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A new form of steel base isolation system for seismic high-rise building

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Abstract. The higher story of a building then it will be more vulnerable to its earthquake or seismic responses. The use of seismic devices will reduce earthquake force. In this study, the steel base isolation material has been proposed. This paper aims to design a new steel base isolation system that have good resistance in both of seismic vibration and axial pull out. The building data are 3D mini three-story, six-story, nine-story steel frame structures. The shaking table is used to test with two types of vibration, medium and maximum. FEM analysis was implemented to find the seismic responses. From the calculation results, a reduced response was obtained in conditions of moderate damage to a three-story frame with an average acceleration of 88% reduction, a maximum acceleration of 22% reduction and a six-story frame in heavy damage with an average acceleration of 73%, the maximum acceleration is reduced into 43%.

1. Introduction

Indonesia is one of the most susceptible to earthquakes such as Japan and California because of its geographical position occupying a very active tectonic zone. This is because the three large tectonic plates of the world and nine other small plates: Eurasian Plate, Pacific Plate, and Indo – Australia Plate. gather each other in the territory of Indonesia and form a conjugate joint of complex plates. Therefore, Indonesia has a high seismicity degree [1]. The Directorate General of Geology and Mineral Resources Ministry of Mines and Energy Republic of Indonesia stated that the interaction between this plates, places Indonesia as an area that is very vulnerable to earthquakes [2].

At present, earthquakes are one of the most important factors in designing buildings, [3] especially high-rise buildings because the higher of building, the effect caused by the earthquake force will be greater for the building because in high buildings the lateral anchoring system is weaker than the force retaining system vertically, while earthquakes cause additional lateral forces that occur dynamically which affect structural stability [4].

Conventional building damage caused by earthquakes can be prevented by strengthening the building structures against the earthquake forces acting on it. However, these results are often unsatisfactory because damage to both structural and non-structural element is generally caused by inter-story drift (difference in deviation between levels). To reduce inter-story drift can be done by affirming the building in the lateral direction. However, this will increase the earthquake force acting on the building. A better method is to reduce earthquake energy to a level that does not endanger the building [5].

Several researchers such as [6] evaluate the seismic performance and they make a review on the retrofitting strategies of existing RC buildings. They discuss seismic assessment to point out the structural deficiencies related to strength and ductility of members and the structural system as awhile. They stated a basic strategy for such structures is to limit the deformation or force demands on the brittle components by adding lateral stiffness or reducing the earthquake input by adopting adequate retrofitting strategy.

The most practical seismic dissipation system to be used in recent years is a passive control system and base isolator because the active control system uses very expensive cost for high technology while the base isolator is designed using high rubber bearings which are usually placed on the connection between the foundation and column which works like a car suspension system when an earthquake occurs so that the upper structure is separated from the lower structure but there is a shortage that is in the high rise building the base insulator can not control a large enough inter-story drift [3].

2. Earthquake

Geographically, Indonesian islands are between 6˚LU and 11˚LS, and between 95˚BT and 141˚BT. Indonesian is located on the clash of three plates of the earth’s crust, namely Eurasian plate, Pacific plate and Indo Australia plate. Geologically, the Indonesian is at the confluence of 2 major earthquake lines, namely Pacific Circum earthquake path and Alpide Trans-asiatic earthquake pathway. Therefore it’s not surprising that the Indonesian is an area prone to earthquakes [7]. An earthquake is a ground-level tremor due to sudden release energy due to the slipping of rock masses in the layers of the earth’s crust [8]. Based on the cause, the earthquake was divided into 3 types [9]:

- Tectonic Earthquake, Tectonic earthquakes are related to tectonis plate activity either on a regional or global scale. The activity of this tectonic plate causes a burst or release of strain energy due to sudden friction between the plates of the earth causing vibrations to be spread in all directions which thenpropagate to the surface of the ground [8].
- Volcanic Earthquake, Volcanic earthquakes are caused by volcanic activity which is the process of forcing out hot magma on to the surface of the ground, so that it can cause explosions from small to large scale. Ground vibration caused by the process of forcing out hot magma (exploding) like an earthquake even though its intensity is smaller than atectonic earthquake [8].
- Earthquake Terban (Ruins), Earthquake terban (ruins) or Earthquake collapses, these earthquakes are caused by landslides or explosions that can’t be resisted or suppressed by the surface of the earth [9].

2.1. Earthquake parameters

Earthquakes have several parameters [10].

2.1.1. Seismic wave. Seismic wave is the slowing of energy from the epicenter or hypocentric (focus) to another place on earth. This wave consists of body wave and surface wave [10].

2.1.2. Large size of earthquakes. The earthquake magnitude is an earthquake charasteristic that is related to the amount of total seismic energy released by the earthquake source. Magnitude is the scale of the magnitude of the earthquake at the source. Body wave magnitude, determined based on the total amount of elastic wave energy transferred in the form of Primary wave (P) and Secondary wave (S) [10].

