International Journal of GEOMATE, Nov., 2023 Vol.25, Issue 111, pp.212-219
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.111.3944
Geotechnique, Construction Materials and Environment

ANALYTICAL STRUCTURAL RESPONSES OF BUILDINGS WITH TRIPLE FRICTION PENDULUM ISOLATION SYSTEM

Vivi Dwi Darmawati[1], *Tavio[1]

[1] Department of Civil Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

*Corresponding Author, Received: 10 May 2023, Revised: 04 Aug. 2023, Accepted: 07 Aug. 2023

ABSTRACT: Earthquakes are disasters that cause vibrations and can cause damage to infrastructures. Thus, there is an urgent need to provide safe buildings against severe earthquakes to avoid any structural failures. One of the most effective systems for buildings against earthquakes is the seismic isolation system. The study aims to analyze and evaluate the efficient configuration of the isolation system to the structural responses of the buildings against earthquakes. The method used was to introduce the isolation system between story levels by placing them on the floors. The most efficient results in terms of structural responses were when the isolations were placed at the 1st and 5th stories, e.g., building periods, inter-story displacements, story shear, and internal forces. Placement of isolations with better response was obtained for isolations located at two stories than only a story. This implied that it served more effectively and better in minimizing structural damage. The isolations were ineffective when they were located on the 7th story, the results indicated that the inter-story displacement and story shear were insignificantly affected. From the analytical results due to the earthquake load, it was also found that the isolations on the 1st and 5th stories experienced the most significant responses, whereas the placement on the 7th story had an insignificant impact in minimizing structural damage due to earthquake load.

Keywords: Building Structures, Disaster Risk Reduction, Isolation System, Structural Response, Triple Friction Pendulum

1. INTRODUCTION

Indonesia is located on top of a stack of three large plates, i.e. Eurasian (Europe-Asia) plate from the North, the Indo-Australia plate from the South, and the Pacific place from the East causing the country to be susceptible to earthquakes [1,2]. The severe impacts due to earthquakes, among others, are casualties of human life, loss of properties, and infrastructure damage or even collapse. The cause of the loss of life and economy is solely due to the collapse of buildings built by humans during an earthquake [3,4]. There are several ways to protect buildings against earthquakes such as by making the building structurally ductile (e.g., using ductile materials) [5] with a higher level of damage, or in other words, by ensuring that the performance of the building is higher. This can be done by reducing the impact of earthquake damage as well as achieving better comfort during an earthquake with the introduction of an isolation system to the building [6]. Seismic isolation provides low horizontal rigidity of a building by shifting the fundamental period of the structure out of the high earthquake range and separating the superstructure from ground motion [7,8].

The dynamic response of the structure can be reduced by the installation of an isolation structure device [9,10]. The use of base isolations in houses and buildings has been widely proven to provide better performance in reducing damage during earthquakes [11]. The use of base isolations is very easy for new buildings, but kind of complicated and relatively higher costs for retrofitting applications, requiring excavation, and load transfer while the concept and application of inter-story isolation were studied both experimentally and analytically and were relatively simple, inexpensive, and hassle-free [12]. One of the basic isolation technologies is the friction pendulum system (FPS).

Friction Pendulum System (FPS) is one type of basic isolation technology, and its effectiveness for isolating transmitted seismic energy has been validated by comprehensive experimental and numerical studies [13,14]. FPS works using curved sliding surfaces that cause the structure to move back to its original position based on the principle of pendulum motion [15]. Part of the FPS applied in this study is the Triple Friction Pendulum System (TFPS), which is a pendulum developed by Fenz and Constantinou by modifying the DCFP system [16,17]. This modification improves the relative performance and measurement capacity of TCFP energy isolations compared to DCFP. The surfaces of each joint piece are convex and concave so that they can easily slide over each other, providing seismic isolation and energy dissipation. The system has four sliding surfaces where the desired seismic capability can be achieved for isolation by adjusting the radius of curvature and coefficient of friction of each surface [15].

2. RESEARCH SIGNIFICANCE

The study was conducted on two seismic-resistant building structures using isolation systems, namely, Building structures A and B. It aims to determine further study and review on the most effective placement of isolation in terms of responses or performance of structures due to earthquake hazards. The case study was used for low-rise buildings, i.e., 8 stories. The buildings were designed with the same story number, different layouts, and the same heights of 8 stories. The placement and selection of the location of the isolation applied to particular stories were then used as an issue for evaluating the inter-story displacement and story shear between the buildings. The building and seismic codes comply with Indonesian standards. The results of the study served as new information on the optimum response or performance regarding the placement or selection of the location of inter-story isolations and further assist in the design of future isolated buildings.

