

Shake Table Test of Scaled Masonry Structure Using Rubber Tire Crumbs Mortar

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Abstract The existence of masonry walls in structures is very useful in increasing the structure's resistance to lateral loads. The role of the walls is more important in providing adequate stiffness and damping than in resisting axial forces. The use of rubber tire crumbs (RTC) mortar on masonry walls is to increase the ductility and damping capacity of the wall. This study examines the application of RTC mortar on masonry walls, in particular for increasing the damping ratio of the wall. This study aims to determine the optimum RTC content in mortar by observing its dynamic properties using the shake table test. The specimens were 4 scaled models with mortar containing 10%, 20%, 30%, and 40% RTC. The prototype is a 3D half-brick wall 2.5 m high and a 2.5 x 2.5 m² plane, with a scale of 2 to provide a miniature model. There are 2 types of loads, namely sinusoidal loads and Yogya earthquake loads. The sinusoidal load has an amplitude of 0.1 g with a frequency range between 4 Hz and 20 Hz, while the Yogya earthquake load has an amplitude between 0.1 g and 0.9 g. The results showed that the use of RTC mortar on the masonry wall structures can increase the damping capacity of the walls and reduce the drift ratio. This study recommends that the optimum RTC content is 30% of the sand volume.

Keywords Masonry Wall, Rubber Tire Crumbs, Mortar Joint, Damping Capacity, Drift Ratio

1. Introduction

A reinforced concrete masonry wall is a very popular structure among people in different countries, because it is easy to build, has qualified strength, and is available at a low price. However, masonry wall structures have brittle nature and low deflection ability [1]. Masonry infill walls have a very significant role in increasing the lateral resistance and in delaying the failure of the structure [2]. When an earthquake occurs, the masonry infill wall will affect the strength and stiffness of the structural frame. The walls interact with the surrounding frame, absorb energy, modify the distribution of internal forces, and contribute to the overall building resistance [3,4]. The addition of the walls can increase the stiffness of the structure up to 3 times and reduce the drift ratio and fundamental period of the structure. In addition, the walls also increase the base shear capacity of the structure by up to 100% [5].

The role of the walls in increasing structural resistance is more significant in resisting lateral forces than axial forces. The walls play a mechanism in increasing the stiffness and in providing a damping effect due to friction between walls and frames, or within wall constituent materials. Therefore, exploitation towards the damping ability of the wall can be made to increase its lateral capability, while its strength can be taken to a minimum. Damping is one of the dynamic structural characteristics that is very influential in preventing earthquake damage [6]. The damping ability of masonry structures can be increased by using a high damping brick unit or mortar, because the strength and

stiffness of masonry walls are a combination of the specific properties of brick unit and mortar [7].

Previous studies have shown that the addition of rubber tire crumbs (RTC) in mortar/concrete can increase its damping ability, but its mechanical strength decreases [8–13]. Rubber tires in the form of crumbs are added to mortar/concrete as a substitute for sand at a certain content. This finding inspires this research, which applies RTC mortar on masonry walls, in order to increase the damping ability of the walls. Although using RTC in mortar can decrease their compressive strength, but it increases its damping. On the other hand, the compressive strength of masonry walls is determined by the mortar but it is limited by the brick unit, so the use of too stronger mortar is not useful [14].

This study applies RTC mortar in masonry walls to optimize the damping ability of the wall at optimum RTC content but it still meets the compressive strength requirements. The Indonesia Public Works Department [15] requires the compressive strength of mortar for masonry to be at least 3 MPa. Some previous studies found that RTC mortar with a compressive strength of more than 3 MPa, required the RTC content less than 40% of the sand volume [13,16], because the higher the RTC content, the weaker the bond between RTC and the cement matrix [17].

This study observes the dynamic properties of the in-plane masonry wall using a shake table with sinusoidal or earthquakes vibration time history. Due to the limited size of the shake table, the specimen is scaled.

the similarity requirement with the prototype structure. Structural model calculations follow Buckingham's Pi Theorem which says that any homogeneous dimensional equation involving a particular physical variable can be reduced to an equivalent equation involving a complete set of dimensionless products. This study uses the geometric scale (S_L) and the material scale (S_E) are 2:1 and 1:1 respectively. The scale factor is taken from the scale factor provisions for the earthquake response model, as shown in Table 1 [18].

2.2. Materials

The masonry walls are composed of clay brick units and mortar joints. Since the modeling geometric scale (S_L) is 2, the scaled clay brick has dimensions of 110 x 55 x 35 (mm) as shown in Figure 1. In this study, the scaled clay brick was made by a manufacturer in the Godean area of the Sleman region (see Figure 2). Before being used, red bricks are tested for strength in the laboratory (Figure 3).

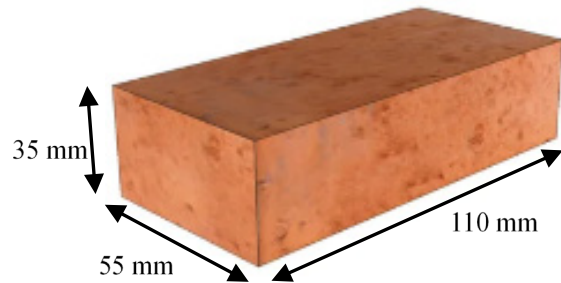


Figure 1. The scaled clay brick

2. Specimens and Materials

2.1. Similarity Requirement

Table 1. The scale factor for the earthquake response model [18]

Groups	Variable	Dimension	Scale factor
Loads	Force (Q)	F	$S_E \cdot S_L^2$
	Stress (q)	FL^{-2}	S_E
	Acceleration (a)	LT^{-2}	1
	Gravity (g)	LT^{-2}	1
	Velocity (v)	LT^{-1}	$S_L^{1/2}$
	Time (t)	T	$S_L^{1/2}$
Geometry	Dimension (l)	L	S_L
	Displacement (δ)	L	S_L
	Frequency (ω)	T^{-1}	$S_L^{-1/2}$
Materials	Modulus (E)	FL^{-2}	S_E
	Strength (σ)	FL^{-2}	S_E
	Strain (ϵ)	-	1
	Poison's ratio (ν)	-	1
	Density (ρ)	$F^{-4}T^2$	-
	Energy (EN)	FL	$S_E \cdot S_L^3$

The specimen in this study is a 3D model of a masonry wall which is assumed as an adequate model that meets



Figure 2. Scaled clay brick production process



Figure 3. The specimens of scaled clay brick strength test

The mortar used is RTC mortar with 10%, 20%, 30%, and 40% RTC contents. To determine the strength and modulus of elasticity of the RTC mortar, laboratory tests were carried out on a cylindrical sample with a diameter of 10 cm and a height of 20 cm. The RTC used is shaped like a fiber that passes through a #4 sieve (4.75 mm) (see Figure 4).