2.1.3. Intensity. Intensity is a quantity used to measure an earthquake other than with magnitude. Intensity can be defined as the amount of damage in a place due to an earthquake measured by the damage that occurs. The Mercali Modification Intensity scale (MMI) is a commonly used intensity scale. [10]. In **Equation 1**, the relationship between earthquake intensity and earthquake magnitude will be describes, the intensity and intensity value in the Richter scale unit.

$$Io = 1,5\ (M-0,5) \tag{1}$$

Where:
Io = Maximum intensity

M = Magnitude (Richter Scale)
1 g = 9,81 m/seconds^2

In general the intensity scale is used by BMKG as in **Table 1.**

Table 1. Earthquake intensity scale BMKG.

SIG BKG Scale	Colour	Description	Detail Description	MMI Scale	PGA (m/second^2)
I	White	Not Felt	Not felt or felt by only a few people but recorded by the device.	I-II	< 0,029
II	Green	Felt	Felt by many people but does not cause damage. Light objects hung swaying and the glass window shook.	III-V	0.029-0,88
III	Yellow	Slight Damage	Non-structural parts of the building suffered slight damage such as hair cracks on the walls, tiles shift down and some fall.	VI	0,89-1,67
IV	Orange	Moderate Damage	Many cracks occurred on the walls of simple building, some collapsed, broken glass window. Part of the plaster is loose, almost most of the tiles shift down or fall. Building structure has mild to moderate damage.	VII- VIII	1,68-5,64

Source : www.bmkg.go.id

2.2. Earthquake resistance building concept

Building is a physical form of the results of a construction work that is united with its place of domicile, partially or wholly above and in land or water, which functions as a place for human activities, both for occupancy or residence, religious activities, business activities, social activities, culture and special activities [11].

The more important a building is, the longer the building must last, so the greater the earthquake force that must be planned in the building plan [8].

2.3. Control of earthquakes

Many factors that can damage the structure of buildings generally are natural loads such as earthquake loads that are difficult to measure both the type and magnitude. Improper dimensions and geometry of structures can enlarge the vibrations that occur due to the occurrence of resonance and the inability of building structures to accept these loads, so that the performance of the building becomes very low and can resukt in unexpected structural damage [12].

Improved structural performance during earthquake loads depends on a stable structural system. Elements related to the effect of earthquake load displacement must be designs to have same rigidity [13]. Efforts to avoid damages that occur in the structure carried out by providing additional tools to the structure, to limit the energy or dissipate the energy of earthquake entering the building. These tools are known as Seismic Devices. By adding these devices, the earthquake energy that enters the structure can be reduced and controlled so that the forces and deviation of the structure become small. Seismic devices can generally be divided into 2 types [5].

2.3.1. Actived seismic devices. Actived seismic devices works by accepting vibration data input from sensors installed around the structure. Through a computer, the data is used to adjust the movements according to the earthquake input to the building. Active devices utilize external resources to adjust the response of the device to react to structural behaviour in real time and achieve the overall desired response.

2.3.2. Passived seismic devices. Passived seismic devices works after the earthquake energy enters the structure by removing large amounts of energy over a short period of time, in general the reaction of seismic devices increases when the response of the structure or energy entering is getting bigger. Passive seismic devices according to their functions can generally be divided into 2 types, Isolation (seismic isolator) and which are energy dissipation (dampers).

2.4. Various types of earthquake damper

2.4.1. Tuned Mass Damper (TMD). Is a device or instrument consisting of a mass, stiffness and a damper that is attached to a structure that works to reduce the dynamic response of a structure [14].

2.4.2. Concentric Brace Frame (CBF). Which is classified as a type of damper, works by dissipating energy through the formation of plastic joints or melting of dampers. CBF, which is usually installed on a structure, can be distinguished according to the way the energy is dissipated [5].

2.4.3. Base isolation systems. Are insulation pads that are connected between columns and foundations. This insulation system is designed to be very rigid in the vertical direction, providing enough initial stiffness under service loads, such as wind loads and providing greater flexibility at the bottom of the structure when ground movement or earthquake [15]. There are 2 types of base isolation system that have often been used, type of rubber bearing and type of pendulum friction [5].

- Friction Damper
- Viscous Damper
- Visco-elastic Damper

2.5. Structural loading analysis
A building will receive an inertial force or earthquake force at the center of the structure of the mass in the vertical direction and in the horizontal direction. Horizontal earthquake forces will react to weak points of the structure where the structure does not have enough strength and will fail. Therefore the basic design of earthquake resistant structures is to provide strength to structures that are usually lacking in facing lateral forces, or by limiting vibrations due to earthquakes to structures. To analyze an earthquake force on the structure can be used as an analysis method include [10].