3. GENERAL DESCRIPTION OF THE BUILDING STRUCTURES

The first phase in the design process of the building structure is the preliminary structural design, which aims to determine the initial dimensions of each member to be used in the building structure. This is also to conform with the required dimensions for seismic-resistant buildings in Indonesia. References for preliminary designs are to “Building Code Requirements for Structural Concrete and Their Explanation” and to “Minimum Design Loads and Associated Criteria for Buildings and Other Structures.”

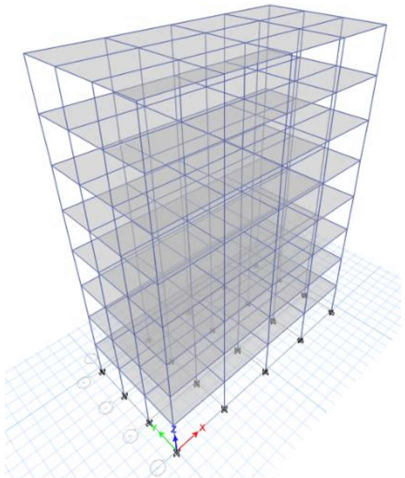

Fig.1 3D perspective view of Building Structure A

The initial dimensions of the members of this structure also affect the total load acting on the building structure, namely the dead load. Furthermore, the building structure is modeled and analyzed with the help of a structural analysis program. The 3D perspective view of the building structure is illustrated in Fig. 1 and 2. Building information is given in Table 1.

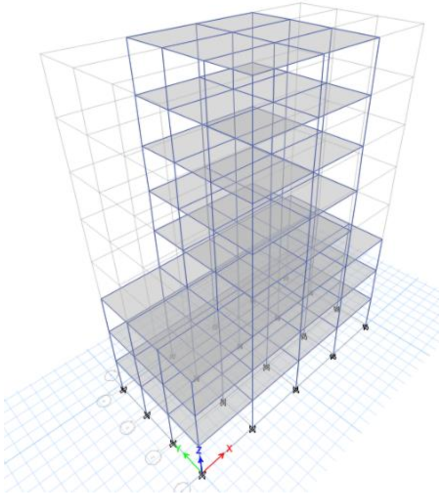

Fig.2 3D perspective view of Building Structure B

Table 1 Building data

Building Item	Informative Data
Building location	Surabaya city
Building function	Office
Number of stories	8 stories
Typical story height	4 meters
Concrete strength (f_c')	30 MPa
Yield strength of longitudinal steel bar	420 MPa
Yield strength of transverse steel bar	280 MPa
Long span length	6 meters
Short span length	4 meters
Slab thickness	12 cm
Beam size	B1: 35 cm × 35 cm B2: 40 cm × 40 cm
Column size	K1: 50 cm × 65 cm

3.1 Seismic Force Application

The seismic force-resisting system needs to consider the response modification coefficient, deflection amplification coefficient, system overstrength factor, and structural total height limitation. The designed seismic force for the seismic force-resisting system should meet one of the structural types specified in Table 12 of SNI 1726:2019 [18]. According to Article 7.2 of SNI 1726:2019 [18], the seismic force-resisting system is determined by the parameters, such as response modification coefficient (R), deflection amplification coefficient (C_d), system overstrength factor (Ω_0), and structural total height limitation.

3.1.1 Stiffness and natural period of the structure

The structural design needs to consider the natural rigidity and period of the structure. Stiffness can be defined as the force required to deform one unit. The rigidity of a structure is inversely proportional to the natural period of the structure, as evidenced by its formulation as follows:

$$\boldsymbol{T = \frac{1}{f} = \frac{2\pi}{\omega}} \tag{1}$$

$$\boldsymbol{\omega = \sqrt{\frac{k}{m}}} \tag{2}$$

The relationship between stiffness (k) and the natural period of the structure (T) is inversely proportional as follows:

$$T \cong \frac{1}{\sqrt{k}} \tag{3}$$

Thus, it can be concluded that the greater the natural period of a structure, the less rigidity it has. This becomes the basis for estimating the period and rigidity according to the design of the structure as follows:

$$T_{minimun} = T_a = C_t h_n^x \tag{4}$$

$$\boldsymbol{T_{maximum} = C_u T_a} \tag{5}$$

3.1.2 Seismic Response Coefficient

According to SNI 1726:2019 [18] Article 7.8.1.1, the seismic response coefficient is determined by the following formula:

$$C_{s-natural} = \frac{s_{D1}}{T\left(\frac{R}{I_e}\right)} \tag{6}$$

The C_s value must not exceed the following equation:

$$\boldsymbol{C_{s-max} = \frac{s_{Ds}}{T\left(\frac{R}{I_e}\right)}} \tag{7}$$

The value of C_s must not be less than:

$$\boldsymbol{C_{s-min} = 0.044 S_{DS} I_e \geq 0.01} \tag{8}$$

For structures located in an area where S_1 is equal to or greater than 0.6g, C_s should not be less than:

$$\boldsymbol{C_{s-min} = \frac{0.5_{s1}}{\left(\frac{R}{I_e}\right)}} \tag{9}$$

3.1.3 Design Response Spectrum

Spectral response is the maximum response of an SDOF (Single Degree of Freedom) structural system, in the form of acceleration, velocity, or displacement of a structure due to loading with a certain pattern. The spectral response curve can show the maximum relative displacement (S_d), maximum relative velocity (S_v), and maximum total acceleration (S_a) on the y-axis and the natural period of the structure on the x-axis.

3.1.4 Load Combinations

The load combinations applied to the structure must be designed in such a way that the design strength of the structure exceeds the influence of the factored load. Based on SNI 1726:2019 Article 4.2.2 [18], the factored load combinations include: (1) 1.4D; (2) 1.2D + 1.6L + 0.5L_r; (3) 1.2D + 1.6L_r + 1.0L; (4) 1.2D + 1.0L + 0.5L_r; (5) 0.9D; (6) 1.2D + 1.0E_v + 1.0E_h + 1.0L; (7) 0.9D – 1.0E_v + 1.0E_h. D is the dead load including self-weight, L is the live load, L_r is the live load of the roof, and E is the earthquake load.

3.1.5 Inter-story Displacement

The inter-story displacement is defined as the difference in the center of mass above and below the level under consideration. Determination of the designed displacement, Δ_α shall not exceed the allowable story displacement. Inter-story displacement is defined in SNI 1726:2019 Article 7.8.6 [18] as:

$$\boldsymbol{\delta_x = \frac{C_1 \delta_{xe}}{C_e}} \tag{10}$$

3.1.6 Isolation System

The isolation system used in the study is a triple friction pendulum (TFP) bearing. The cross-sectional elevation and dimensional properties of the TFP are illustrated in Fig. 3.

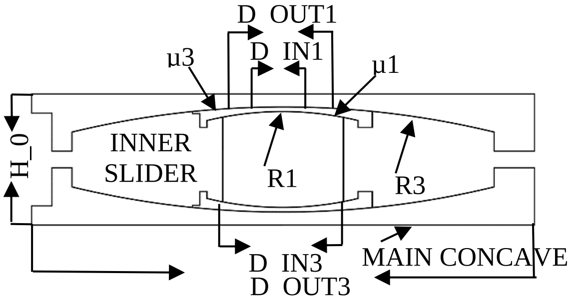

Fig.3 Cross-sectional elevation view and dimensional properties of triple friction pendulum (TFP) bearing isolation system [19]

The properties and parameters of triple friction pendulum bearing are given in Table 2.

Table 2 Properties and parameters of triple friction pendulum bearing.

Surface	R (m)	H (m)	μ	D_{out} (m)	D_{in} (m)
1	5	2	5	0.4	0.1
3	6	1	6	1	0.5

Note: R= curvature radius, μ= friction coefficient

3.2 Addition of Isolations

3.2.1 Addition of Isolations to Building Structure A

TFP was used in both buildings using the same TFP with a difference in the number of bearings. Building Structure A placed the isolations on the 1st, 5th, and 7th stories with a total of 20 bearings on each story (Fig. 4).

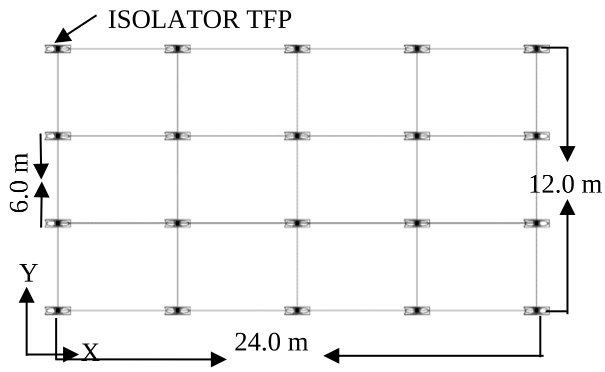

Fig.4 Isolations on the 1st story

3.2.2 Addition of Isolations to Building Structure B

Building Structure B placed the isolations on the 1st story with a total of 20 bearings. The 5th and 7th stories used 12 bearings for each story (Figs. 5 and 6).

