Numerical Study of Potential Indonesian Rubber for Elastomeric Base Isolators in Highly-Seismic Zones

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Abstract. Indonesia is located in high seismic zones. Therefore, earthquake dissipated devices such as elastomeric base isolator is needed to minimize building's damages when an earthquake occurs. In this study, a numerical two-stage analysis was carried out to evaluate the behaviour of elastomeric base isolators. First, elastomeric base isolators were modelled in the finite element software to obtain vertical and horizontal stiffness and damping values based on local rubber of mechanical properties that is obtained from the previous tests. Second, the values of vertical and horizontal stiffness and damping values were analysed in a case study of a ten-stories hospital building located in Padang, West Sumatra, Indonesia using nonlinear time history analysis of seven different ground motion values. The studied results showed that the structure with base isolators using a local rubber base material can reduce damage caused by the earthquake with an indication of an increase in time period, decreased base shear, and also a decrease in displacement of the structure. Therefore, the use of local rubber for elastomeric base isolators is promising a good future for the advancement of the construction industry in Indonesia.

1. Introduction

Indonesia is located above four tectonic plates namely, namely the Eurasian, the Indo-Australian, the Philippine, and the Pacific plate. For this reason, the country constantly encounters earhquake risk due to tectonic plate movement. It is extremely difficult to predict exactly when the earthquakes will likely to strike and thus their emergence becomes inavoidable. In 2009, the 7.9 magnitude earthquake shook the city of Padang. The 2009 quake killed 675 people, and caused 527 people seriously injured and 528 slightly injured. In addition, the quake brought down 70,833 buildings and caused major damage of 12,630 units and minor damage of 4,442. The losses caused by the earthquake in Padang reached IDR 7.8 billion [1].

Instability of a building to withstand the earthquake force leads to a major damage and even collapse. Therefore, the design for earthquake-resistant building becomes necessary to reduce human fatalities and avoid building's collapse. Each building has its own risk category. The hospital is among the high-risk categories because when an earthquake occurs the building must continue to operate [2].

With the development of technology in the design of earthquake-resistant structures, a system has been developed to reduce the risk of building damage due to earthquake, and to be able to maintain structural components. The system works by reducing such emitting earthquake force that only a small part of the force will be handled by the building structure. The system is called base isolation [3].

Various studies have been conducted to improve the performance of the base isolator to handle the earthquake forces. Unfortunately, the system has not been applied in Indonesia, a country which lies in a highly seismic zone. Therefore this study is conducted rise public awareness in Indonesia on construction design in the seismic zone to reduce the risks caused by earthquakes using a base isolator. This study follows up the previous research by Wijaya et al (2019) on the use of local rubber for base isolators. In this study, the mechanical properties of the test results in Wijaya et al (2019) was simulated with a finite element software to obtain an effective stiffness and dissipated energy ratio through damping values and subsequently analyzed using nonlinear time history analysis of seven ground motion to determine the behavior of elastomeric base isolators using local rubber.

2. Method

Base isolation is a structural design that is intended to minimize the potential building damage caused by an earthquake by reducing the earthquake force acting on buildings [4]. Base isolation is a system of separating building structures with horizontal components from ground movement and adding structural elements that have low horizontal stiffness between the main structure and the base [5]. With such a concept, the earthquake force acting on the structure can be reduced. In addition, base isolation can restore the original position of the building when an earthquake occurs as in figure 1.

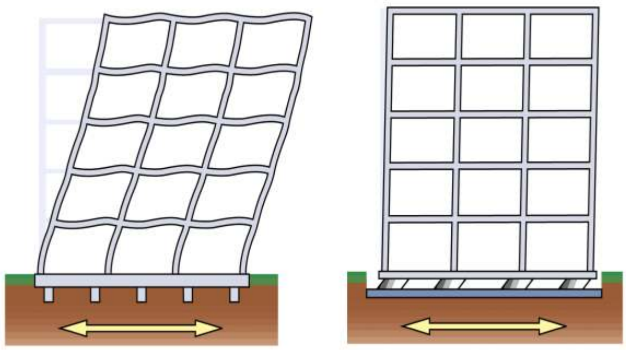

Figure 1. Conventional system VS base isolation system [6]

