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SEISMIC RISK ANALYSIS OF PUBLIC BUILDINGS WITH BASE ISOLATION USING INCREMENTAL DYNAMIC ANALYSIS (IDA) METHOD

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Abstract. *Earthquake can induce dynamic vibrations in building structures, which may compromise their durability and pose significant challenges to structural integrity, thereby necessitating effective protective measures. In this study, seismic base isolation was applied to reinforced concrete building structures. Base isolation is one of the effective techniques in protecting structures exposed to earthquake stimuli. In assessing the effect of the isolation system, a comparative analysis is conducted between 7-story reinforced concrete buildings without seismic protection and those equipped with Lead Rubber Bearing (LRB). In analyzing the dynamic response of the structure, Incremental Dynamic Analysis (IDA) was performed through numerical simulations using nine selected earthquake acceleration records with the aid of the Seismostruct application. The analysis results indicate that the structural resistance of the building significantly affects the seismic forces, particularly when comparing the existing structure with the base-isolated model. The structure quipped with a base isolation system demonstrates a more controlled behavior and a substantially reduced displacement response compared to the non-isolated building. In addition, the fragility curves of the two buildings show clear differences. According to the HAZUS-MH MR5 guidelines, the base-isolated structure remains below the significant damage threshold, demonstrating an overall enhancement in seismic performances.*
Keywords: *Fragility Curve, Incremental Dynamic Analysis, Lead Rubber Bearing, Reinforced concrete building, Seismic Base Isolation*

INTRODUCTION

When an earthquake occurs, the building structure will experience vibrations dynamically. This condition causes shocks to the structure that can reduce its resilience capacity. Therefore, an adequate structural protection system is required. Various innovations have been developed by researchers to overcome this problem, one of which is the use of base isolation systems. Jayapura City is included in an area that represents a high level of earthquake vulnerability. This is due to the tectonic condition of the region which is in line with the regional tectonic configuration in Papua. Research by Lunga et al. (2015) showed that the frequency of earthquake events around the Jayapura City area was high from 2000 to 2014, with earthquake strengths ranging from 4.0 to 6.5 on the Richter scale.Introduction (Lunga et al., 2015).

According to SNI 1726-2019, hospital buildings are categorized as essential facilities. Buildings classified in Risk Category IV require special handling of potential earthquake loads that can occur at any time. The hospital that is the object of this research is located in an earthquake-prone area and has not been equipped with a special earthquake retrofitting system. Therefore, structural strengthening efforts are needed to minimize the risk of damage in the event of a high-intensity earthquake. The planned retrofitting method is the application of a base isolation system.

Base isolation is one of the effective techniques to protect structures subjected to earthquake stimuli. A variety of these isolation devices have been developed such as elastomer-based systems and shear-based isolation systems, e.g. friction pendulum system (FPS). Inter-storey isolation is considered as one of the most attractive solutions in structural engineering that enables the construction of sustainable multifunctional buildings for densely populated areas (Zhang et al., 2023). The base isolation that will be used in this research is a thin rubber layer reinforced by steel plates or called Lead Rubber Bearing (LRB). This character of LRB allows it to carry significant vertical loads due to its high vertical stiffness and move laterally with relatively lower stiffness than other isolation systems (Zhao et al., 2019). Compared to other isolation devices, LRBs require minimal cost and maintenance. An important element in LRBs is the lead

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core that provides initial earthquake stiffness and exhibits nonlinear behavior aimed at adding damping to the structure when exposed to strong earthquakes (Zordan et al., 2014).

The method used to determine the behavior of structures against earthquakes is by using Incremental Dynamic Analysis (IDA). The concept of this analysis method is to simulate structural damage due to various earthquakes based on earthquake records. Different earthquake records will produce different levels of scale. The advantage of the IDA method is the ability to assess the structural response in the entire range of earthquake intensities studied by considering the uncertainty of possible future earthquake records (Jouneghani & Haghollahi, 2020). Compared to Static Pushover Analysis, the IDA method is considered more accurate because the structural response is analyzed using the actual earthquake data available. Thus, the results obtained reflect the real response of the structure to earthquake loads. Although the IDA method requires a relatively longer analysis time, its use is highly recommended when the structure being analyzed requires a high level of accuracy (Rahul & Uttam, 2018).

Based on these innovative applications, the base isolation system was chosen as the main focus in this study. The research was conducted through advanced tridimensional numerical simulations that consider the dynamic interaction between the superstructure and substructure of the building. The model analyzed is a hospital structure assumed to be located in Jayapura City, Papua, which is known as a region with a high level of seismic activity. This case study aims to evaluate the effect of using a Lead Rubber Bearing (LRB) type base isolation system on the dynamic response of the structure, particularly in relation to high-level vibration methods. In this study, a comparison is made between the seismic performance of the existing structure without isolation and the structure that has been equipped with a base isolation system. This analysis is expected to provide a more comprehensive picture of the effectiveness of isolation systems in reducing seismic response, as well as contributing to the development of earthquake disaster mitigation strategies in vital facility buildings such as hospitals. This approach is important given the function of hospitals that must remain operational after an earthquake, so improving structural resilience through base isolation technology becomes a crucial aspect.