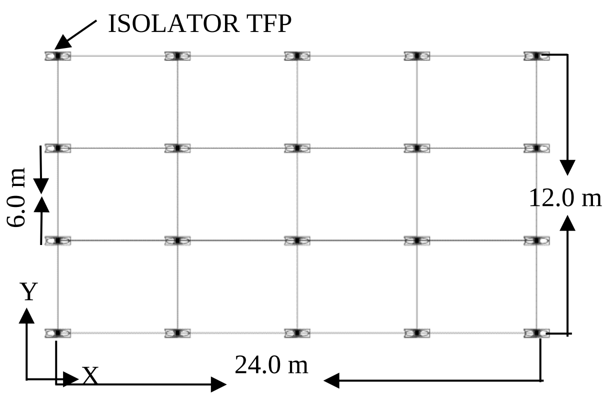

Fig.5 Isolations on the 1st story

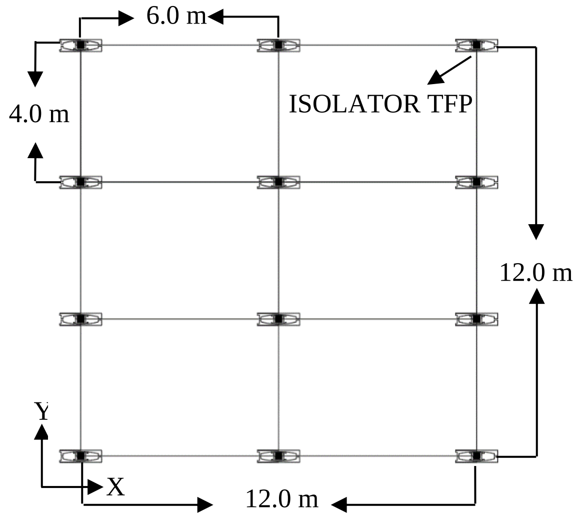

Fig.6 Isolations on the 5th story

4. RESULTS AND DISCUSSION

4.1 Structural Members

Structural modeling was carried out by using the structural analysis program. Both Building Structures A and B were assigned using identical member sizes and dimensions (Table 3).

Table 3 Member sizes and dimensions

Story	Beam Dimension (mm)	Column Dimension (mm)	Slab Thickness (mm)
1 to 7	B1 350 × 350	K 650 × 850	S120
	B2 450 × 450		
8	B1 350 × 350	K 650 × 850	S 100
	B2 450 × 450		

4.2 Earthquake Loading Conforming SNI 1726:2019

The calculation of earthquake load or story shear force of the building structure used the linear time-history dynamic analysis method with a surface peak ground acceleration (PGA) of 0.3152*g*. Referring to the building function category in SNI 1726:2019 [18], it can be defined as Category IV such that according to the spectral response parameters of SNI 1726:2019, the importance factor *I* equals 1 and the response modification coefficient (*R*) for special moment reinforced concrete frames is determined in Table 12 of SNI 1726:2019 equals 8.

The dynamic earthquake data in the study used 11 earthquake data obtained from the website of peer.berkeley.edu. The designed earthquake load for the building used time history earthquake data (ground motion) shown in Fig. 7 (plotted reference time history). By converting it into spectral response data at the location of the building, the plotted reference spectral response can be obtained as seen in Fig. 8. It is then matched to the spectral response at the location of the building (plotted matched spectral response) as can be seen in Fig. 8. Then, it is converted back to an accelerogram as shown in Fig. 7 (plotted matched time history). The blue and red colors indicate the plotted reference and matched, respectively.

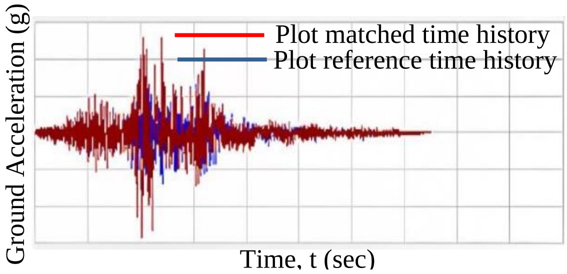

Fig.7 Dynamic earthquake ground motion (an example of landers earthquake accelerogram)