2.5.1. Dynamic analysis is a structural analysis where the distribution of earthquake shear forces at all levels is obtained by taking into account the dynamic influence of ground motion on the structure [16].

Dynamic analysis can be done in elastic and inelastic ways. Dynamic analysis is divided into 2 [17].

- Response Spectrum Modal Analysis
- Time History Modal Analysis

2.5.2. Static equivalent analysis. Analysis of equivalent static load can only be used in elastic structures. The inertial force in this analysis can be considered as statis force using empirical formulation where the inertial force works at the center of mass [10].

2.6. Degree of freedom
In the dynamics of the structure of the number of independent coordinates needed to determine the configuration or position of a system at any time is called the Degree of Freedom, while for a continous structure has an unlimited degree of freedom. In some cases of dynamics, generally the choice of degrees of freedom in a mass or point is only at the level of a single freedom. That is a structure that can be modeled as a system with one coordinate displacement in the horizontal direction. This system

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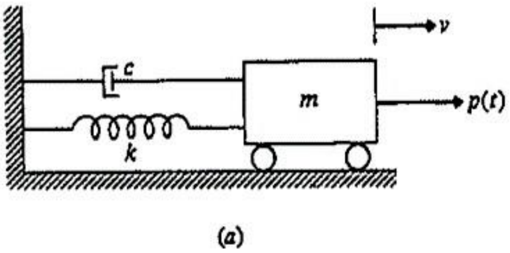
of one degree of freedom can be described by a one dimensional or two dimensional mathematical model [18].

2.6.1. Single degree of freedom differential equations. Single Degree of Freedom will only have one coordinate that is needed to state the position of the mass at a particular time that is reviewed. One-level building is one example of building a single degree of freedom [10].

In SDOF system the simplest modeling with each property is assumed to be concentrated in one phsyical element such as described in Figure 1 [19].



Source: Clough and Penzien, 1975

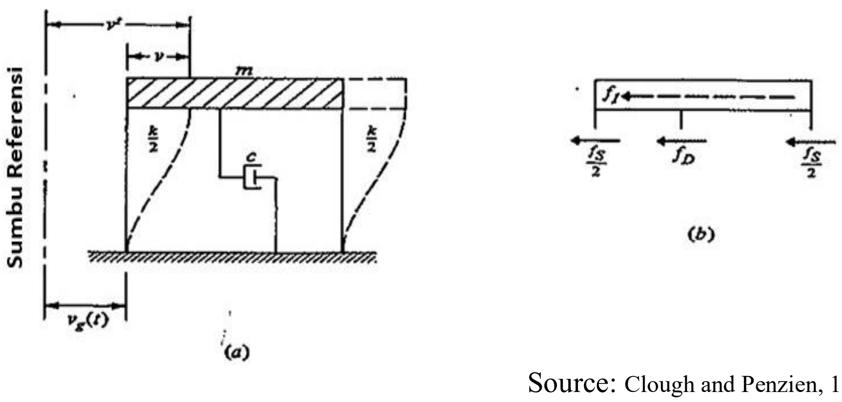
Figure 1. Ideal SDOF System (a) Basic Components, (b) Force of Equilibrium.

Then will get the derivation of **Equation 2.**

$$m\ddot{v} + c\dot{v} + kv = p(t) \tag{2}$$

m	= Massa	(kg.cm/s^2)
$\ddot{v}$	= Acceleration	(m/s^2)
c	= Reducer	
$\dot{v}$	= Speed	(m/s)
k	= Stiffness	(kg/cm)
v	= Displacement	(m)
$p(t)$	= load	(m/s^2)

2.6.2. Single degree of freedom differential equations due to base motion. Dynamic pressure and deflection can be induced in a structure not only by a load that varies in time, as the example of excitation is the movement of a building foundation caused by an earthquake or the basic movement of an equipment due to the vibration of the building where the house is located. Simple models of earthquake excitation problems are shown in Figure 2, where horizontal ground movements caused by earthquakes [19].



Source: Clough and Penzien, 1975

Figure 2. Effect of SDOF Excitation Support Equilibrium (a) Movement System, (b) Force of Equilibrium.