After the analysis, fragility curves can be derived for both structural conditions, i.e. the existing structure and the structure equipped with a base isolation system. The seismic fragility evaluation aims to identify the probability of structural damage or collapse at various levels of earthquake intensity. The assessment includes the likelihood of collapse in both empty-frame and filled structures (e.g., with partitions or non-structural elements), which have different vulnerabilities to a single earthquake and a series of seismic events, such as a main earthquake followed by aftershocks. These results are expected to provide a deeper understanding of the behavior of structures under successive earthquake loads and support more reliable earthquake-resistant design strategies (Di Trapani & Malavisi, 2019).

METHODOLOGY

Structural modeling was performed using SeismoStruct software, with building specifications consisting of 6 main floors and a roof top. The building specifications are shown in Table 1 and Table 2. The building is designed as a regional hospital. The structural analysis is carried out by comparing two building conditions, namely a structure without an isolation system and a structure equipped with a base isolation system using Lead Rubber Bearing (LRB). Before entering the seismic analysis stage, the initial modeling of the building was prepared using Building Modeler. The modeling included a review of structural elements such as column and beam dimensions, floor and roof slabs, staircases, and gravity and lateral loads acting on the structure. All of these parameters were included to produce a realistic and accurate representation of the structure for simulating the dynamic behavior of the building under earthquake loading.

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Table 1. Elevation of each floor

No	Floor	Elevation (m)	Inter-story elevation (m)
1	1st Floor	1.05	4.5
2	2nd Floor	4.95	4.5
3	3rd Floor	9.45	4.5
4	4th Floor	13.95	4.5
5	5th Floor	18.45	4.5
6	6th Floor	22.95	4.5
7	Roof Top Floor	26.45	3.5

Table 2. Sectional size of coloumn and beam structural elements

	Cross-section size used	
	Length (mm)	**Width (mm)**
Coloumns	850	850
	1000	850
	700	700
	500	500
	Width (mm)	Height (mm)
Beams	450	850
	450	750
	450	500
	300	500
	250	500
	250	450

The floor slab structural elements were modeled with a thickness of 150 mm for floors 1 to 6, and 120 mm for the roof top floor. The entire slab was modeled as a membrane element to represent the in-plane stiffness behavior without bending contributions in the perpendicular direction of the slab, as assumed by the structural idealization. The building structure is shown in Figure 1. Once the structural modeling is complete and all components have been defined in the software, the next process is the structural analysis stage. The first step in the analysis is the Eigenvalue analysis, which aims to obtain the value of the natural period of the structure. These values are very important as a basis in the process of calibrating and matching the dynamic response to the earthquake load to be analyzed at a later stage.

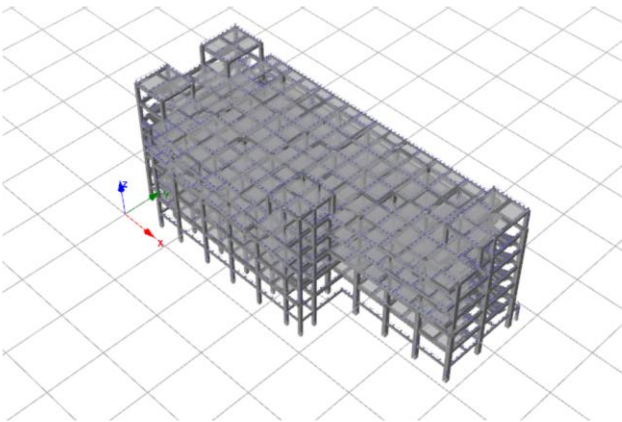

Figure 1. Hospital building structure to be analyzed

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RESULT AND DISCUSSION

Design and Basic Isolation Characteristic of Lead Rubber Bearing

Lead rubber bearing (LRB) is currently one of the most widely used insulators among all other types of insulators. In terms of construction, the addition of a lead-plug in the center hole of the bearing differentiates the Lead Rubber Bearing from elastomers. Therefore, this lead core will undergo plastic deformation under shear stress, resulting in increased energy dissipation in contrast to low-damping natural rubber bearings (elastomers). LRB is an elastomeric bearing made from a rubber layer with steel plates, cover plates and lead core. The advantage of LRB is the incorporation of isolation and re-centering functions in a single element that provides structural support, horizontal flexibility and centralizes forces to the isolation system (Bhagat & Wijeyewickrema, 2017).

The literature has extensively reviewed aspects of the theory, development and application of seismic isolation technology. Kelly highlights that the technology began as a basic concept of seismic isolation, which then evolved through various researches. Buckle and Mayes added a list of early applications of seismic isolation that were instrumental in expanding its application. Meanwhile, Tayor et al. reviewed the use of elastomeric bearings with a focus on their long-term performance. In conventional structures, earthquake forces propagate through the damage. To prevent this, isolation systems with flexible elements such as elastomeric bearings are placed between the structure and the foundation, along with additional damping mechanisms to control relative displacement (Warn & Ryan, 2012) (Shekarisoleimanloo, 2012).