2.1 Geometric properties

To obtain geometric properties of a base-isolator, the following formula can be used [7]:

2.1.1 Horizontal Stiffness

$$K_{\mathrm{H}} = \frac{G \, . A}{tr} \tag{1}$$

where:

G = Elastomer shear modulus, (MPa)
A = Total area (mm)
tr = Total thickness of the rubber (mm)

2.1.2 Vertical Stiffness

$$K_V = \frac{Ec\,.A}{tr} \tag{2}$$

where:
Ec = Compression Modulus (MPa)

2.1.3 Compression Modulus

$$E_C = 6\,.\,G\,.\,S^2 \tag{3}$$

where:
S = Shape Factor

2.1.4 Horizontal Stifness

$$K_H = \frac{GA}{t_r} \tag{4}$$

2.1.5 Effective stiffness

$$K_{eff} = \frac{(F_{\max} - F_{\min})}{(d_{\max} - d_{\min})} \tag{5}$$

2.1.6 Damping ratio

$$\beta = \frac{W_d}{(4\pi W_s)} \tag{6}$$

W_d is obtained from the total area of hysteresis loop. And W_s is calculated using equation 7 [8].

$$Ws = \frac{(K_{eff}(\Delta_{\max})^2)}{2} \tag{7}$$

Δ_{max} is the average of positive and negative displacement and calculated according to equation 8 [8].

$$\Delta_{\max} = \frac{(\Delta^+ + |\Delta^-|)}{2} \tag{8}$$

2.2. Cross section of base isolators

The base isolator used in this study has a diameter of 600 mm and a total height of 420 mm, as can be seen in figure 2.

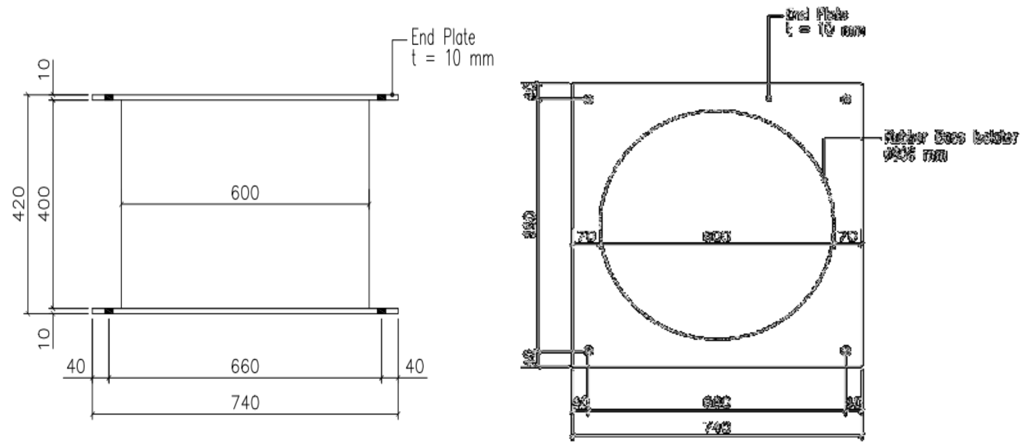

Figure 2. Cross section of the base isolator

2.3. *Mechanical properties*

Mechanical properties of the rubber used were local rubbers which had previously been examined in the previous study by Wijaya et al (2019). From the study, mechanical properties were obtained as shown in table 1 [9].

Table 1. Mechanical properties local rubber

Description	Type A
Hardness (shore A)	42
Elongation at break	>500%
Elastomer shear modulus (G)	0.56 MPa
Young's modulus of glass fiber	4200 MPa
Poisson ratio of glass fiber	0.21

2.4. *Response spectrum of Padang (West Sumatra, Indonesia)*

In this research, the case study of the building location was in Padang which is an earthquake-prone area, assuming that the rock sites in the location is classified into Soft Soil as shown in figure 3 [10].