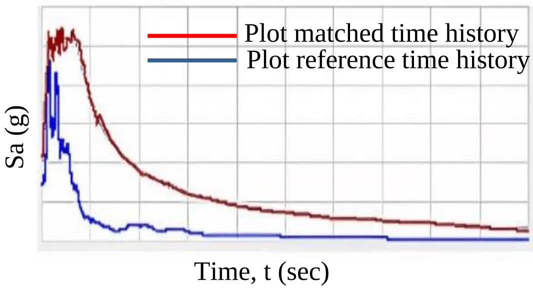

Fig.8 Spectral responses from dynamic earthquake ground motion and at the location of the building (Surabaya city)

4.3 Triple Friction Pendulum (TFP) Modeling

The triple friction pendulum isolations were placed at every column in a story or certain stories. The dimensions and properties of the TFP used are presented in Table 4.

Table 4 Dimensions and properties of TFP

Properties	Value
$R_{1eff} = R_{4eff}$ (mm)	19585.21
$R_{2eff} = R_{3eff}$ (mm)	3030.06
$d_1^* = d_4^*$ (mm)	3118.857
$d_2^* = d_3^*$ (mm)	380.62188
$\mu_1 = \mu_4$ lower bound	0.10659
$\mu_2 = \mu_3$ lower bound	0.11625
μ lower bound	0.10801
$\mu_1 = \mu_4$ upper bound	0.12791
$\mu_2 = \mu_3$ upper bound	0.13951
μ upper bound	0.12970

4.4 Modeling of Isolated Building Structure

The model of Building Structure A with isolations on the 1st story is shown in Fig. 9.

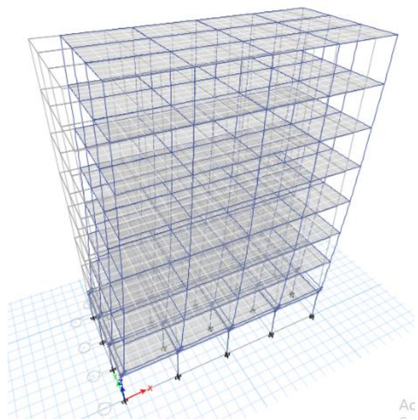

Fig.9 Deformed shape of Building Structure A model with isolations on the 1st story

4.4 Evaluation of Analytical Results of Isolated Building Structures

4.4.1 Building Period

Building structure A, where the isolation location is on the 1st and 5th stories, has the largest period compared to other isolation placements, which is 2.901 seconds. The period of Building Structure A can be seen in Fig. 10.

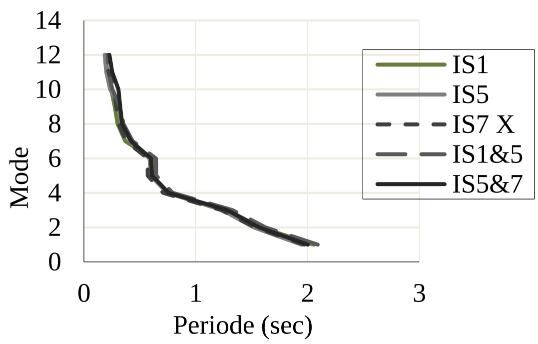

Fig.10 Period of Building Structure A

Building B, where isolations are located on the 1st and 5th stories, has the largest period compared to the other isolation placements, which is 2.091 seconds. The period of Building B can be seen in Fig. 11. Building A has better rigidity compared to Building B which produced a period of 2.901 seconds while Building B produced a period of 2.091 seconds. This shows that the greater the period of the stiffness of a structure the better, such that the earthquake force received by Building A is smaller. The placement of isolations that produces the best stiffness is located on the isolations of the 1st and 5th stories of Building A.

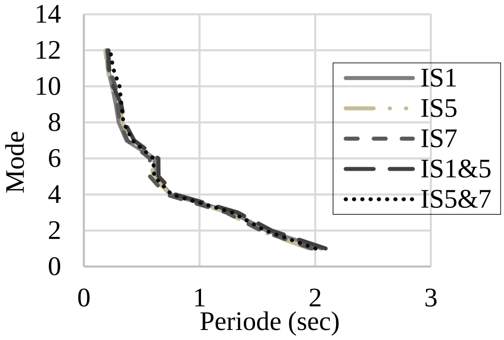

Fig.11 Period of Building Structure B

4.4.2 Inter-story Displacement

In SNI 1726:2019 Article 12.6.4.4 [18], the maximum inter-story displacement of the building structure above the isolation system should not exceed 0.020h_{sx}. A comparative analysis of the inter-story displacements of Building A is given in Fig. 12. The inter-story displacements for the placement of isolations on the 5th and 7th stories gave the largest value of 48.898 mm in the y-direction. The lowest value occurred in the isolated 7th-story of 2.65 mm in the y- direction.