The horizontal girder in this framework is assumed to be rigid and includes all the moving mass of the structure. Vertical columns are assumed to be weightless and cannot move in a vertical (axial) direction, and resistance to the disagreement of the girder provided. So we get **Equation 3**.

$$m\hat{\upsilon} + c\dot{\upsilon} + k\upsilon = -\, m\hat{\upsilon}_g \equiv p_{eff} \tag{3}$$

p_{eff}	= Load (m/s^2)	
m	= Massa	(kg.cm/s^2)
c	= Reducer	
k	= Stiffness	(kg/cm)
$\hat{\upsilon}$	= acceleration	(m/s^2)
$\dot{\upsilon}$	= Speed	(m/s)
υ	= Displacement	(m)

2.6.3. Multi degree of freedom differential equations. To express the differential equation of movement in structures with many degrees of freedom, assumptions and approaches are used as in structures with a single degree of freedom SDOF. Assumptions such as the principle of shear building still apply to structures with multi degrees of freedom. To obtain the differential equation, the principle of dynamic equilibrium is still used in a mass that is reviewed. To obtain this equation, the MDOF structure model is taken [10].

2.7. Characteristic of mechanical friction pendulum system

The working system of the friction pendulum is to use articulated displacement along a concave surface which causes the structure to move in simple harmonic movements to increase natural periods. This movement creates dynamic friction which dampens the lateral force of the earthquake as in Figure 3 [20].

Source : Nikolay Kravchuk et al (2008)

Figure 3. The concept of *Base Isolator Friction Pendulum* system.

For friction pendulum mechanical charateristics that can reduce the lateral force of the earthquake, if the load on the insulator is W, the horizontal displacement is D, and the coefficient of friction is then for forces that can be held is F like **Equation 4** [21].

$$F = \frac{W}{R} D + \mu W \; (sgn\; D) \tag{4}$$

3. Methodology

This research was conducted by modeling the structure to be reviewed from the variance in height difference, which in this study made three dimensional steel frame; three levels, six levels and nine levels. In calculating physical parameters and dynamic parameters, steel frame models are idealized as a three dimensional shear building.

The next stage of the tree dimensional steel frame structure will be installed a base isolation system with steel material that connects the column and foundation. By adopting an isolator friction pendulum where the system works by utilizing friction between concave surfaces which increases the ability of the structure to return to its original position. For research steps as shown in Figure 4.

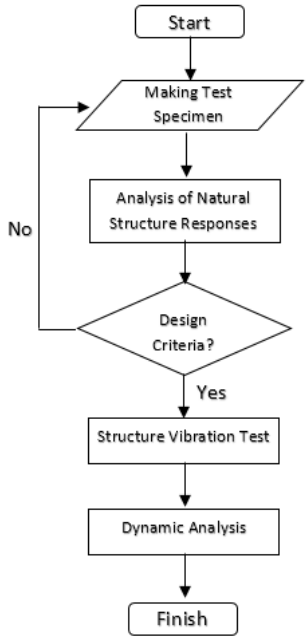


Figure 4. Flow chart diagram.

3.1. *Structural modeling*

3.1.1. Steel frame structures. The steel frame structure material used BJ37 steel with a yield stress 2400 kg/cm^2, with a size 10 mm x 10 mm. Then it will be connected by welding in every corner. Each frame structure has a different height, as explained in UU number 28 year 2002 paragraph 5 about building. Then the design plan of the test object as shown in Figure 5.

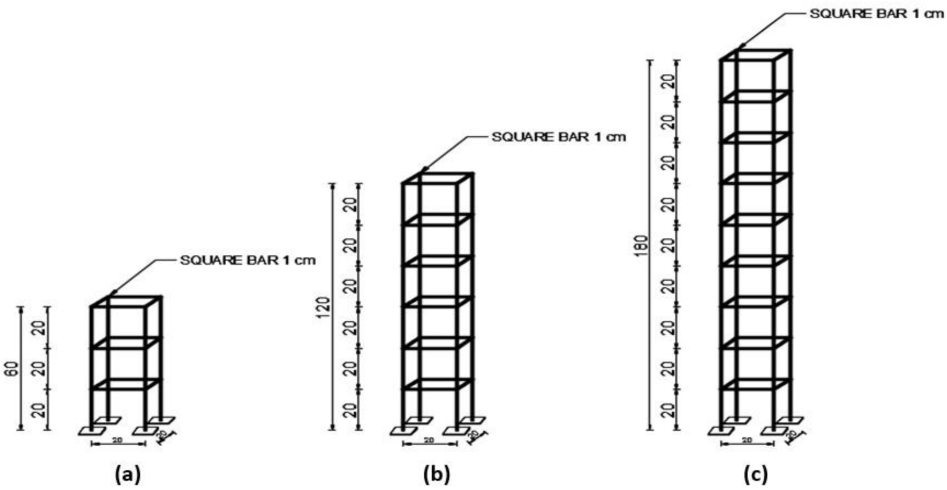


Figure 5. Steel frame structures: (a) Low rise building, (b) Medium rise building, and (c) High rise building.

3.1.2. Base isolator. The steel base isolation material used BJ37 steel with a yield stress 2400 kg/cm^2 and its surface make a curvature at 30˚. These geometry shown in Figure 6 and base steel isolation specimens in the field were shown in Figure 7.

