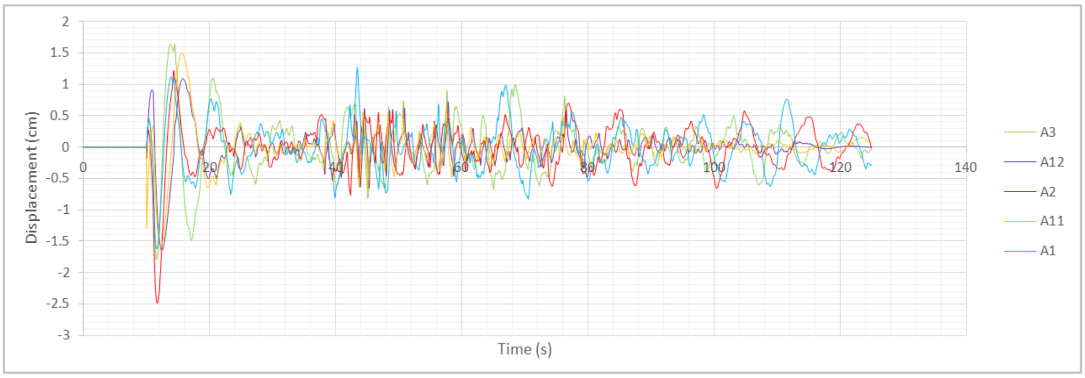
Column Model		**Accelerometer**				
		A1	**A11**	**A2**	**A12**	**A3**
Soft Rubber Layer	*Time (s)*	40.46	41.475	40.34	41.80	41.70
	Max Acceleration (g)	0.3018	0.1900	0.1826	0.1381	0.2386
Hard Rubber Layer	*Time (s)*	44.14	45.05	43.72	45.325	43.78
	Max Acceleration (g)	0.1165	0.0861	0.0906	0.0858	0.1165
Hard Rubber Block	*Time (s)*	50.48	51.075	49.90	51.45	51.52
	Max Acceleration (g)	0.2841	0.1838	0.2051	0.2050	0.2799

3.2 Time History Displacement

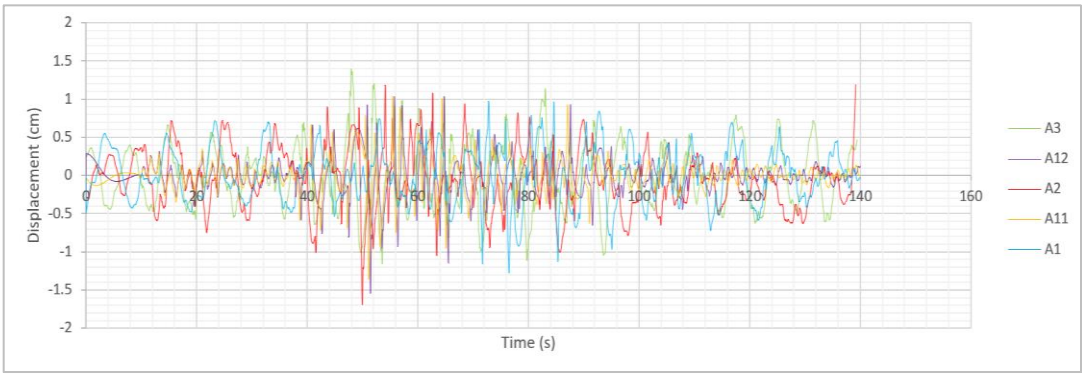
From the data recorded by accelerometers, the values of displacement were computed and plotted for each three column models at all the five targeted positions. Figure 12 illustrates the Time History Displacement Graph and the maximum displacements of the three column models are computed in Table 4. By comparing the oscillation motion at point A1 and A3, it is seen that the Hard Rubber Layer Column has the smallest displacement difference between the top and bottom of column. This demonstrate the seismic stability of the damped column under the time history test. The oscillation displacement at the top of Soft Rubber Layer Column (A3) is 58% larger compared to the base oscillation (A1). The soft rubber layer seems to be fully compressed like undamped column system, hence the oscillation motion at A3 is large. For Hard Rubber Block Column, the displacement value at A3 is 37% larger than the value at A1.



(a) Soft Rubber Layer Column



(b) Hard Rubber Layer Column



(c) Hard Rubber Block Column

Figure 12. Time history acceleration of (a) soft rubber layer column, (b) hard rubber layer column, and (c) hard rubber block column

Table 4. Maximum displacement at targeted position of column models

Column Model	Displacement (mm)				
	A1	**A11**	**A2**	**A12**	**A3**
Soft Rubber Layer	16.10	15.67	12.05	12.94	25.50
Hard Rubber Layer	9.83	6.49	6.92	7.20	9.85
Hard Rubber Block	15.26	10.35	11.82	10.32	20.88

3.3 Response Spectra

Figure 13 shows the acceleration response spectra of three column models with a damping of 5%. In accordance with International Building Code (IBC) and Eurocode 8 standard, the 5% of damping ratio is nominal and assumed to be critical damping.

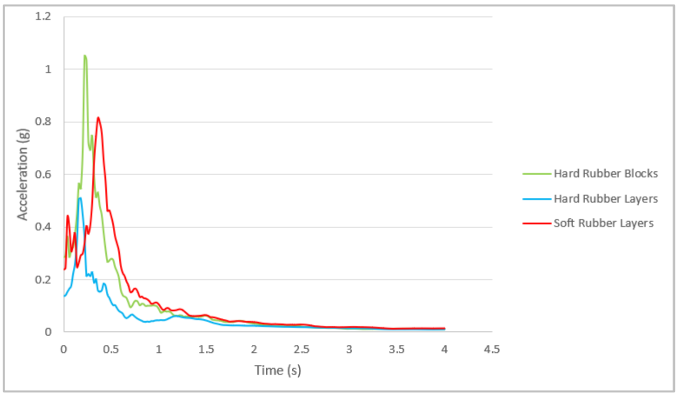


Figure 13. Acceleration response spectra of three column models with 5% damping.

4. Conclusions

This study investigates the effect of xy-plane horizontal dampers on the structural behaviour of a column system under an earthquake event. Time history test in obtaining the dynamic properties such as elastic hysteresis, acceleration, displacement and response spectra was accomplished. Based on the observation of the results, it can be concluded that the hard rubber has better damping properties than soft rubber. The column models with hard rubber dampers give a higher resistance toward seismic load. It reduces the oscillation motion and has a more stable displacement response.

The Hard Rubber Block Column indicates the different application of rubber damper in the column system. However, rubber block dampers increase the flexibility of the column and roof displacement, as a result the stiffness of column system is reduced. Hence, for a system to withstand the loads while it is damped, the stiffness and damping in a vibratory system need to be well-tuned.

From the plot of acceleration response spectra, it can be summarised that the Hard Rubber Layer Column showed the most suitable damping system among the three tested column models. This study also indicates xy-plane horizontal rubber dampers can be an effective vibration isolator.

Acknowledgement

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