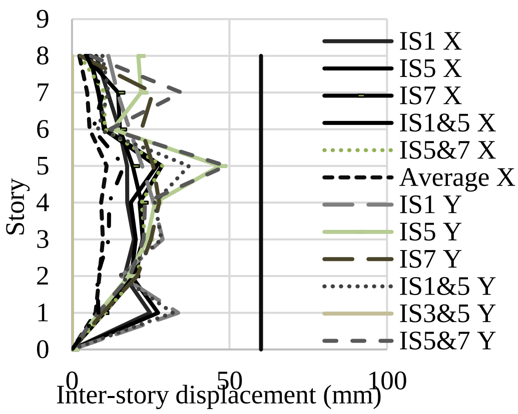

Fig.12 Inter-story Displacements Of Building Structure A

A comparative analysis of the inter-story displacements of Building B is shown in Fig. 13. The inter-story displacements for the placement of isolations on the 5th story gave the largest value of 43.736 mm in the y-direction. The lowest value occurred in the 5th and 7th isolated story of 3.673 mm in the y-direction. The largest inter-story displacement that occurred in Building B (isolated 5th story) is 43.736 mm, while in Building A (isolated 5th and 7th stories) is 48.898 mm which approaches the inter-story displacement limit. However, the inter-story displacements of both Buildings A and B did not exceed the limitation indicating that the structure is far from any damage.

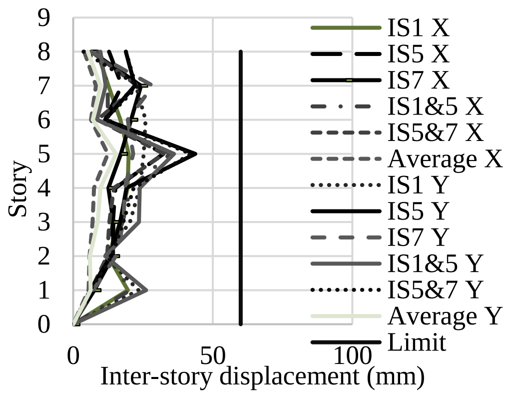

Fig.13 Inter-story displacements of Building Structure B

4.4.3 Internal forces

The internal forces that occur in the structural members such as columns and beams due to the load could be in the forms of bending moment, shear, and axial force. The internal forces were obtained from the structural analysis and the results are given in Table 5.

Table 5 Column internal forces of Building A

Case	Axial (kN)	Shear (kN)	Moment (kN-m)
IS 1	621.552	180.9562	611.9952
IS 5	689.7921	178.1546	666.8586
IS 7	665.2305	178.3165	664.7181
IS 1&5	722.9883	174.638	449.0463
IS 5&7	735.28	175.2608	470.1624

The internal forces in the columns that occur due to the placement of the isolation on the 5th story show the largest among other placements in the table for the x-direction which is 689.7921 kN in axial force, 178.1546 kN in shear, and 666.8586 kN-m in the bending moment. The placement of isolations on the 1st and 5th stories resulted in the smallest force in the column, i.e. axial force of 722.9883 kN, shear of 174.638 kN, and bending moment of 449.0463 kN-m.

Table 6 Beam internal forces of Building A

Case	Shear (kN)	Moment (kN-m)
IS 1	115.897	218.75
IS 5	111.557	236.713
IS 7	107.6144	244.1251
IS 1&5	115.643	247.13
IS 5&7	108.946	208.293

The largest internal forces in the beams (Table 6) for the placement of isolations on the 1st and 5th stories are the shear force and bending moment of

115.643 kN and 247.13 kN-m, respectively. The placement of isolations on the 5th and 7th stories has the smallest shear and bending moment values of 108.946 kN and 208.293 kN-m, respectively.

The internal force in the column that occurs in the placement of isolations on the 5th story is the largest among other placements in the table for the x-direction, which is 658.103 kN in axial force, 165.619 kN in shear, and 382.078 kN-m in the bending moment. The placement of the isolation on the 1st story produces the smallest force in the column, i.e., axial force of 696.469 kN, shear of 154.116 kN, and a bending moment of 323.81 kN-m. While the internal forces in the beams show that the largest values were obtained when the isolations were placed on the 7th story which gave the shear and bending moment of 96.9811 kN and 230.644 kN-m, respectively. The placement of the isolations on the 1st, 5th, and 8th stories gave the smallest values of 104.934 kN in shear and 212.753 kN-m in bending moment (Table 7).