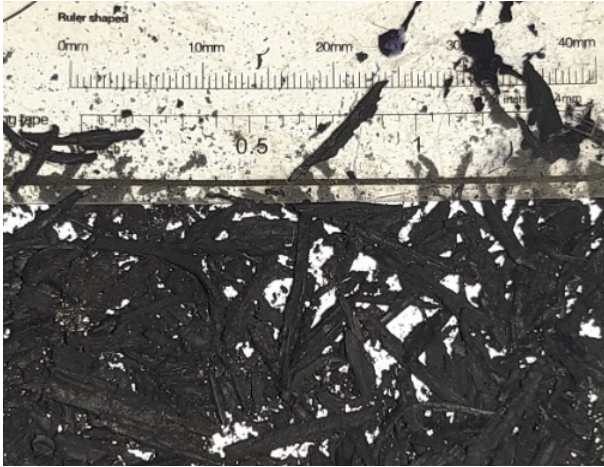


Figure 4. The RTC that passes through a #4 sieve



Figure 5. The specimens of concrete and RTC mortar strength test

Reinforced concrete frame is made with D8 rebar, D6 stirrups, and 24 MPa (f_c) of concrete strength, 12 ± 2 cm of concrete slump, and 0.53 of w/c ratio [19]. Concrete samples were tested in the laboratory using cylindrical samples to obtain their strength and modulus of elasticity. The specimens for the strength test of concrete and RTC mortar are shown in Figure 5. The properties of all materials from laboratory tests are shown in Table 2.

Table 2. The properties of materials

Material	Properties		
	Density (kg/m^3)	Compressive strength (MPa)	Modulus of Elasticity (MPa)
Concrete	2253.47	28.86	25249.11
RTC mortar 10%	1961.29	8.86	691.34
RTC mortar 20%	1815.03	7.20	560.04
RTC mortar 30%	1721.10	8.11	566.38
RTC mortar 40%	1630.08	5.09	430.96
D8 rebar	7857.57	517.72	194705.47
D6 stirrups	7852.85	520.51	216121.60
Scaled clay brick	1475.26	4.93	-

2.3. Prototype and Model

The prototype is assumed to be part of a 3D masonry wall of building with reinforced concrete frame to follow the Technical Guidelines for Earthquake Resistant Houses and Buildings [15]. The prototype is a 3D half-brick wall 2.5 m high and a 2.5×2.5 m² plane, with a scale of 2 to provide a miniature model. Therefore, the scaled model has 1.25 m high and a 1.25×1.25 m² plane (see Figure 6). The design specification of the prototype and the scaled models are presented in Table 3. The prototype specifications are determined based on the specifications for simple house construction in Indonesia [20], then scaled into model specifications.

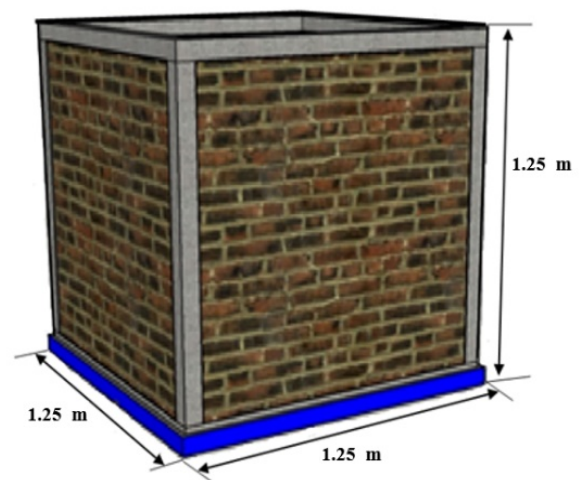


Figure 6. The design of 3D scaled model

Table 3. The design of specification of prototype and scaled model

Dimension variable	Unit	Prototype	Scaled Model
Column	mm	150x150	75x75
Beam	mm	150x150	75x75
Sloof	mm	150x200	75x100
Mortar thickness	mm	20	10
Concrete covers	mm	20	10
Diameter of rebar	mm	12	8
Diameter of stirrups	mm	8	6
Spacing between stirrup	mm	150	75

Four scale models were prepared in this study and were coded by M10, M20, M30, and M40, meaning for mortar with 10%, 20%, 30% and 40% of the volume of sand, respectively. These models don't consider the weight of the roof, wall openings, and plastering. Figures 7 and 8 show the process of reinforcement and wall construction.



Figure 7. The process of reinforcement



Figure 8. The process of wall construction

Furthermore, numerical modeling was also carried out using SAP2000 software to predict the natural frequencies and weights of the prototype and model. Then, the additional mass on the model can be predicted to meet the similarity requirements. The wall is modeled with a shell-thin type with fixed restraints on the column supports and at each joint meshing (Figure 9).

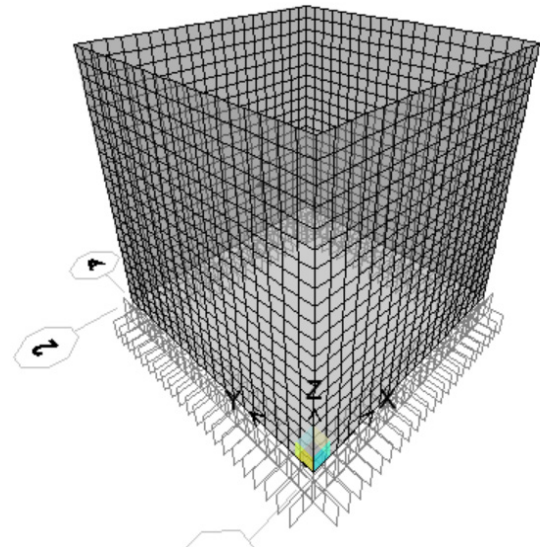


Figure 9. Prototype modeling using SAP2000 software

The natural frequency and weight of the prototype and scaled model from numerical modeling using SAP2000 are shown in Table 4. Based on the similarity requirements, the weight of model should be $\frac{1}{4}$ times of prototype and the natural frequency of model should be $\sqrt{2}$ times the prototype. Therefore, it is needed to give additional mass to meet the similarity requirements. In this study, the additional mass was determined to be 822 kg.

Table 4. The result of numerical modeling using SAP2000

Code	Weight (kg)		Natural frequency (Hz)	
	Prototype	Model	Prototype	Model
M10	6070.8	694.0	11.1	22.3
M20	5870.8	669.0	10.5	19.6
M30	5926.8	676.0	10.4	21.0
M40	5518.8	625.0	9.8	18.3

3. Testing Method

3.1. Experimental Setup

The 3D scale model is placed on the shake table and evenly clamped to the table area using bolts. The accelerometer sensor is mounted at the top and bottom positions to measure the movement of the in-plane wall, as shown in Figure 10. The accelerometer sensor is connected to the dynamic data acquisition application (Dewe-43) and the Dewe software installed in the computer, is elaborated to record acceleration in both the time and frequency domains. Then, the acceleration data can be converted into velocity and displacement through multiple integration processes, in order to analyze the natural frequency, drift ratio, and damping.