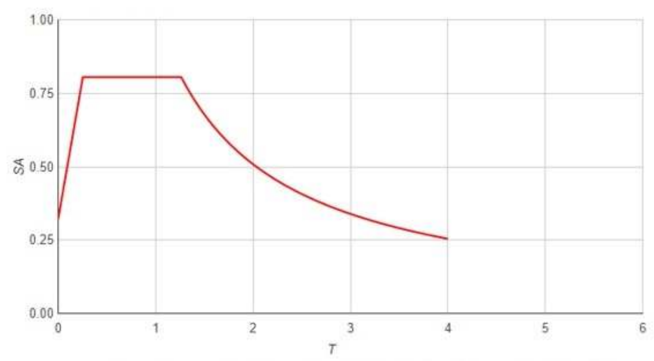

Figure 3. Response spectrum of Padang

2.5. Time history analysis

Time history analysis was conducted to scale the response spectrum of the recorded earthquake into the response spectrum of Padang. Thus, for analysis, this study used the scaled ground motion. The number of earthquake histories was based on SNI 1726: 2012 requirements, as seen in table 2. Meanwhile the seven ground motion scaling can be seen in figure 4 [10].

Table 2. Lists of ground motion used

Earthquake case	Year	Magnitude	Distances (km)	Vs 30 m/s	Scale	
					X	Y
Imperial Valley	1979	6.53	2.66	223.03	0.592	0.454
Kobe	1995	6.9	1.47	256.00	1.277	2.463
El-Centro	1979	6.53	2.66	223.03	0.593	0.437
Friuli	1976	6.50	1.,82	505.23	1.189	0.909
Northridge	1994	6.69	8.44	380.06	0.479	0.432
Taiwan	1999	7.62	2.69	496.21	0.318	0.363
San Fernando	1971	6.61	1.81	2016.13	0.562	0.588

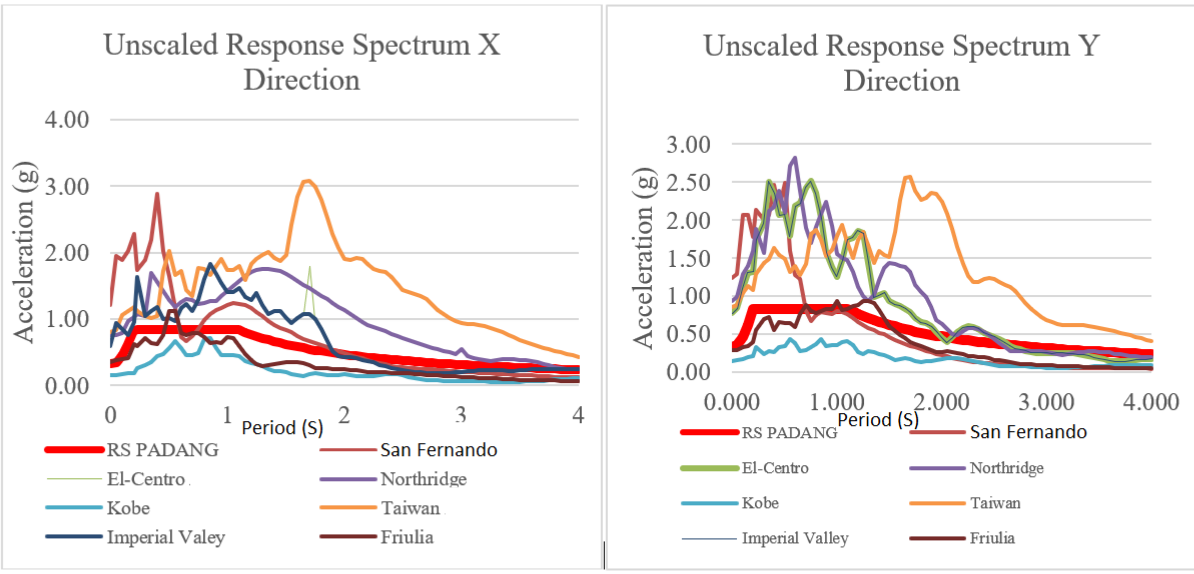

Figure 4. Ground motion vs response spectrum in X and Y direction

3. Results and discussions

The mechanical properties from the laboratory test of the local rubber of 42 Shore A Hardness Grade by Wijaya et al (2019) were inputted using finite element numerical simulations and it is obtained that the most appropriate and fittest local rubbers for all testing models are the Yeoh model with constitutive model constants of C_{10} = 0.202 MPa; C_{20} = -0.004 MPa and C_{30} = 0.0003 MPa. Simulation to find out the characteristics of elastomeric base isolator is shown in Figure 5.