Referring to the provisions in SNI 1726:2019, the planning of structures that use basic isolation systems must take into account both vertical loads and lateral loads caused by wind and earthquakes. In addition, the isolation system must also consider various environmental factors and service life, including the effects of material aging, creep, material fatigue, operational temperature fluctuations, as well as humidity conditions and exposure to chemicals that can damage insulator components.

The configuration of the isolation system must take into account the material property limitations, i.e. the upper and lower limits of the isolator performance characteristics, in order to keep the system functioning optimally within the planned working range. One important requirement that must be met is that the lateral restoring force at maximum displacement must be at least 0.025W greater than the lateral force that occurs at 50% of maximum displacement, where W is the total weight of the structure. This is intended to ensure that the isolation system is able to effectively return the structure to its original post-earthquake position.

The selection of Lead Rubber Bearing (LRB) is carried out after first knowing the maximum vertical load that the isolation system must withstand. The LRB selection process refers to the technical specifications available in the MAGEBA product catalog, which provides various types and capacities of insulators according to structural needs. After making adjustments to the load and isolation performance requirements, the Lead Rubber Bearing (LRB) specifications selected for the structure are shown in Table 3.

Table 3. Specifications of LRB used

Dimension	D (mm)	Bearing Area (mm^2)	Vertical Stiffness (kN/mm)	Vertical Stiffness (kN/m)	Horizontal Stiffness (kN/mm)	Horizontal Stiffness (kN/m)	Shear Yield Strength	Hardening Ratio	Rubber Total Height (mm)	Total Height of Isolator (mm)
700x700	800	502857.1429	3729	3729000	2.98	2980	50	26	152	314
850 x 850 ; 1000 x 850	900	636428.5714	4703	4703000	3.41	3410	75	26	168	338
500 x 500	600	282857.1429	1742	1742000	1.86	1860	20	28	136	290

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Earthquake Recording Scenario

Based on the ASCE/SEI 7-16 standard, the selection of ground motion records for dynamic analysis should consider several key parameters, namely earthquake magnitude, distance from the source, and soil conditions at the site. However, the most essential aspect in record selection is the suitability of the shape of the response spectrum of the earthquake recordings with the response spectrum of the design target (ASCE, 2022). In this study, the research object is a hospital building located in Jayapura City. Based on data from the Center for Settlement Research and Development (Puskim, 2021), the acceleration value of the response spectrum of the area is Ss = 1.5 g for a short period and S1 = 0.620 g for a period of one second. The site location is categorized as medium soil class (Soil Class SD) according to SNI 1726:2019 classification. These values were used as the basis in the formation of the target response spectrum, which is further displayed in Table 4, to ensure compatibility between the input earthquake data and the actual seismic conditions of the study area.

Table 4. Medium Ground Acceleration Coefficient of Jayapura City

Jayapura City Medium Ground Acceleration Coefficient Data	
Variable	**Value**
PGA (g)	0,600
Ss (g)	1,500
S_1 (g)	0,620
T_0 (s)	0,070
Ts (s)	0,370
Sds (g)	0,900
Sd_1 (g)	0,330

This research requires several records of earthquakes that have occurred previously. Table 5 shows a series of 10 seismic records. These seismic records were selected from the ground motions recommended by FEMA and the detailed acceleration information of each seismic record was obtained from the Pacific Engineering Research Center (PEER) Earthquake database.

Table 5. Selected Ground Motion Recordings

Event	Year	Station	Magnitude
Imperial Valley - 02	1940	El Centro Array #9	6.95
Parkfield	1966	Chloma-Shanndon Array #12	6.19
Imperial Valley	1979	Cerro Prieto	6.53
Coalinga-02	1983	Sulpur Baths (temp)	5.09
Loma Prieta	1989	Coyoto Lake Dam (Downst)	6.93
Cape Mendocino	1992	Shelter Cove Airport	7.01
Landers	1992	Joshua Tree	7.28
Northridge - 06	1994	LA - Temple & Hope	5.28
Kobe, Japan	1995	Kobe University	6.9

The results obtained from the PEER Earthquake database are acceleration data (accelorogram) so they need to be converted into spectral responses with the help of the Seismosignal application. An accelerogram is a record of an earthquake produced by an accelerograph. Accelerograms should be compatible with the elastic design response spectrum of the region. Each accelerogram has a relationship with an accelerogram response spectrum for a given damping ratio (Lagaros et al., 2014). All earthquake data used in this study

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are in the longitudinal (x-axis) and transverse (y-axis) directions. The result of Seismosignal itself is to convert the data into response spectra. Figure 1 shows the conversion results of the 10 selected earthquake records.