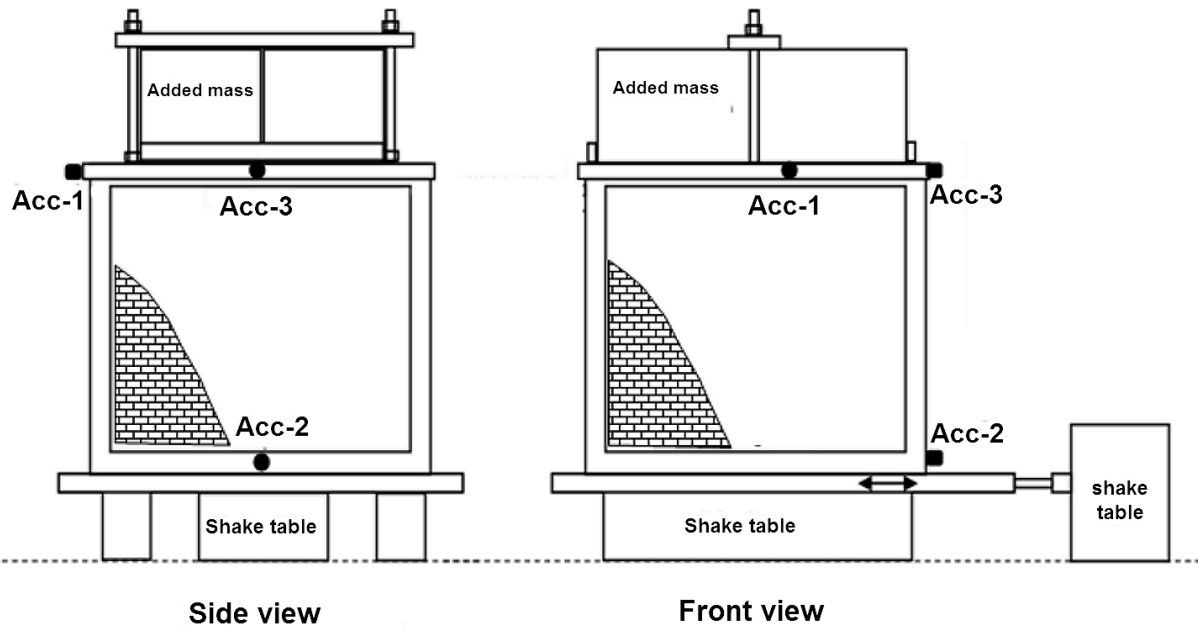


Figure 10. Experimental setup

3.2. Loading System

Two loading types are used in this test, namely a sinusoidal load (Figure 11) and a Yogya earthquake load (Figure 12). The sinusoidal load has an amplitude of 0.1g and a frequency of 4 to 20 Hz with 2 Hz intervals. The Yogya earthquake load refers to the time history published by Elnashai [20] whose amplitude is normalized to 0.1 to 0.9 g with 0.1 g intervals. The sinusoidal load aims to examine the resonance effect, while the Yogya earthquake load aims to investigate the response of the structure due to real earthquake amplitude. The loading stages follow the flow chart as shown in Figure 13. Each model is loaded with 18 stages, namely 9 stages of sinusoidal load (Sin 4Hz to Sin 20Hz), and 9 stages of Yogya earthquake load (Yg 0.1g to Yg 0.9g). In addition, the natural frequency (NF) and damping ratio (DR) are also checked after each load stage.

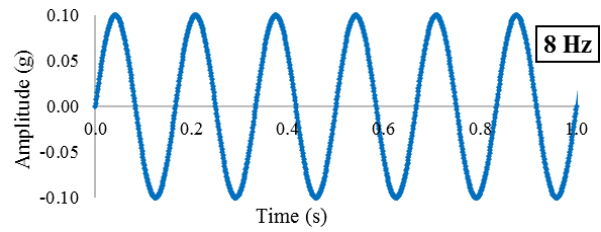


Figure 11. The sinusoidal loads of 6 Hz

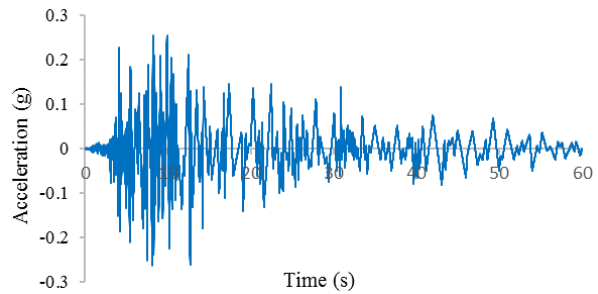
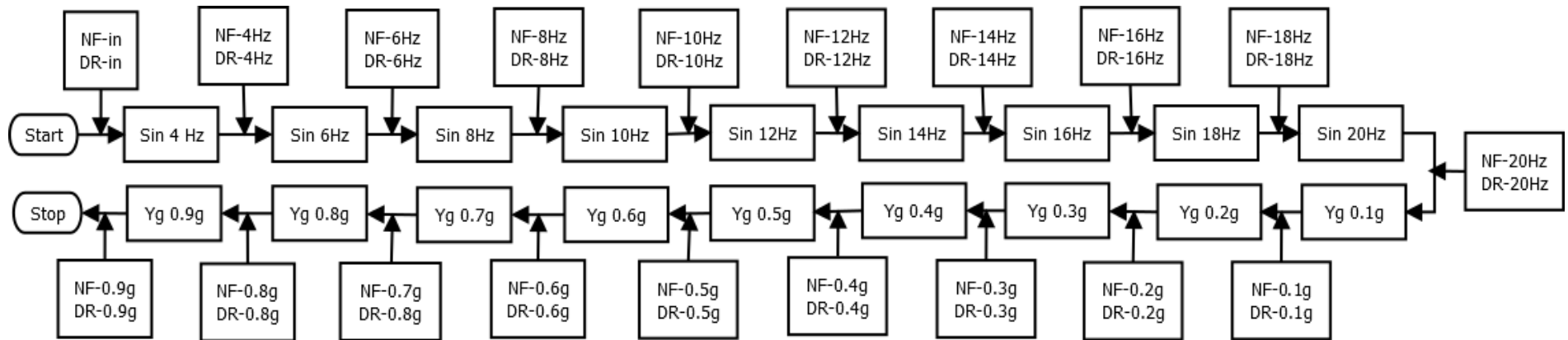


Figure 12. The Yogya earthquake loads [21]



Descriptions: NF-in is an initial natural frequency, DR-in is an initial damping ratio, NF is a natural frequency, DR is a damping ratio, Sin is a sinusoidal load, and Yg is a Yg earthquake load.

Figure 13. The loading stages

4. Result and Discussion

4.1. The Natural Frequency and Weight of the Model

After 28 days from casting, the weight and natural frequency of the model were experimentally examined as shown in Figure 14. Natural frequencies and weights of the model obtained from experimental tests (Table 5) have almost the same as the results of numerical modeling (Table 4).