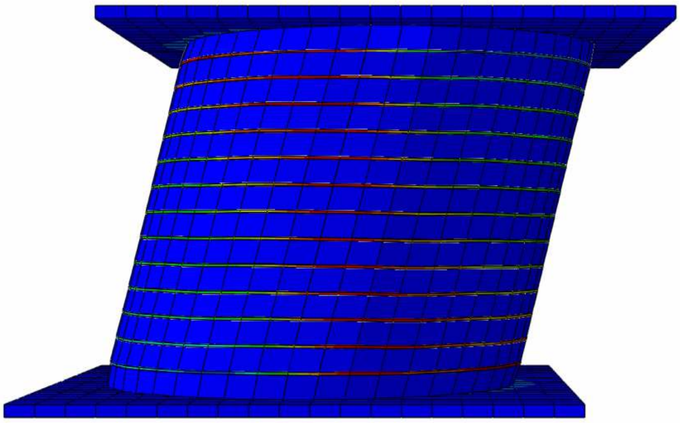

Figure 5. Deformed base isolator

From the simulation results using finite element software and solving equations (1) to (8), the horizontal stiffness value for elastomeric base isolator with a diameter of 600 mm and a height of 420 mm is 879.75 kN/m and the damping value for the base isolator is 11 %.

To find out the behavior of elastomeric base isolator using local rubber, the results of the first stage simulation using finite element were followed up in the second stage using non linear time history analysis of seven ground motion scaled with earthquake response spectrum of the Padang (West Sumatra) earthquake. Then, base isolator and the fixed based support were compared. From the results of the non-linear time history analysis of seven ground motion time periods, shear forces, story drift, displacement, and structure performance were obtained for each fix based support and base isolator.

3.1 Time period
Non linear time history analysis is carried out on two models namely the fix based support model and the model with base isolators as shown in Table 3.

Table 3. Comparison of natural time period between the fixed based structure and base isolator

Mode	Fixed Based Period	Base Isolator Period
1	1.34	3.78

In terms of the period, it is found that the structure with base isolator has increased significantly. The period for the base isolator structure is 3.78, while for the fixed based it is only 1.34 seconds. This shows that the base isolator structure is more flexible than the fixed based. With an increase in the time period, the received base shear can be reduced.

3.2 Shear Forces
To identify behavior of elastomeric base isolator using local rubber, it is necessary to compare base shear of the fixed based support and the base isolator support, as shown in table 4.

Table 4. Comparison of base shear between the fixed based structure and base isolator

Fixed Based		*Base Isolator*		Ratio
Dynamic		Dynamic		
Shear forces		Shear forces		
Vx ton	Vy Ton	Vx ton	Vy ton	
123.8	108.1	23.5	23.0	72.4%
254.4	217.6	49.7	48.4	
374.3	315.3	75.6	73.2	
483.4	403.0	101.1	97.4	
581.6	481.2	126.2	120.8	
669.7	551.3	151.1	143.9	
747.8	613.4	175.9	166.7	
813.8	665.9	200.3	188.9	
865.6	706.9	224.2	210.5	
898.2	731.6	247.5	231.4	

The comparison between the fixed based and base isolator produces a ratio of 72.4%, so that the shear force acting on the base isolator will be reduced by 27.6%. Thus, the earthquake force will be firstly absorbed by the rubber bearing of base isolator before transferred to the structure above.

As for the ductility study, the use of a local rubber base isolator has a significant impact, as seen from the comparison of the response modification coefficient (R) of elastic condition = 2.5 to inelastic condition of R = 8 as presented in table 5.