Each pair of earthquake records needs to be scaled such that with a period range from 0.2T to 1.5T, the SRSS spectrum values of all pairs of horizontal components should not be less than the corresponding ordinate values on the predefined response spectrum. The spectral acceleration (Sa) in both response spectra is compared to obtain the scale factor. The calculation of the scale factor (SF) can be seen in the following formula (1) (Bayyinah & Faimun, 2017)(Kalkan & Chopra, 2010):

$$\Sigma\Phi = \frac{\sum_{i=1}^{n} \bar{A}i \, .Ai}{\sum_{i=1}^{n} Ai \, .Ai} \qquad (1)$$

Where SF is the scale factor, A¯is the spectral acceleration of the target response spectrum at period i, A the spectral acceleration of the response spectrum to be scaled at period i.

Spectral Acceleration of the response spectra of ground motion recordings obtained from the Pacific Engineering Research Center (PEER) Earthquake database shown in Figure 2, does not yet have a similar shape with Sa from the target response spectra so it is necessary to match the two data to match. The matching method if done manually is very complicated, therefore it requires the help of Seismomatch software. The calculation of the scale factor uses the Sa value of the recorded ground motion spectra response and Sa from the target spectra response. The spectral acceleration value used to calculate the scale factor is in the range of 0.2T to 1.5T where T is the first vibration period of the eigenvalue of the structure itself which is T = 1.274 sec, so the range of values used is 0.2 T = 0.255 s and 1.5 T = 1.911 s. Figure 3 shows the alignment of the multi-response spectra to the target response spectra of Jayapura City.

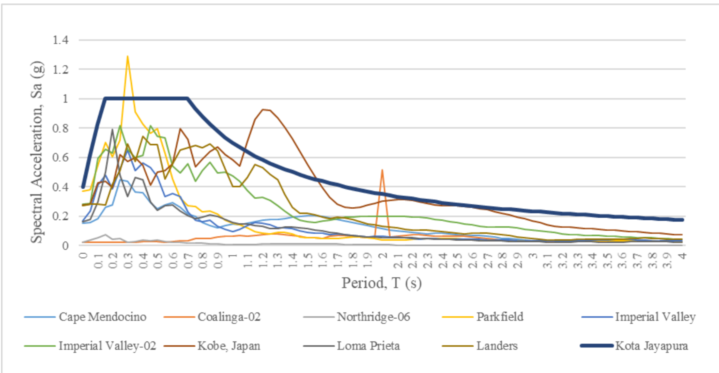

Figure 2. Multi-record spectral response and target spectral response

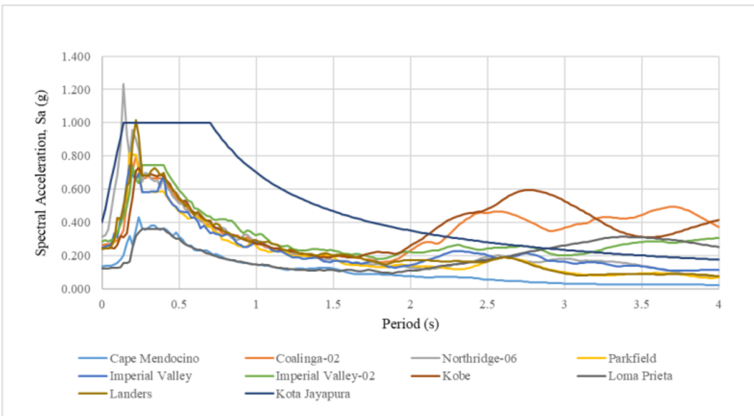

Figure 3. Graph of matching results with target response spectra

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Analysis Method

The analysis conducted was using Incremental Dynamic Analysis with a scale of 1, the results of which can be seen in Table 6. The IDA curve represents the response and behavior of structures subjected to ground motion. IDA depends on the stiffness, strength and ductility of the building to withstand earthquake loads. IDA was conducted using 10 earthquake records to determine the seismic behavior of various structures (Mirtaheri et al., 2017). The result of IDA is a structural behavior curve and the slope of the curve is used to measure the structural behavior. Generally, if the scale factor of the curve is low, the curve produces a straight line, while if the scale factor becomes very high, the curve starts to curve, indicating a nonlinear shape. The building will be declared collapsed when the curve becomes a flat line (Desai et al., 2022).

According to Vamvatsikos and Cornell, 2002, the first step is to define all that is required. Assume if given a single acceleration time history obtained from a ground motion database. The data may have been pre-processed by seismologists. In accounting for milder or more severe ground motions, the transformation can be performed by uniformly increasing or decreasing the amplitude by a scalar $\lambda \in [0, +\infty]$. The acceleration formula is listed in formula (2).

$$a_\lambda = \lambda \, . \, a1 \qquad (2)$$

Where aλ is the scaled earthquake record, λ is the scale factor (SF), a_1 is the ground motion record acceleration. Such an operation can be easily thought of as scaling the elastic acceleration spectrum by λ or equivalently, in the Fourier dominant, as scaling λ amplitudes across frequencies while keeping the phase information intact (Vamvatsikos & Allin Cornell, 2002).