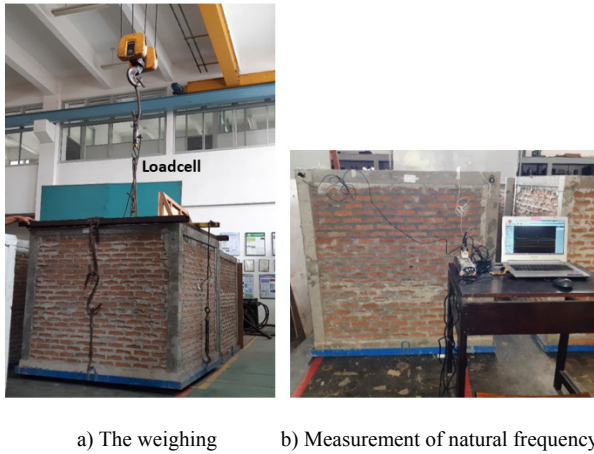


Figure 14. The examination of weight and natural frequency of model

Table 5. The properties of model from experimental tests

Model	Weight (kg)	Natural frequency (Hz)
M10	694.0	22.3
M20	669.0	18,2
M30	676.0	20.7
M40	625.0	17.9

In this study, it was found that the natural frequency of M10 to M20 decreased and then increased for M30 and again decreased for M40. Based on previous studies which found that the higher the RTC content would result in a decrease in the natural frequency [10,13], there was an inconsistency in the M20 results. The M20's natural frequency should be higher than the M30's natural frequency, but the result is the opposite. This can be explained by Figure 15. The trend according to the previous study is shown by the dotted line, so it can be seen that the natural frequency of M20 should be higher than M30.

The low natural frequency of M20 is thought to be caused by the compressive strength and modulus of elasticity of the 20% RTC mortar which is lower than the 30% (see Table 2). This results in low stiffness and also low natural frequencies of M20. This phenomenon is an experimental result, so it can be caused by technical aspects, such as weighing, mixing, and so on.

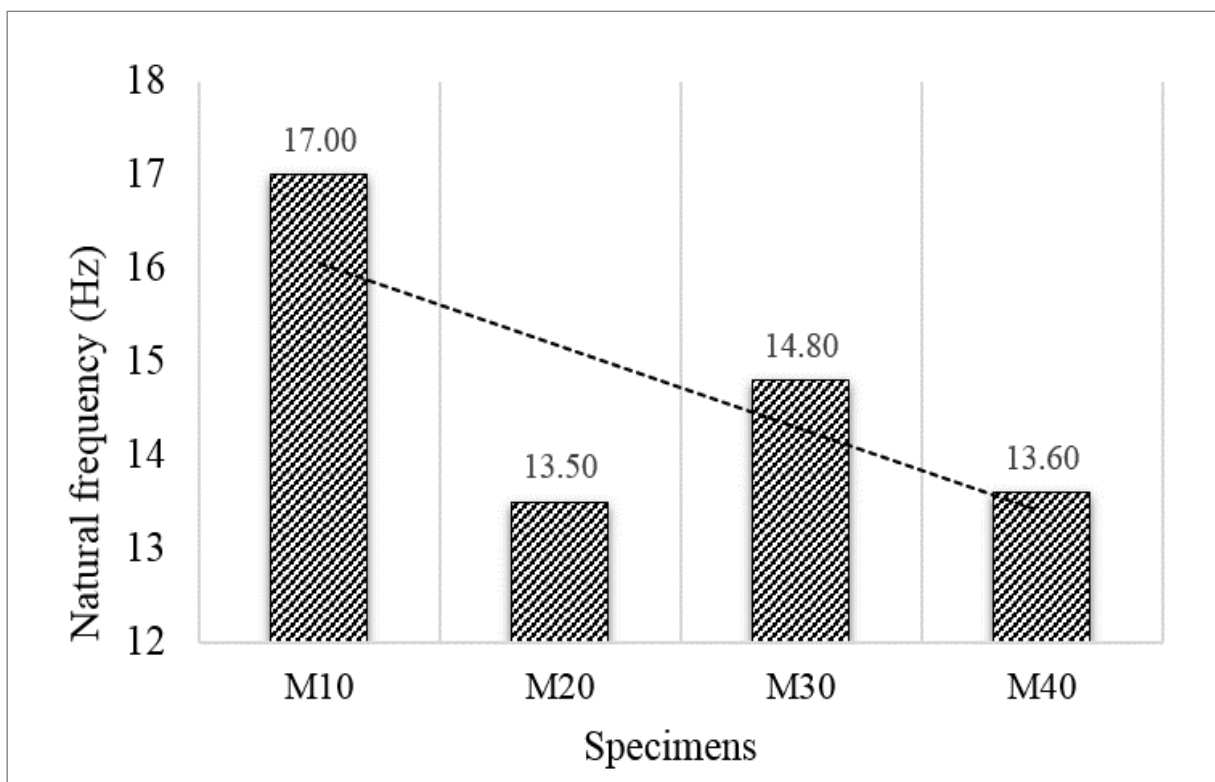


Figure 15. The trend of natural frequency of models

Furthermore, the model is placed on a shake table and mass 822 kg is added, as shown in Figure 16. In this condition, the model is ready to be tested using sinusoidal and earthquake loading. The natural frequency measurements are also carried out before starting loading and during loading. The results are presented in Figure 17 - 19.

Figure 17 shows that the higher the RTC content in the mortar, the lower the natural frequency of the wall. The lower natural frequency can be caused by the elastic effect of rubber that reduces the wall stiffness and so does the natural frequency of the wall.

Along with change of frequency loading, there was no significant decrease in natural frequency either using sinusoidal or Yogya earthquake loading (Figure 18 and 19), except at first change of frequency. It indicates that the model does not experience significant changes in stiffness nor a decrease in structural performance after loading. The decrease in natural frequency is proportional to the occurrence of cracks in the structure and is a

function of the location of the crack, the depth of the crack, and the number of modes [22]. This means that all models can provide better homogeneity of the wall with change of frequency loading.



Figure 16. The model on the shake table (ready to be tested)