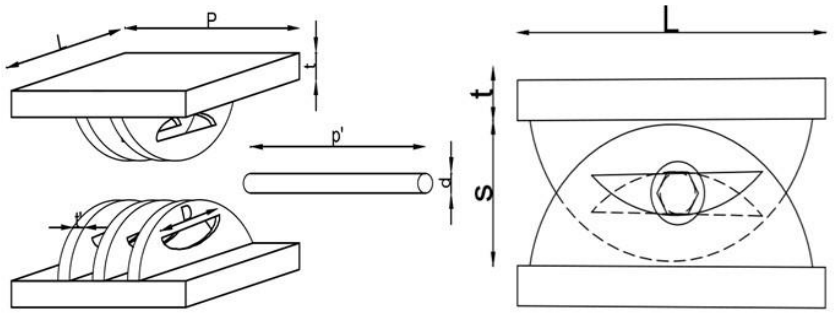


Figure 6. Base steel isolation geometry.

Figure 7. Base steel isolation test material.

Then for the schematic testing plan table plan as shown in Figure 8 and picture of the condition when testing the test object shown in Figure 9 and Figure 10.

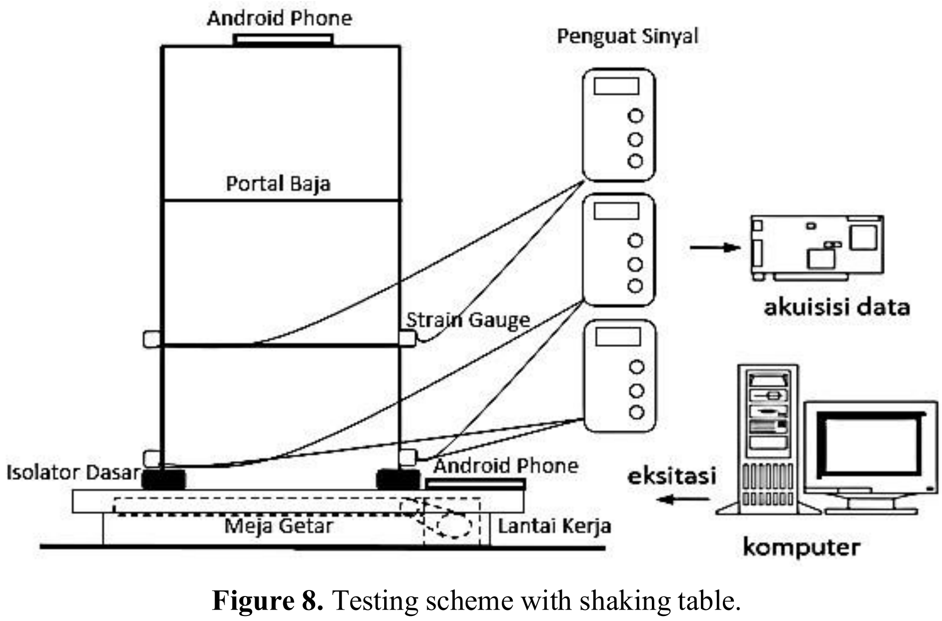


Figure 8. Testing scheme with shaking table.

Figure 9. Loading condition when the shake testing was performed.

Figure 10. Specimen lay on the shaking table.

Then for the plan to install a strain gauge on a steel frame as shown in Figure 11.

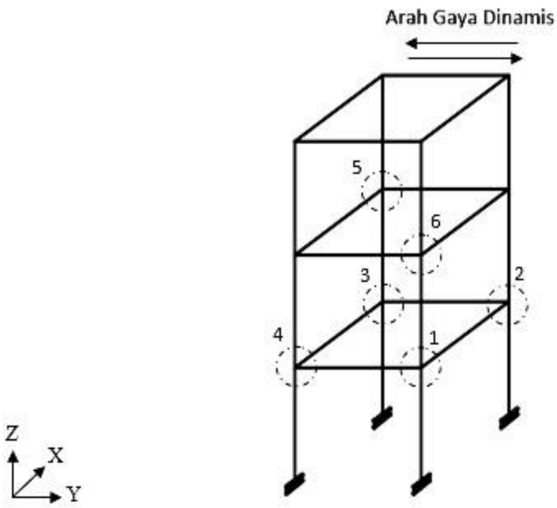


Figure 11. Strain gauge location at six column joints.