Table 6. PGA Earthquake Data at Scale 1

Earthquake Event	Longitudinal Earthquake PGA, x-axis	Transverse Earthquake PGA, y-axis
Cape Mendocino	0.433	1.511
Coalinga-02	0.849	0.701
Northridge-06	1.235	1.190
Parkfield	0.821	0.687
Imperial Valley	0.745	1.301
Imperial Valley-02	0.745	0.483
Kobe	0.730	1.238
Loma Prieta	0.362	0.786
Sanders	1.014	0.783

Displacement Response

In describing the overall condition of the hospital building structure, the part of the top floor joint close to the axis point is used as a review point to see the displacement response that occurs. The point was chosen because it is the part that is rigidly connected to the beams and columns of the building. The point can also describe the behavior of the hospital column structure and at the same time provide an overview of the deviation that occurs at the support. So that researchers can find out whether the hospital collapsed due to column failure.

The large amount of earthquake data used in the analysis results in very diverse responses. Moreover, with the addition of earthquake intensity to run IDA, the structural response created becomes even more. Therefore, proper data processing must be done. Figure 3 shows a comparison of the displacement response that occurs due to the Imperial Valley earthquake load used at scale 1 or equivalent to the target spectrum on non-LRB structures and structures with LRB systems.

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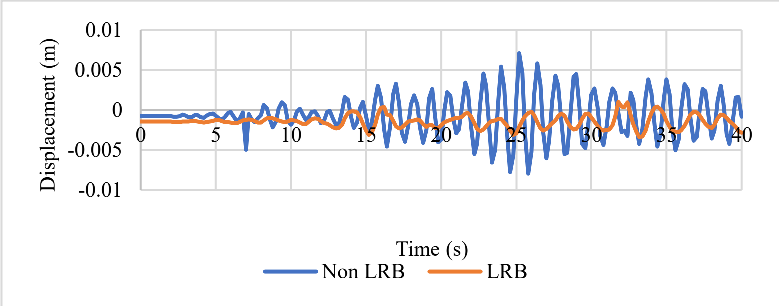

Figure 4. Imperial Valley earthquake displacement response

Thus, based on these displacement response results, the application of Lead Rubber Bearing significantly improves the seismic performance of the structure by reducing the displacement response, especially at the top of the structure which is most susceptible to earthquake effects. From an earthquake planning perspective, this displacement reduction becomes one of the important indicators in assessing the effectiveness of the isolation system.

Incremental Dynamic Analysis (IDA) Curve

Incremental Dynamic Analysis (IDA) is a parametric analysis to determine the overall structural performance under seismic loading. The application of this structural method involves one (or more) earthquake records scaled to several intensity levels in order to obtain response curves parameterized by these intensity levels. Initial steps include selecting Intensity Measure (IM) parameters, such as Sa(T1,5%) which is the spectral acceleration for the fundamental mode with 5% attenuation, and defining Damage Measure (DM), such as the maximum ratio between floors in the entire structure. After these parameters are set, process the dynamic analysis results.

The selection of appropriate parameters for IM and DM plays an important role in the IDA process, as a well-chosen IM will result in a more accurate evaluation of the seismic performance of the structure. These parameters should also be scalable to accommodate appropriate variations in seismic intensity, and be able to represent the dynamic characteristics of each earthquake record. In this study, IDA curves were developed using Peak Ground Acceleration (PGA) as the Intensity Measure (IM) and drift ratio (δ/h) as the damage measure (DM). PGA was chosen because it facilitates the process of scaling earthquake intensity linearly in the IDA analysis. Meanwhile, the drift ratio is used as a damage indicator, given that the limit states applied in this study are based on drift ratio limits.

Drift ratio is the ratio between the lateral displacement and the height of the review point. In this study, displacement was monitored at a height of 24.6 meters (the top floor of the structure). The development of the IDA curves began with sorting out the displacement responses from the time history analysis, which was run repeatedly with a gradual increase in earthquake intensity, and recording the PGA of each record. For each intensity, the maximum displacement was taken and plotted against the corresponding PGA value. This process was applied to all earthquake data to generate IDA curve data. A comparison of the IDA curves can be seen in Figure 5 and Figure 6.

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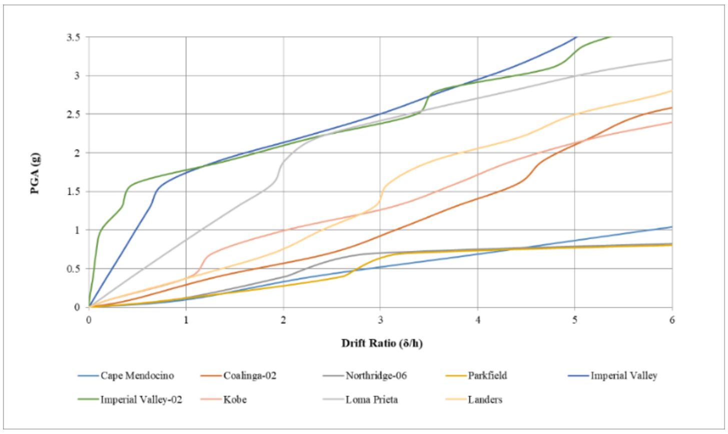