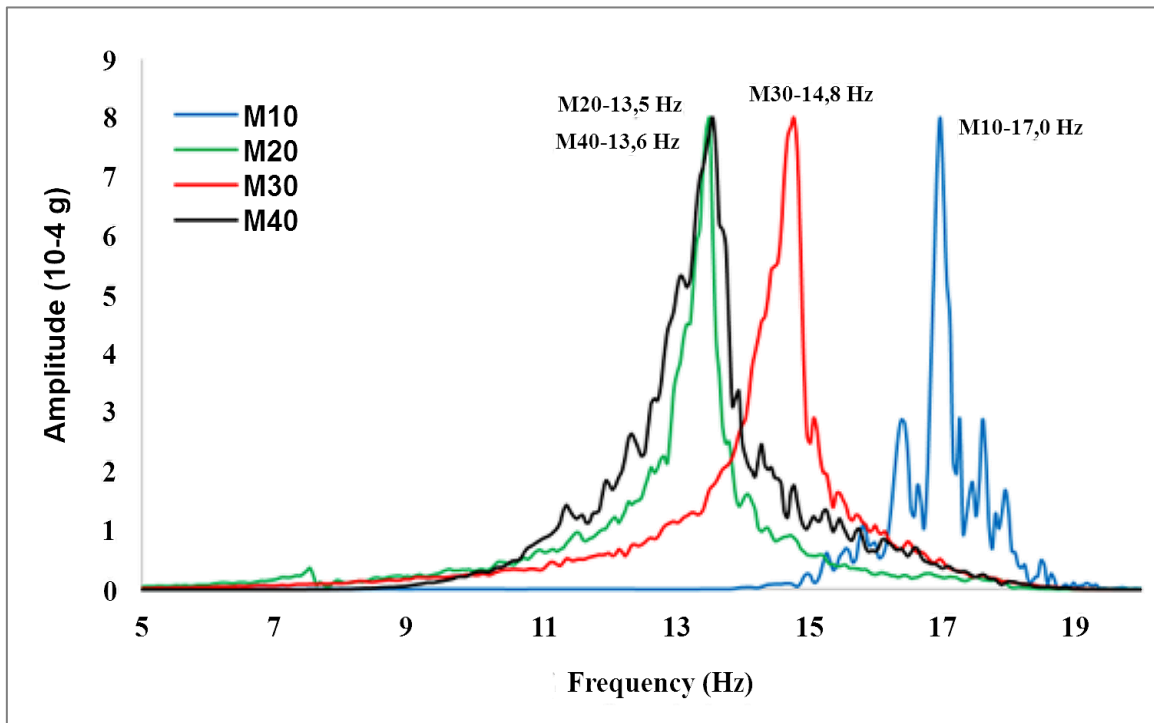


Figure 17. Natural frequency of model before starting loading

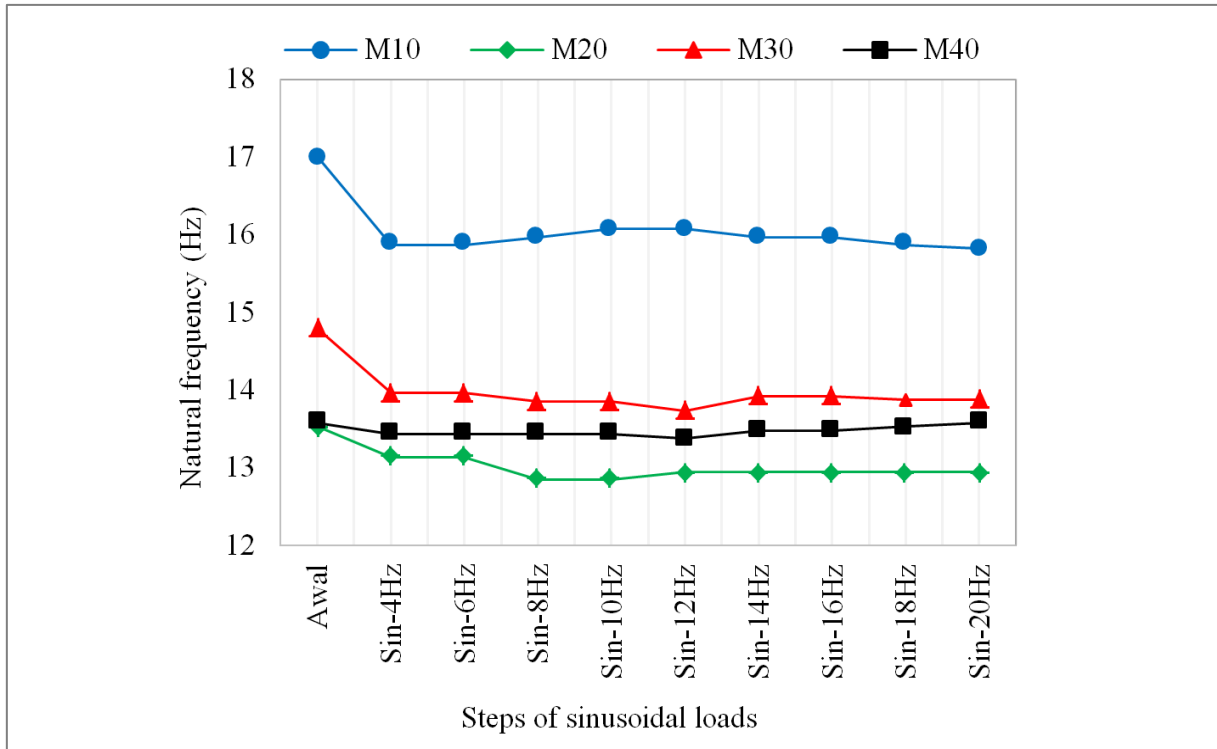


Figure 18. Natural frequency of model during sinusoidal loading

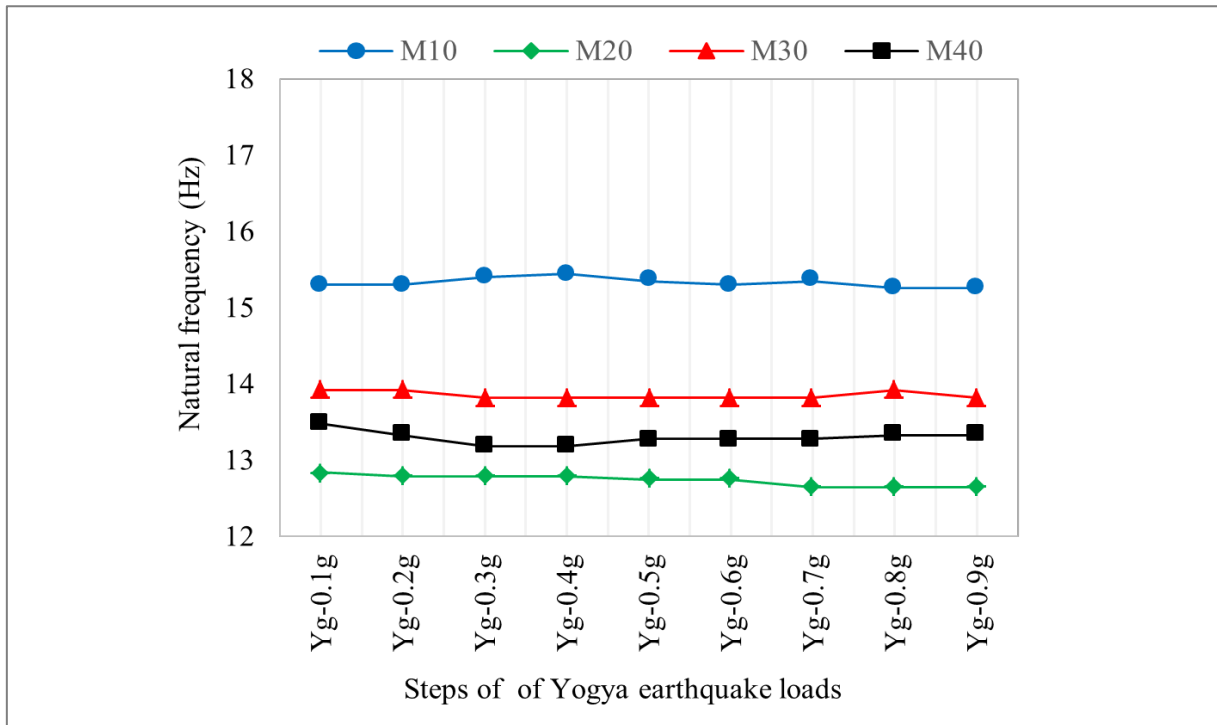


Figure 19. Natural frequency of model during earthquake loading

4.2. Drift Ratio

The drift ratio can be calculated by dividing the difference between the top and bottom displacements of the wall, by the height of the wall. Figures 20 and 21 show the drift ratio of the in-plane wall due to sinusoidal and Yogy

earthquakes loads.