3.2. Natural structure response analysis
To find out the system of natural structure movement in each steel frame that has not been tested at the vibration tables, a natural structure response analysis is carried out by first analyzing the mass matrix and the rigidity matrix can then be entered in **Equation 5**.

$$[k] - \omega^2[m] \tag{5}$$

Where:
k = Stiffness / Rigidity (kg/cm)
ω = Frequency (rad/detik)
m = mass

3.2.1. Three story frame. After getting the equation, the frequency of the three floor frame is obtained, then for the frame natural period equals 2 that is:

ω = 1531,33 radians/second T_1 = 0,0041 second
ω = 4571,68 radians/second T_2 = 0,0014 second
ω = 6949,33 radians/second T_3 = 0,0009 second

3.2.2. Six story frame. After getting the equation, the frequency of the six floor frame is obtained, then for the frame natural period equals 2 that is:

ω = 132,65 radians/second T_1 = 0,0473 second
ω = 132,65 radians/second T_2 = 0,0473 second
ω = 159,26 radians/second T_3 = 0,0394 second
ω = 411,94 radians/second T_4 = 0,0152 second
ω = 411,94 radians/second T_5 = 0,0152 second
ω = 483,94 radians/second T_6 = 0,0129 second

3.2.3. Nine story frame. After getting the equation, the frequency of the 9th floor frame is obtained, then for the frame natural period equals 2 that is:

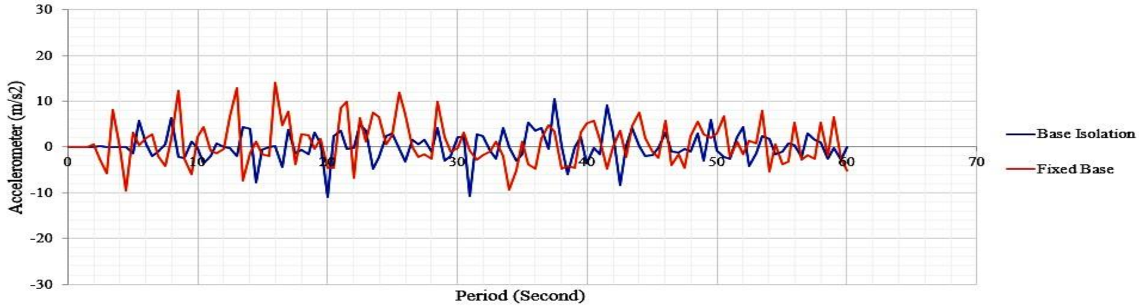
ω = 86,09 radians/second T_1 = 0,0729 second
ω = 86,09 radians/second T_2 = 0,0729 second
ω = 105,66 radians/second T_3 = 0,0594 second
ω = 264,37 radians/second T_4 = 0,0237 second
ω = 264,37 radians/second T_5 = 0,0237 second
ω = 319,42 radians/second T_6 = 0,0196 second

4. Dynamic analysis
After doing several test in the shaking table on the test object with a variation of the floor number in the form of a steel frame using steel base isolation and without steel base isolation, the acceleration were found. With the results of shaking table data on the specimen it can be classified as a type of BKG IV GIS for moderate damage and SIG BKG V for heavy damage. The results of shaking table testing found an acceleration response to steel frame was shown in Table 2.

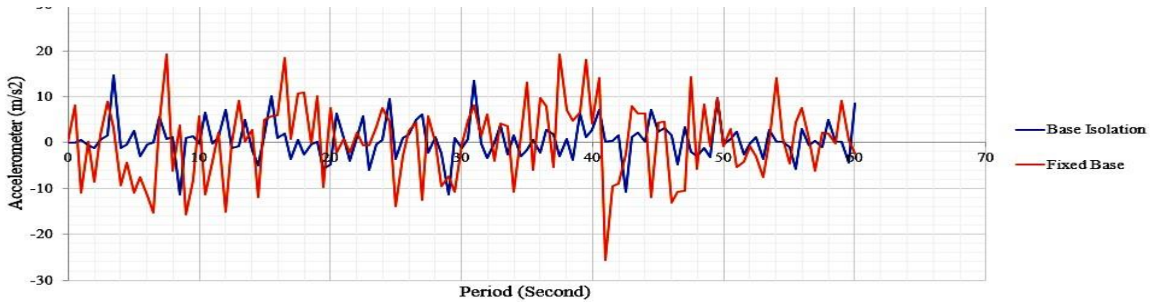
Table 2. Comparison percentage of steel frame acceleration.

Type of Frame	Acceleration ($m/second^2$)							
	Sa Med $_{Average}$		Sa Med $_{Maximum}$		Sa Max $_{Average}$		Sa Max $_{maximum}$	
3 Floor $_{Fixed\ Base}$	0.8	12%	14.06	78%	0.25	211%	25.62	58%
3 Floor $_{Base\ Isolation}$	0.10		10.95		0.53		14.74	
6 Floor $_{Fixed\ Base}$	0.79	17%	12.04	143%	0.99	27%	31.61	57%
6 Floor $_{Base\ Isolation}$	0.13		17.26		0.27		18.08	
9 Floor $_{Fixed\ Base}$	0.60	67%	17.78	109%	0.27	162%	26.76	88%
9 Floor $_{Base\ Isolation}$	0.40		19.44		0.43		23.64	

For a comparison of the results of the frame roof acceleration response 3 floors, the shaking table testing as shown in Figure 12.