Table 5. Comparison of base shear between response modification coefficients of base isolators

2.5		3.5		5		8	
Shear forces		Shear forces		Shear forces		Shear forces	
Vtx Ton	Vty Ton	Vtx Ton	Vty Ton	Vtx Ton	Vty Ton	Vtx Ton	Vty Ton
75.1	73.6	53.6	52.5	37.6	36.8	23.5	23.0
159.1	154.9	113.6	110.6	79.5	77.4	49.7	48.4
242.0	234.3	172.8	167.3	12.,0	117.1	75.6	73.2
323.6	311.5	231.1	222.5	161.8	155.8	101.1	97.4
403.8	386.7	288.4	276.2	201.9	193.3	126.2	120.8
483.5	460.5	345.4	328.9	241.8	230.3	151.1	143.9
563.0	533.4	402.1	381.0	281.5	266.7	175.9	166.7
641.0	604.5	457.9	431.8	320.5	302.3	200.3	188.9
717.5	673.6	512.5	481.2	358.7	336.8	224.2	210.5
791.9	740.5	565.6	528.9	395.9	370.3	247.5	231.4

From table 5 it can be seen that the base isolator structure with a higher R-value will reduce the shear force experienced by the structure. Meanwhile, with a smaller R-value, the structure will receive a greater base shear.

3.3 Story Drift

From the comparison of story drift between the base isolator and fixed based, it is found that the system with base isolator will increase the drift on the ground floor by 15 mm in the x-direction and 20 mm in the y-direction. Meanwhile, for the fixed based it will be 7.5 mm for the x-direction and 8 mm in the y-direction. The relatively large story drift on the base isolator structure on the ground floor is caused by rubber properties that have good ductility and damping values. Comparison of drift between the fixed based and base isolator can be seen in figure 6.

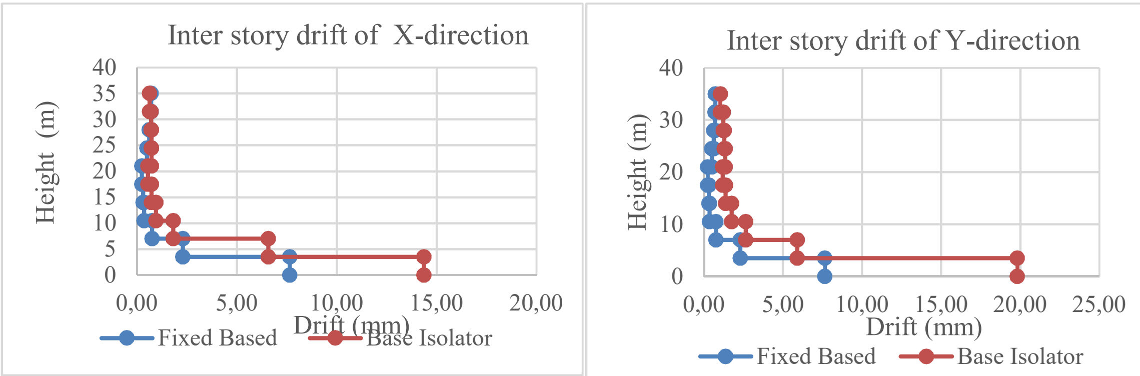

Figure 6. Comparison of story drift

3.4 Displacement

After time history analysis, a displacement of each structure was obtained. For the fixed based, displacement occurs on the roof by 352 mm for the x-direction and by 355 mm for the y. As for the base isolator, roof displacement occurs at 71 mm for the x-direction and 72 mm for y-direction. Displacement at the base isolator is smaller than the fixed based, primarily caused by damping of the rubber bearing. This can be seen from the displacement graph for the base isolator in figure 7, where the largest displacement occurs on the ground floor.