Table 7 Column internal forces of Building Structure B

Case	Axial (kN)	Shear (kN)	Moment (kN-m)
IS 1	696.469	154.116	323.81
IS 5	658.103	165.619	382.078
IS 7	629.621	157.26	356.18
IS 1&5	702.63	158.714	325.34
IS 5&7	653.734	174.186	381.473

The internal forces in the beams (Table 8) show that the placement of isolations on the 1st and 3rd stories gave the largest shear and bending moment of 113.779 kN and 238.985 kN-m, respectively. The placement of isolations on the 7th story gave the smallest values of shear and bending moment of 96.9811 kN and 230.644 kN, respectively. In terms of internal forces, Building B with the placement of isolations on the 5th story shows better in resisting the internal forces which produces a smaller bending moment than that of Building A which produces a larger bending moment such that Building B can perform better compared to Building A

Table 8 Beam internal forces of Building Structure B

Case	Shift (kN)	Moment (kN-m)
IS 1	105.834	228.407
IS 5	105.549	220.086
IS 7	96.9811	230.644
IS 1&5	104.934	212.753
IS 5&7	105.597	221.423

4.4.4 Story Shear

The story shear was obtained from the calculations using the aid of a structural analysis program and presented in the form of a graphical representation shown in Fig. 14. The story shear of Building A is the largest when the placement of isolations on the 1st and 5th stories with a value of 2119.01 kN. The smallest story shear value is 305.988 kN when the placement of isolations is on the 5th story. This happened due to different structural responses for different isolation placements or story shear which was obtained from the structural analysis which the output is represented in the graphical form.

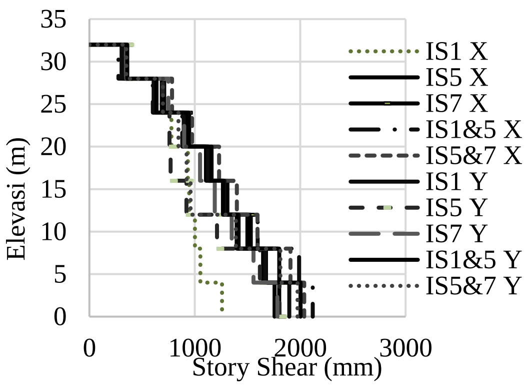

Fig.14 Story Shear of Building Structure A

The largest value of the story shear of Building B (Fig. 15) occurred when the placement of isolation on the 1st and 5th stories, i.e. 2119.02 kN. This can be seen in Fig. 16, the graphical comparison of story shear values between the x- and y-directions. The smallest shear value of 275.096 kN was found when the placement of isolations was on the 1st and 5th stories. This was caused by a different structural response. The story shear of Building B with the placement of isolations on the 1st and 5th stories is the most ideal compared to Building A because it produces a smaller value of story shear which minimizes the building from progressive collapse.

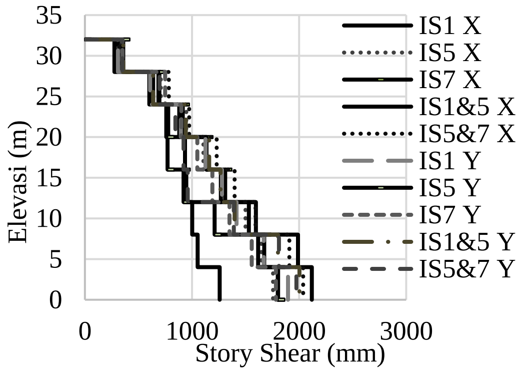

Fig.15 Story Shear of Building Structure B

5. CONCLUSION

The greatest structural response due to earthquake load occurred when the isolations were located on the 1st and 5th stories as can be seen from the results of the building period, inter-story displacement, story shear, and internal forces. The placement of isolations with better results can be obtained when the isolations were placed at two stories rather than only at one story. The corresponding results obtained are more effective and better in minimizing structural damage. However, the placement of isolations is not suitable to be located on the top story. The results show an ineffective impact in terms of internal forces, story shear, and inter-story displacement. Based on the analytical results obtained from the structural analysis program due to the earthquake load, it was found that the placement of isolations on the 1st and 5th stories provided the best response. The placement of isolations on the 7th story gave ineffective results due to earthquake load in terms of internal forces, story shear, and inter-story displacement in the effort to minimize structural damage due to the earthquake impact.

6. ACKNOWLEDGMENTS

The authors also gratefully acknowledge the financial support received from the Institut Teknologi Sepuluh Nopember for this work, under the project scheme of the Publication Writing and IPR Incentive Program (PPHKI) 2023.