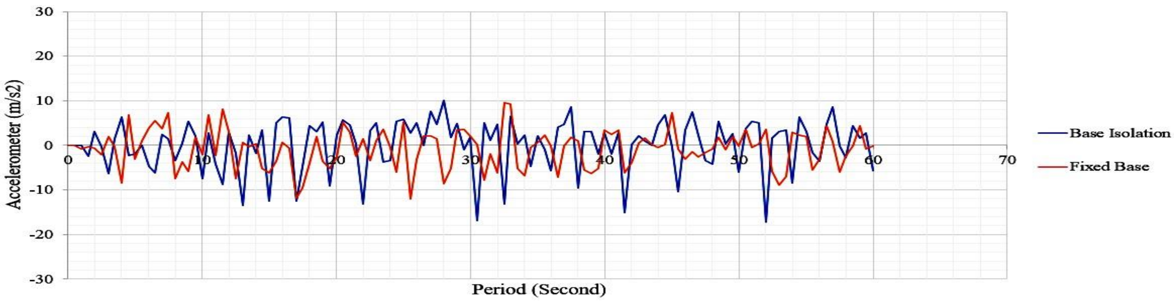


(a)



(b)

Figure 12. The 3-story frame top acceleration response (a) Medium vibration and (b) Maximum vibration.



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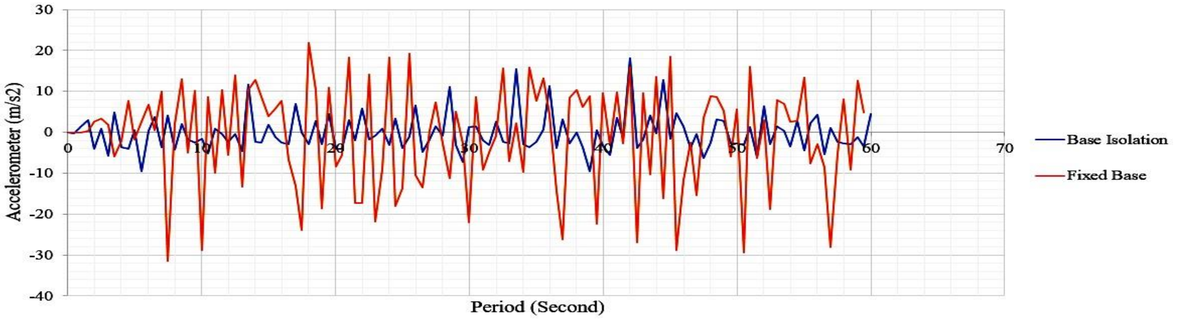
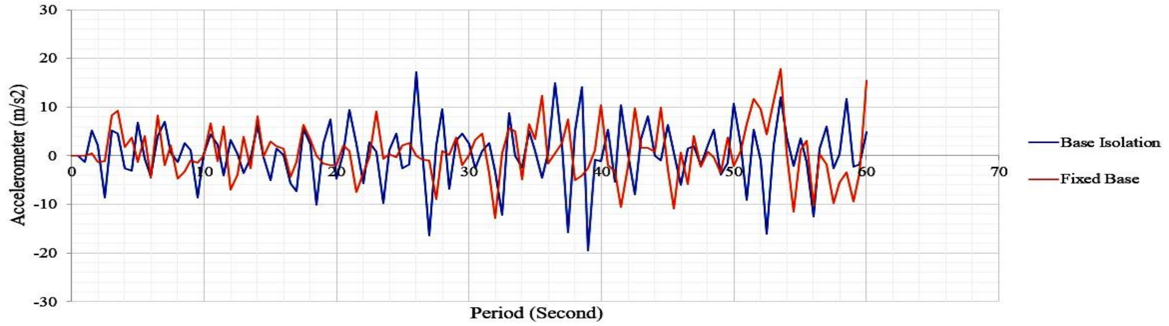