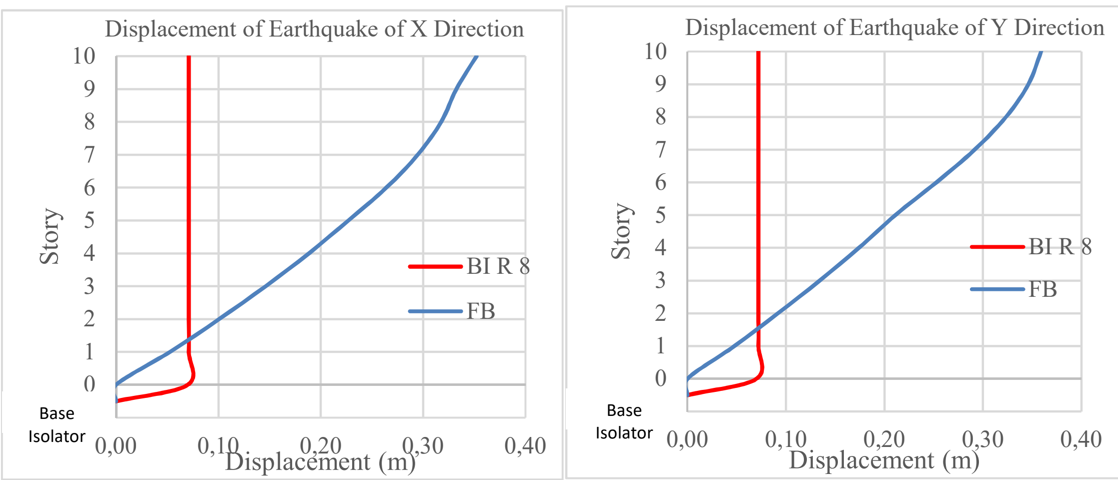

Figure 7. Comparison of displacement between base isolator and the fixed based

3.5 Performance of the structure

For the fixed based structures with nonlinear time history analysis, the most decisive and appropriate ground motion for the Padang's spectrum response is the Kobe's ground motion with the structural performance level of Damage Control (DC) for x-direction and y-direction (see table 5). While the structure with base isolator has a Max Roof Drift of 0.02 for x and y-direction so that the performance of the base isolator is at the level of expected performance for hospital buildings, which is Immediate Occupancy (IO). As building's function is intended for hospitals, according to SNI 1726: 2012 the permissible structure performance is the IO.

Table 6. Performance of structure of base isolator and the fixed based

Story	Base Isolator		Fixed Based	
	Max. Roof Drift X	Max. Roof Drift Y	Max. Roof Drift X	Max. Roof Drift Y
Roof	0.0020	0.0020	0.0101	0.0103
Performance	IO	IO	DC	DC

Furthermore, nonlinear time history analysis is performed on each response modification of R = 2.5; R = 3.5; R = 5; and R = 8.0 to determine the level of performance of each level of response modification (R). From the results of the analysis it was found that all modifications still meet the level of structural performance of IO. Therefore, the structure with the base isolator confirms the use of SNI 1726: 2012 for the response modification coefficient of 2.5. The drift value is the best among the other response modification values as shown in table 7.

Table 7. Structural performance between of modification coefficients base isolator response

Story	R 2.5		R 3.5		R 5		R 8	
	Max. Roof Drift X	Max. Roof Drift Y	Max. Roof Drift X	Max. Roof Drift Y	Max. Roof Drift X	Max. Roof Drift Y	Max. Roof Drift X	Max. Roof Drift Y
Roof	0.005	0.00414	0.00383	0.00311	0.00257	0.00303	0.00203	0.00206
Performance	IO	IO	IO	IO	IO	IO	IO	IO

4. Conclusion

The numerical study of the use of elastomeric base isolators with local rubber materials was carried out in two stages. The first stage involved simulation of elastomeric base isolator using local rubbers based on the test results of Wijaya et al (2019). It can be concluded that the most compatible local rubber with the mechanical properties of the finite element is the Yeoh model. The elastomeric base isolator product was simulated using a finite element software to obtain stiffness properties and a damping value of 11% which corresponds to a 10-story building for hospital functions located in the earthquake-prone areas in the city of Padang. The second stage used nonlinear time history analysis of scaled seven ground motion to the spectrum response of the Padang city to obtain a local rubber base isolator product that has competitive behavior equal to imported products such as being able to extend the period of building vibrations, able to reduce base shear by 28% and reduce displacement up to 20%. The performance of the building structure is in accordance with SNI 1726: 2012 regulations for hospital buildings, namely Immediate Occupancy. As for the correlation factor modification response (R), the use of a local rubber base isolator shows positive results where according to SNI 1726: 2012 the response modification value (R) for buildings that use elastomeric base isolators must be in an elastic state or R = 2.5. However, the simulation results indicates an inelastic condition of R = 8 even though it still produces the performance structure of the Immediate Occupancy building so that future research can address this response modification (R) to produce an optimal and safe design. The results of this two-stage numerical study shows that local rubber has a bright future for the extensive use in construction projects in Indonesia, as the country has abandon sources of rubbers to produce low cost elastomeric base isolator and to develop the rubber industry for the construction project.

Acknowledgement
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