7. REFERENCES

[1] Wijaya U., Soegiarso R., Tavio, and Wijaya A., Numerical study of potential Indonesian rubber for elastomeric base isolators in highly-seismic zones, Journal of Physics: Conference Series, Vol. 1477, No. 5, 2020, pp. 1-7.

[2] Wijaya U., Soegiarso R., and Tavio, Seismic performance evaluation of a base-isolated building, International Journal of Civil Engineering and Technology, Vol. 10, No. 1, 2019, pp. 285-296.

[3] Habieb A.B., Milani G., Tavio, and Milani F., Seismic performance of a masonry building isolated with low-cost rubber isolators, WIT Transactions on the Built Environment, Vol. 172, 2017, pp. 71-82.

[4] Habieb A.B., Milani G., Tavio, and Milani F., Low-cost frictional seismic base-isolation of residential new masonry buildings in developing countries: A small masonry house case study, Open Civil Engineering Journal, Vol. 11, No. M2, 2017, pp. 1026-1035.

[5] Tavio, Anggraini R., Raka IG.P., and Agustiar, Tensile strength/yield strength (TS/YS) ratios of high-strength steel (HSS) reinforcing bars, AIP Conf. Proc., Vol. 1964, No. 020036, 2018, pp. 1-8.

[6] Wijaya B.T.W., and Tavio, Mechanical properties of Indonesian rubber for low-cost base isolation, International Journal of Civil Engineering and Technology, Vol. 10, No. 1, 2019, pp. 884-890.

[7] Harsono B., and Tavio, Tensile properties of fiberglass as reinforcement of low-cost rubber base isolator for small houses, International Journal of Civil Engineering and Technology, Vol. 10, No. 1, 2019, pp. 1933-1940.

[8] Rofiq H.I., Tavio, and Iranata D, Model validation of carbon-fiber and glass-fiber reinforced elastomeric isolators using finite element method, IOP Conference Series: Earth and Environmental Science, Vol. 1116, No. 012001, 2022, pp. 1-12.

[9] Tavio, and Purniawan A., Behavior of rubber base isolator with various shape factors, AIP Conference Proceedings, Vol. 1903, No. 020021, 2017, pp. 1-7.

[10] Zhou F., Xiang W., and Zhu H., Theoretical study of the double concave friction pendulum system under variable vertical loading, Advance in Structural Engineering, Vol. 22, No. 8, 2019, pp. 1-8.

[11] Tavio, and Wijaya U., Experimental study of Indonesian low-cost glass fiber reinforced elastomeric isolators (GFREI), International Journal on Advanced Science, Engineering and Information Technology, Vol. 10, No. 1, 2020, pp. 311-317.

[12] Ryan K.L., and Earl C.L., Analysis and design of inter-story isolation system with nonlinear devices, Journal of Earthquake Engineering, Vol. 14, 2010, pp. 1044-1062.

[13] Almazan J.L., de La Llera J.C., and Inaudi J.A., Modelling aspects of structures isolated with the frictional pendulum system, Earthquake Engineering and Structural Dynamics, Vol. 27, No. 8, 2015, pp. 845-867.

[14] Wang Y.P., Chung L.L., and Liao W.H., Seismic response analysis of bridges isolated with friction pendulum behavior, Earthquake Engineering and Structural Dynamics, Vol. 27, No. 10, 2015, pp. 1069-1093.

[15] Shahabi A.B., Ahari Z.G., and Barghian M., Base isolation system-a state of the art review according to their mechanism, Journal of Rehabilitation in Civil Engineering, Vol. 8, No. 2, 2020, pp. 37-61.

[16] Fenz D.M., and Constantinou M.C., Behaviour of the double concave friction pendulum bearing, Earthquake Engineering and Structural Dynamics, Vol. 35, No. 11, 2010, pp. 1403-1424.

[17] Fenz D.M., and Constantinou M.C., Spherical sliding isolation bearings with adaptive behavior: experimental verification, Earthquake Engineering and Structural Dynamic, Vol. 32, No. 2, 2008, pp. 185-205.

[18] National Standardization Agency. Procedures for designing earthquake resistance for building and non-building structures (SNI 1726:2019), BSN, Jakarta, 2019, pp. 1-238.

[19] Schellenberg A.H., Becker T.C., and Mahin S.A., Hybrid shake table for the testing of midlevel seismic isolation system, 13th World Conference on Seismic Isolation, Paper No. 901421, 2013, pp. 1-9.