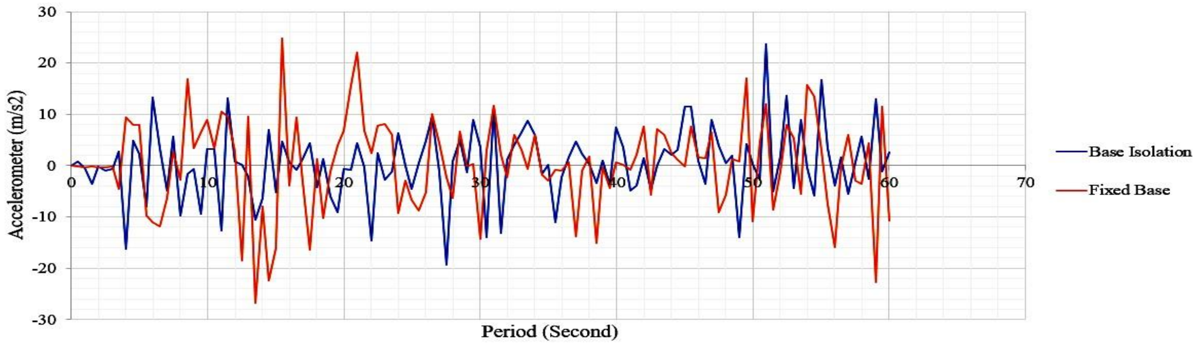
(b)

Figure 13. The 6-story frame top acceleration response (a) Medium vibration and (b) Maximum vibration.

For a comparison of the results of the frame roof acceleration response 9 floors, the vibration table testing as shown in Figure 14.



(a)



(b)

Figure 14. The 9-story frame top acceleration response (a) Medium vibration and (b) Maximum vibration.

The strains of the each frame resulted from of the strain gauge on the vibrated steel frame can be seen in figure 15 and figure 16.

Type of Frame	Frame Strain (10^{-6}) Sa Med Average									
	SG1	SG2	SG3	SG4	SG5	SG6	$SG_{Average}$		SG_{min}	SG_{max}
3 Floor Fixed Base	0.0075	0.0028	0.0098	0.0002	-0.0183	-0.0086	-0.0011	696%	-0.0410	0.0225
3 Floor Base Isolation	0.0039	0.0030	0.0067	-0.0040	0.0225	0.0141	0.0077		-0.0484	0.0523
6 Floor Fixed Base	-0.0021	-0.0071	0.0044	-0.0029	-0.0002	-0.0152	-0.0039	241%	-0.0611	0.0220
6 Floor Base Isolation	0.0350	0.0002	0.0170	0.0438	-0.0145	-0.0257	0.0093		-0.0581	0.1192
9 Floor Fixed Base	-0.0036	-0.0049	-0.0094	-0.0048	0.0181	0.0094	0.0008	1227%	-0.0230	0.0400
9 Floor Base Isolation	0.0122	0.0018	0.0788	0.0094	-0.0127	-0.0307	0.0098		-0.0821	0.1919

Figure 15. The comparison of steel frame strains in medium acceleration/motion of shaking table.

Type of Frame	Frame Strain (10^{-6}) Sa Max Average									
	SG1	SG2	SG3	SG4	SG5	SG6	$SG_{Average}$		SG_{min}	SG_{max}
3 Floor Fixed Base	0.0092	-0.0048	0.0124	-0.0078	0.0162	0.0266	0.0086	166%	-0.0195	0.0586
3 Floor Base Isolation	-0.0419	-0.0030	-0.0132	-0.0225	0.0153	-0.0209	-0.0144		-0.1011	0.0444
6 Floor Fixed Base	0.0105	-0.0003	0.0000	0.0264	-0.0125	0.0096	0.0056	317%	-0.0352	0.0552
6 Floor Base Isolation	0.0313	0.0103	0.0261	0.0287	0.0021	0.0086	0.0179		-0.0254	0.0869
9 Floor Fixed Base	-0.0198	-0.0104	0.0004	0.0354	0.0138	0.0144	0.0056	502%	-0.0405	0.0762
9 Floor Base Isolation	0.0549	-0.0031	0.0701	0.0326	0.0015	0.0139	0.0283		-0.0630	0.2007

Figure 16. The comparison of steel frame strains in maximum acceleration/motion of shaking table.

5. Conclusion

From the analysis and experimental results, the behavior of steel frames with at the variation of story number due to vibrations from the medium and maximum shaking table, it can be concluded that:

- Steel base isolation is designed by utilizing a displacement system that can return to its original position so that the dynamic displacement can be obtained, and needs to be reviewed from several aspects especially the building mass aspects, building height and curvature angle of the steel base isolation used.
- From the shake testing for steel frames using the steel base isolation, the smallest average comparison ratio when the medium vibration for the three floor frame acceleration averaged 12% smaller, resulting in a 78% smaller acceleration with an average strain that occured 696% more greater that without steel base isolation and on the six floor frame when the maximum acceleration vibration is 27% smaller, resulting in a maximum acceleration of 57% smaller with an average strain that occurs 317% greater than without steel base isolation.
- The use of steel base isolation on steel frames can reduce seismic load in moderate damage conditions for the three floor frame type, namely reducing the average acceleration by 88% and the maximum acceleration of 22% while in heavy damage conditions for the six floor frame types with average acceleration reduced by 73% and 43% maximum acceleration.

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