Figure 20 shows that the drift ratio of the wall increases significantly when the sinusoidal load frequency is closer to the natural frequency of the wall. From these observations, it can be concluded that the significant increase in the drift ratio is caused by the resonance effect

where resonance produces amplification [23].

Meanwhile, the drift ratio due to the Yogya earthquake load shows an increase only if the loading amplitude is increased (Figure 21). M30 shows the most stable drift ratio behavior, during the Yogya earthquake loading. However, another model experienced a significant increase in the drift ratio after 0.6 g of the Yogya earthquake loading

amplitude. This shows that at an amplitude of 0.6 g, the magnitude of the Yogya earthquake is able to reduce the friction between the RTC and the cement matrix or loss of friction occurs. The loss of friction can result in a higher drift ratio. From this observation, it seems that 30% is the RTC optimum content.

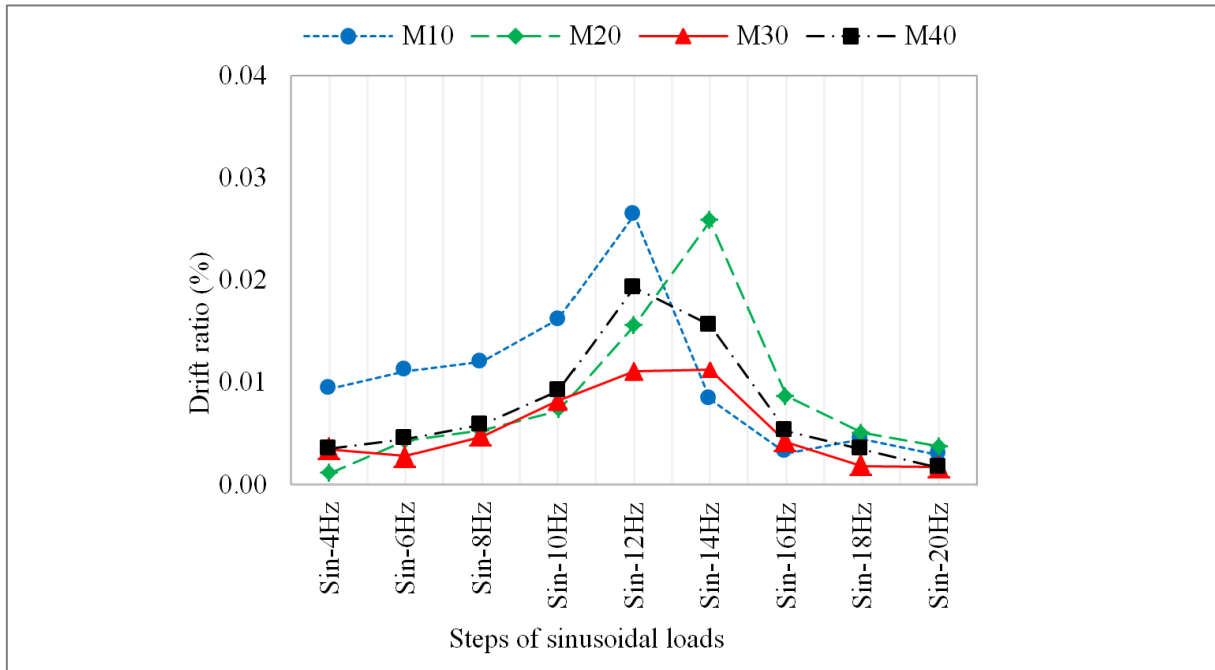


Figure 20. Drift ratio of in-plane wall during sinusoidal loading

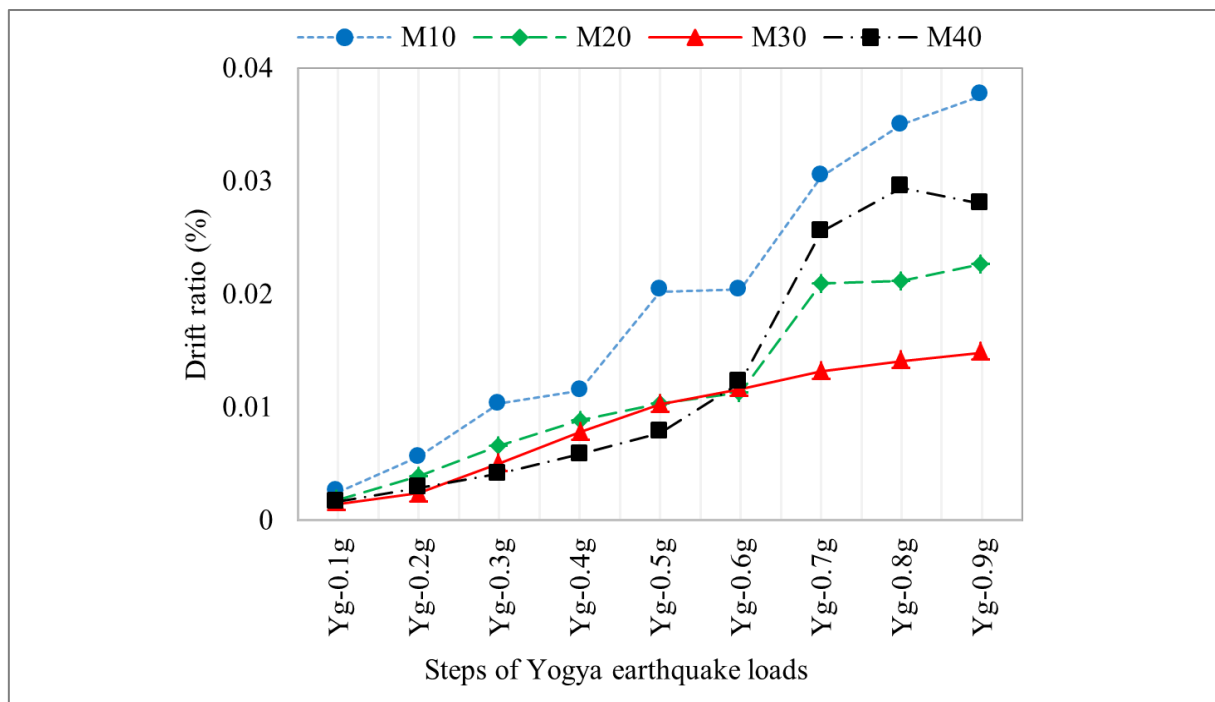


Figure 21. Drift ratio of in-plane wall during Yogya earthquake loading.

