*Journal of Harbin Engineering University*
*ISSN: 1006-7043*

Vol 44 No. 7
July 2023

# Development of Elastomeric with HDPE Filler

Dimas Maulana Syirodjudin[1], Tavio[1]*, Bambang Piscesa[1]

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

## Abstract

An earthquake, being a catastrophic event, possesses the potential to induce significant structural damage, particularly to buildings. Henceforth, it is imperative to incorporate seismic protection measures into the design and construction of buildings. Over the past two decades, there has been a notable surge in the adoption and implementation of seismic engineering methodologies. Utilizing an isolation system is a viable approach to implementing seismic protection measures. The fundamental operational concept of the isolation system entails the transmission of seismic activity from an impending earthquake to the isolation system before it infiltrates into the primary structure. Subsequently, the implementation of the isolation system shall effectively mitigate the seismic forces, thereby ensuring that the oscillation experienced by the superstructure remains within acceptable limits. One of the numerous classifications of isolation systems encompasses the Lead Core Rubber Bearing, commonly referred to as LCRB. The prolonged utilization of lead within the isolation core may result in soil contamination. In this study, isolation bearings with high-density polyethylene (HDPE) filler core systems were developed. These bearings incorporate a locally sourced rubber material known as PCLRB (HDPE Core Local Rubber Bearing). The purpose of this development is to enhance the performance of the base isolation in effectively dissipating seismic energy during earthquakes. The substitution of the lead core with HDPE is recommended due to HDPE's superior capacity to enhance damping, dissipate energy, and improve bearing stiffness. In order to assess the performance of bearings constructed with filler-core local rubber bearing systems, it is imperative to analyze the behavior of the HDPE core. This can be achieved through the use of finite element analysis. The numerical findings demonstrate the efficacy of the base isolator employing a regional rubber-bearing core filler core system that imparts heightened damping, and substantial stiffness, and mitigates lateral locking. The implementation of PCLRB (HDPE Core Local Rubber Bearing) has the potential to effectively mitigate the detrimental effects induced by seismic events.

**Keywords**: Base isolation, Core materials, Disaster risk reduction, HDPE, Seismic protection.

## 1. Introduction

Indonesia is a country renowned for its significant seismic activity. The phenomenon at hand is attributed to the presence of three significant tectonic plates, specifically Eurasia, Indo-Australia, and the Pacific, which traverse the region of Indonesia [1]. During the initial years of 2022, a seismic event of considerable magnitude, measuring 6.7 on the Richter scale, transpired, thereby impacting the Banten area. According to the Pusgen data for the year 2018, it has been noted that Indonesia has witnessed a rise in the count of active faults, primarily attributed to the dynamic behavior exhibited by the Palu-Koro faul [2]. Based on the research conducted by Pawirodikromo it is imperative for Indonesia to prioritize the development of structures with robust seismic resistance capabilities [3]. A multitude of methodologies have been developed and adopted by the scientific community in order to mitigate the potential for structural damage resulting from seismic events. Within this array of methodologies, the implementation of base isolators as seismic dampers has emerged as a feasible and effective resolution [4]. To date, the structural design methodologies employed in civil buildings align with established and customary practices. Regarding the design of structures that can withstand earthquakes, it is customary to employ fixed bases as the predominant methodology [5]. Numerous methodologies have been devised and implemented by diligent researchers in order to mitigate the potential for structural harm resulting from seismic occurrences. Among these approaches lies the utilization of base isolators as a means of seismic damping [6].

Base isolators, as per the findings of Mayes have gained extensive utilization since the 1950s [7,8].