Figure 5. IDA curve of structure without LRB

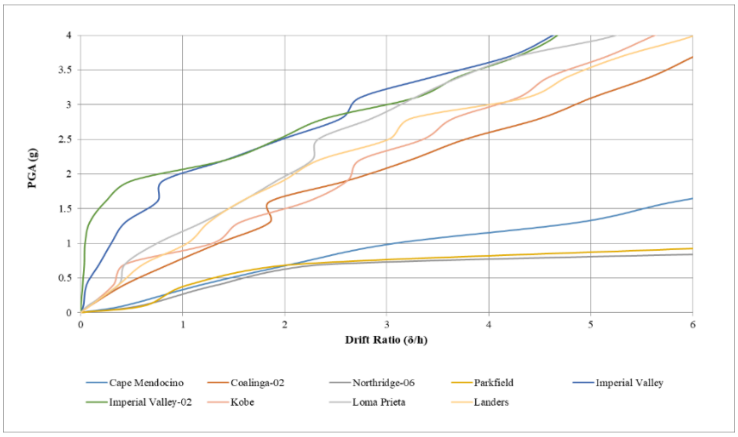

Figure 6. IDA curve of structure with LRB

Overall, the comparison of the two IDA curves confirms that the implementation of the Lead Rubber Bearing isolation system significantly improves the seismic performance of the structure. The isolation system not only reduces the drift response, but also improves the structure's resistance to collapse under large earthquake loads by increasing the deformation capacity and distributing the input energy more efficiently.

Damage Limit

Damage to elements and components of the structural system must be tabulated based on the lateral displacement function of the building, measured by the average inter-story drift ratio (roof displacement divided by building height). However, in multi-story building structures, not all are expected to have the same displacement, and the inter-story drift will also not be the same at all specific floor locations. Inter-story drift provides an accurate measure of the building's response that can be compared to the default average inter-story drift value, determining the damage condition for the general HAZUS building type.

Damage state criteria are applied with reference to the provisions set by HAZUS. However, to obtain results that are more in line with the characteristics of the analyzed structure, the damage limits (limit state) used were adjusted as conducted by Kim and Shinozuka (2004). This adjustment is made because the study offers a more representative approach in correlating inelastic deformation of structures with the level of damage due to seismic loads, particularly for steel and reinforced concrete structures (Kim & Shinozuka, 2004).

The drift ratios adopted for each level of damage are as follows: 0.7% for slight damage, 1.5% for moderate damage, 2.5% for extensive damage, and 5% for complete damage. These values have been

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widely used in seismic research and are considered capable of reflecting the actual behavior of structures at various levels of damage. These damage limits are subsequently applied in structural analysis. To determine the Peak Ground Acceleration (PGA) value corresponding to a specific damage threshold, a horizontal line is drawn at the damage threshold level until it intersects the Incremental Dynamic Analysis (IDA) curve. The intersection point is then used to draw a vertical line to the earthquake intensity axis, resulting in the corresponding PGA value. The dataset resulting from the identification of damage thresholds is subsequently analyzed to calculate the median capacity parameter (θ) and structural uncertainty (β), which are generally assumed to follow a lognormal distribution. The results of this analysis are presented in Table 7 and Table 8.

Table 7. The PGA value at each damage limit on the structure without LRB

Earthquake Event	Slight, PGA (g)	Moderate, PGA (g)	Extensive, PGA (g)	Complete, PGA (g)
Cape Mendocino	0.1	0.3	0.45	0.8
Coalinga-02	0.3	0.5	0.75	2.2
Imperial Valley-02	1.6	1.9	2.25	3.3
Parkfield	0.1	0.25	0.45	0.78
Imperial Valley	1.6	1.9	2.4	3.5
Northridge-06	0.18	0.38	0.6	0.83
Kobe	0.35	0.8	1.25	2.3
Loma Prieta	0.65	1.35	2.3	3
Landers	0.32	0.61	1.11	2.5

Table 8. The PGA value at each damage limit on the structure with LRB

Earthquake Event	Slight, PGA (g)	Moderate, PGA (g)	Extensive, PGA (g)	Complete, PGA (g)
Cape Mendocino	0.22	0.45	0.75	1.4
Coalinga-02	0.6	1.2	1.8	3.1
Imperial Valley-02	2	2.25	2.75	4.4
Parkfield	0.25	0.55	0.7	0.85
Imperial Valley	1.6	2.25	2.7	4.3
Northridge-06	0.2	0.5	0.75	0.7
Kobe	0.7	1.3	1.7	3.7
Loma Prieta	0.85	1.6	2.7	3.9
Landers	0.7	1.5	2.3	3.5

Fragility Curve

The fragility curve functions as a probabilistic tool used to evaluate the potential seismic risk of structural systems. Detailing the vulnerability of transportation networks in earthquake-prone areas requires fragility curves that can be used to evaluate the risk associated with highway bridges for specific seismic events. The seismic fragility curve represents the performance damage conditions that have been determined as a result of various levels of ground motion intensity. Fragility can be represented by a conditional probability.