4.3. Damping Ratio

The in-plane wall damping ratio was measured at each loading stage, and the results are shown in two parts; that are due to a sinusoidal load as in Figure 22, and due to the Yogya earthquake load as in Figure 23.

The damping ratio of the M30 shows the effective one

compared to other models (see Figures 22 and 23). The M30 has a relatively higher damping ratio than other models and be able to maintain a drift ratio. This shows that M30 has a better interfacial lock mechanism that reduces excitation energy so that the deviations due to sinusoidal loads or earthquake loads become relatively smaller.

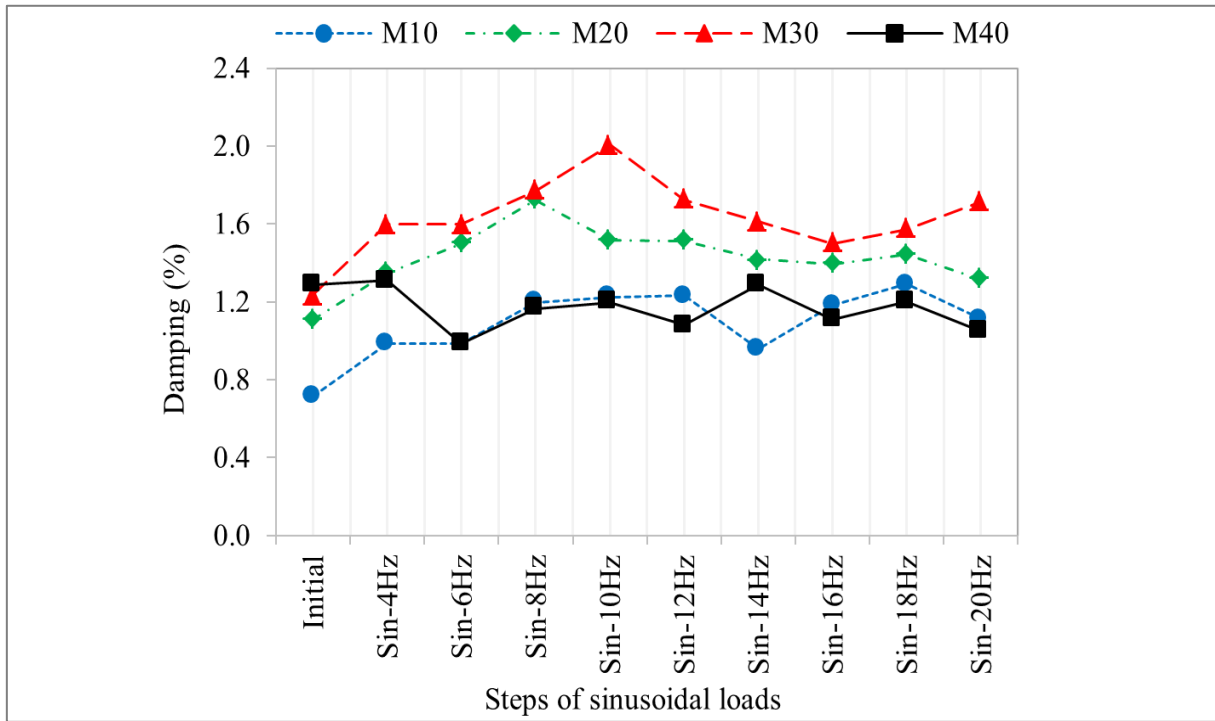


Figure 22. Damping ratio of the wall during sinusoidal loading

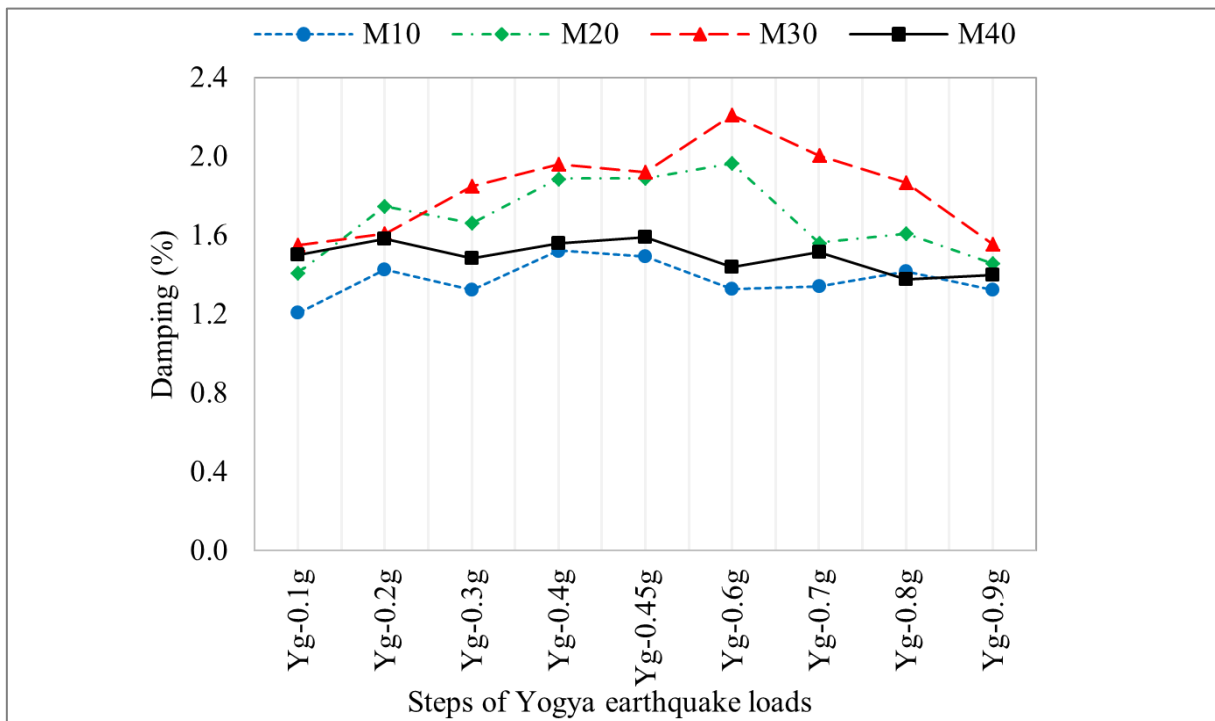


Figure 23. Damping ratio of the wall during Yogya earthquake loading

M30 also provides a better damping ability, either due to sinusoidal or the Yogya earthquake load. This damping ability is claimed to be due to the role of RTC in mortar joints which have elastic properties, which are able to lengthen and shorten along with the vibration pattern. As a result, the mechanical activity of this RTC can generate friction that increases the damping ratio.