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$$\text{Fragility} = P\,(DS^{+}\,|IM\,) \tag{3}$$

Where, DS+ represents a condition where several structural damage states have been met or exceeded related to several limit states determined by IM, indicating the intensity of ground motion. This conditional probability statement can be represented in the form of predetermined limit states as.

$$Fragility = P\,(DS^{+}\,|IM\,)\;P\,(LS^{+}\,|IM\,) \tag{4}$$

Where LS+ is the condition where a certain limit state has been exceeded. This fragility curve refers to the PGA distribution in correspondence with the collapse limit state, which is generally a lognormal distribution as shown in Figure 7.

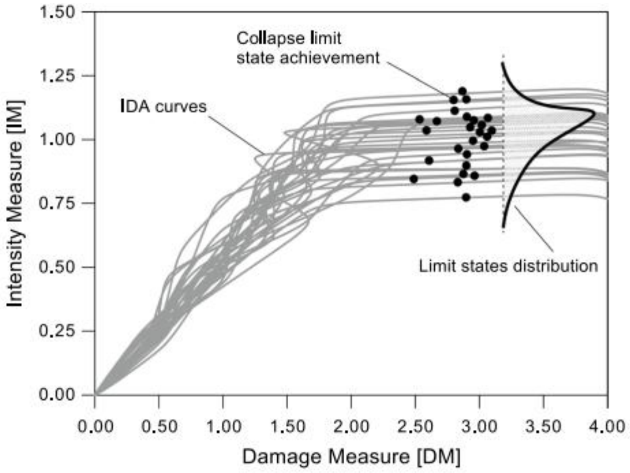

Figure 7. Boundary condition distribution on the curve IDA

The function of this lognormal cumulative distribution is then used to define the fragility curve analytically. The analytical fragility curve can be expressed as,

$$P\,(DM \geq DM_{CO}) = \phi\left(\frac{\ln X - \mu_{\ln X}}{\sigma_{\ln X}}\right) \tag{5}$$

Where, ϕ is the standard cumulative distribution function, ln X is the natural logarithm of the variable X (PGA collapse), and $\mu_{\ln X}$ and $\sigma_{\ln X}$ are the mean and standard deviation of the natural logarithm of the respective X distributions. The fragility curve obtained analytically is then compared with the discrete cumulative distribution data from IDA sequentially to test its resilience. The assessment of seismic fragility will provide the likelihood of collapse for both empty and filled frames that are vulnerable to single seismic events and main/aftershocks in sequence (Di Trapani & Malavisi, 2019). The function of fragility based on the formula used by Papalia (2011) (Fardis et al., 2012):

$$P\,(ds \geq S_a) = \phi\left(\frac{1}{\beta_{ds}}\right)\ln\left(\frac{S_a}{\overline{S_a},ds}\right) \tag{6}$$

Where, ϕ = cumulative probability function, β_{ds}= standard deviation for total uncertainty of each damage condition, S_a = spectral acceleration, $\overline{S_a}$, ds = mean spectral acceleration at the time the structure experiences damage. The standard deviation values for the total uncertainty of each damage condition are determined based on HAZUS.

$$\beta_{ds} = \sqrt{[(CONV[\beta_c, \beta_d])]^2 + [B_{M(ds)}]^2} \tag{7}$$

(Source: HAZUS MH-MR5, Page 6-13)

With, β_c = standard deviation of structural capacity uncertainty, β_d = standard deviation of demand spectrum uncertainty (β_d= 0.45 for the short term and 0.5 for the long term), $B_{M(ds)}$) = standard deviation

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of HAZUS damage condition threshold uncertainty, taken as 0.4.The standard deviation value of uncertainty (β) plays an important role in the development of the fragility curve. Total uncertainty is calculated based on three main sources, namely: uncertainty regarding structural capacity (β_c), uncertainty regarding the demand spectrum (β_d), and uncertainty regarding the damage condition threshold ($B_{M(ds)}$). According to Papailia (2011), the value of β_c, which reflects the variation or uncertainty of the structural capacity, can be calculated using the following formula.

$$\beta_c = \sqrt{\ln\left(\frac{s^2}{m^2}+1\right)} \quad (8)$$

The parameter "m" refers to the average value of the spectral acceleration capacity of the analyzed structure, while "s" is the standard deviation of that spectral acceleration capacity (Tropormera, 2016).

The fragility curve can be formed after all standard deviation values have been obtained. The probability calculations that will form the fragility curve are repeated starting from a PGA value of 0 g to 5 g. Here is an example of the structural fragility probability calculation when PGA = 0.1.

$$P_{(ds|sd)} = \phi\left(\frac{1}{\beta_{ds}}\right) ln\left(\frac{S_d}{S_{d,ds}}\right)$$

$$P_{(ds|sd)} = \phi\left(\frac{1}{0,513}\right) ln\left(\frac{0,1}{0,761}\right)$$

$$P_{(ds|sd)} = 0,099$$

The results of the probability calculations can be used to form the fragility curves shown in Figures 8 and 9.

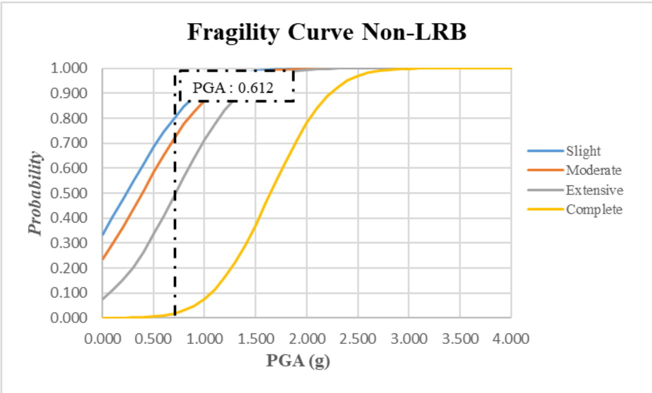

Figure 8. Non-LRB structural fragility curve

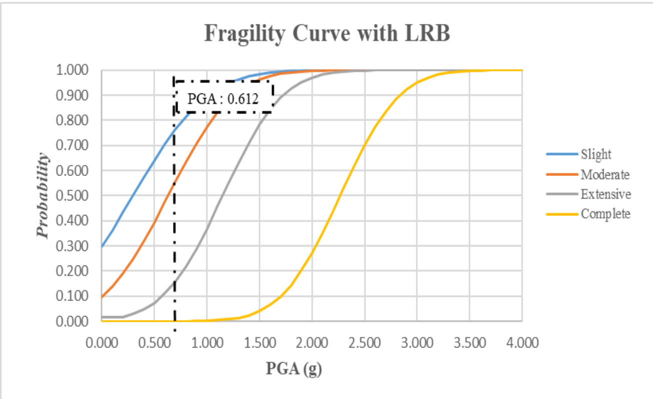

Figure 9. Structure fragility curve with LRB

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Figure 8 shows the fragility curve for the structure without LRB, while Figure 9 shows the curve for the structure with LRB. This curve illustrates the probability of damage at various damage levels (Slight, Moderate, Extensive, and Complete) against ground acceleration (PGA) in units of g. If we examine the PGA value of 0.612 g, the probability of damage for each condition can be seen in the following Table 9:

Table 9. Comparison of Fragility Curves for Both Structural Conditions

Damage States	Non-LRB	LRB	Risk Reduction
Slight	76%	72%	4%
Moderate	67%	50%	17%
Extensive	42%	12%	30%
Complete	1%	0%	1%

The installation of LRB successfully reduced the probability of damage at all levels. The damping effect is most significant in the Extensive categories, with a risk reduction of about 30%. The application of LRB significantly enhances the seismic resilience of structures, especially in the medium PGA range (around 0.6–2 g), which is a critical zone in many earthquake designs. The curve shows that LRB is effective in reducing the likelihood of moderate to severe damage, but its benefits begin to diminish at very high ground acceleration levels.

CONCLUSION

The results of the analysis and discussion regarding the behavior of building structures with Lead Rubber Bearing base isolation using the Incremental Dynamic Analysis method are described in the following explanation are Structures without isolators exhibit unstable dynamic response, with large drift ratio jumps as the peak ground acceleration (PGA) increases. This indicates a softening effect due to inelastic damage that reduces the capacity of the structure. In contrast, structures with Lead Rubber Bearing (LRB) isolators have a more stable and controllable response, with a more gradual increase in drift ratio. LRBs help to effectively dissipate earthquake energy, reduce the acceleration transmitted to the superstructure, increase the deformability of the system, and increase the capacity and reduce the response uncertainty of the structure.Damage criteria (damage state) Applied with reference to the provisions set by HAZUS. The probability of damage according to the fragility limit on structures without basic isolation has a fragility probability value of slight conditions of 76%, moderate of 67%, extensive of 42%, and complete of 1%. While the results of the structure with LRB base isolation have a probability of damage in the slight condition of 72%, moderate by 50%, extensive by 12%, and complete conditions by 0%. From these results, it can be seen that the installation of LRB successfully reduces the probability of damage in all conditions. The most significant dampening effect is seen in the moderate and extensive categories, with a 30% reduction in risk. Determination of the fragility level of the structure is carried out using a probability approach limited by 4 damage limits. The probability of 100% structural fragility will be damaged or collapse in the longitudinal direction (X) with a value of 3 g for structures without isolation and a value of 4 g for structures with basic isolation. In this study, the Hospital building structure with a PGA value of 0.612 is still resistant to earthquakes despite the probability of damage in all conditions and the structure can still stand without significant repairs. However, it can be seen that the addition of LRB can extend the acceleration of the structure until collapse.

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