However, increasing the RTC content by up to 40% actually reduces the damping ratio and increases the drift

ratio. This 40% RTC content may have exceeded the optimum limit because there has been more loss of friction between the RTC and the cement matrix that has resulted in the decrease of the damping ratio and the increase of the drift ratio. A comparison of the damping ratio and the drift ratio between one model and another is shown in Figure 24 and 25. Trends due to sinusoidal loads and earthquake loads in both the drift ratio and damping ratio results for all models are shown by dotted lines in Figures 24 and 25.

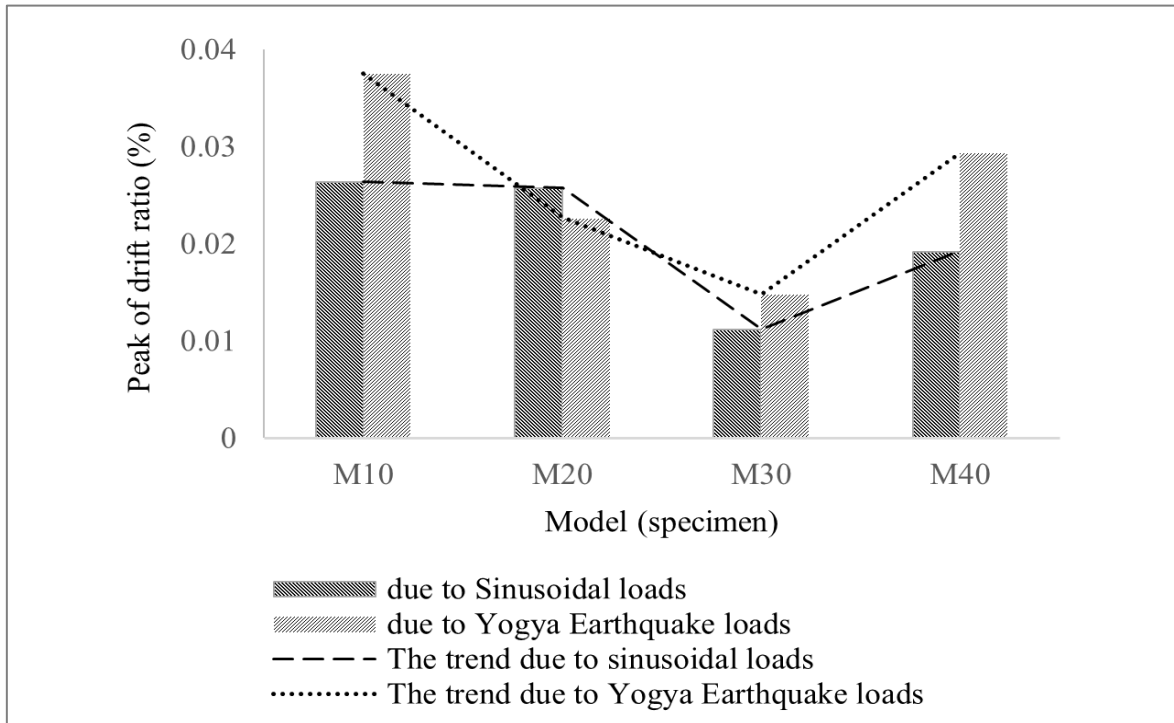


Figure 24. The comparison of drift ratios of the model

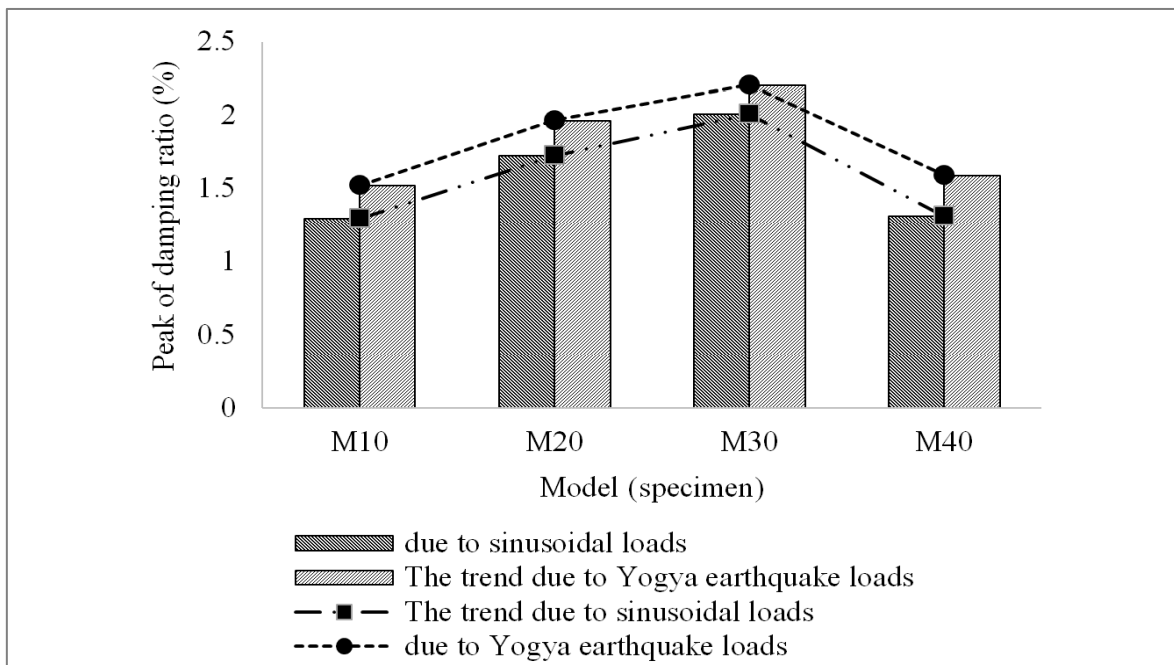


Figure 25. The comparison of damping ratios of the model

It can be seen that the addition of RTC up to 30% can increase the damping ratio and decrease the drift ratio, while the addition of RTC more than 30% is on the contrary. Based on the phenomenon of damping ratio and drift ratio, it can be concluded that 30% is the optimum RTC content in the mortar mixture for its application as mortar joints in masonry wall structures.

Strukar [23] also said that the maximum rubber content in concrete is of 30% replacing aggregate. At 40% content, the strength and modulus of elasticity of rubber concrete decreased up to 60%. The results of this study also inspire further research to develop treatments to increase the strength of RTC mortars.

5. Conclusions

This study resulted in several conclusions as follows:

- 1) The use of RTC mortar as a mortar joint in masonry wall structures is proven to increase the damping capacity of the walls.
- 2) The model that uses 30% RTC mortar (M30) has the best damping behavior, both due to the sinusoidal and the Yogyakarta earthquake loads.
- 3) The damping ratio of the M30 is able to maintain a drift ratio despite resonance effects and an increase in loading amplitude.
- 4) Maximum damping ratio of M30 is 150% of M10.
- 5) Maximum drift ratio of M30 is 40% of M10.

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