The progressive expansion of the rubber sector has persistently advanced the production of stratified rubber pads utilized in base isolators. The fundamental operational concept of the isolation system entails the transmission of seismic activity from an impending earthquake to the isolation system prior to its infiltration into the primary structure. Subsequently, the implemented isolation system shall effectively mitigate the prevailing seismic forces, thereby ensuring that the amplitude of vibration experienced by the superstructure remains within acceptable limits [9]. The Lead Core Rubber Bearing (LCRB) is a frequently employed isolation system in buildings. The specified system necessitates the utilization of an insulating component fabricated from an elastomeric block, commonly comprised of natural rubber or neoprene, that is additionally strengthened with steel lead. The placement of these leads has been strategically determined to effectively encompass one or two central cylinders, thereby augmenting the overall structural integrity of the system [10,11]. The utilization of Lead Core Rubber bearings (LCRB) possesses the inherent capability to ameliorate the detrimental repercussions of seismic occurrences on edifices through proficiently diminishing acceleration and displacement [12]. The performance of lead-core rubber bearings (LCRB) can be enhanced through the incorporation of a lead core, a concept initially introduced by Robinson in 1977 [13]. This addition results in a notable increase in shear and compression stiffness within the lead core rubber bearing (LCRB). Furthermore, the utilization of lead results in a diminished pressure level of 10 MPa and undergoes recrystallization at ambient conditions. This, in turn, leads to an augmentation in the damping characteristics of the bearings and an elevation in the elastomeric stiffness [14]. In the course of investigating the behavior of a lead-rubber-bearing isolated structure, it was observed that the incorporation of LCRB within a 20-story edifice led to certain notable outcomes [15]. These included an elongation of the natural period, a decrease in the mitigation of base shear, an elevation in lateral displacement, and a diminution in the occurrence of significant displacements caused by seismic activity.

The use of lead in bearing technology presents both merits and demerits. The presence of lead in soil poses a significant concern as it has the potential to endure for extended periods, spanning several centuries [16]. According to the research conducted by Juberg et al, it has been observed that individuals residing in close proximity to the lead core rubber bearing (LCRB) zone face a significant susceptibility to lead exposure [17]. It is imperative to note that exposure to lead is universally detrimental to human well-being. In order to foster scientific innovation, it is imperative to explore alternative materials that can effectively substitute the lead core. n order to foster innovation, it is imperative for scientists to diligently explore alternative materials that can effectively substitute the lead core. The innovative contribution put forth by Katsamakas et al in order to facilitate scientific innovation, it is imperative to explore alternative materials that can effectively substitute the lead core. The innovative contribution put forth by Katsamakas et al entails the development of a rubber ball bearing (BRB) [18]. This novel bearing design incorporates rubber aminations and features a centrally positioned aperture within a traditional bearing structure, wherein a rubber ball is situated. The proposed mechanism has demonstrated its efficacy in augmenting the dissipation of bearing energy as well as enhancing both vertical and lateral stiffness. Tan & Hejazi proposed a new elastomeric bearing with a steel core and a filler system consisting of a granular and/or polymer filler as an improvement over the conventional elastomeric bearing. Researchers have found that the application of a steel core and filler increases the shear strength and energy dissipation of the bearing while reducing damping [19]. The researchers said that the system with fully filled sand was the most profitable because the increase achieved was the highest, while the decrease in damping was not significant.

A supplementary innovative measure was undertaken, which entailed the replacement of the bearing pad with vulcanized rubber sourced from Indonesian natural rubber. The aforementioned modification was executed with the objective of reducing production costs, thus making the base isolation economically feasible and appropriate for utilization in diverse architectural constructions. The research undertaken by Rofiq et al sought to develop Lead Rubber Bearing (LRB) materials using Indonesian natural rubber as a basis. Based on the findings of the investigation, it was determined that the inclusion of carbon in the mixture resulted in hyperplastic characteristics that were comparable to those observed in mixtures without carbon addition [20].

The present study introduces a novel approach to enhancing the performance of Indonesian rubber elastomeric bearings by incorporating a steel core and employing a filling system comprising HDPE filler. This eco-friendly solution serves as a viable substitute for lead-core-bearing isolation s. Given the inherent properties of HDPE, it possesses a notable advantage in the form of SMA (Shape Memory Allow). This characteristic enables the material to revert back to its original state when subjected to a tensile force, as elucidated [21]. By using ABAQUS finite element simulation, the performance of the proposed elastomeric bearings is compared with that of lead rubber bearings.

## 2. Materials and Methods

### 2.1. *Bearing Dimension*

In the analysis presented in Figure 1, the provided dimensions pertain to the design of a PCLRB (HDPE Core Local Rubber Bearing) rubber-bearing core filling system. The suggested elastomeric bearing, in a circular configuration, comprises a rubber layer ($n_r$ = 12) and a steel shim layer ($n_s$ = 11). The dimensions of the top and bottom plates are as follows: The width ($W_{top}$ = $W_{bot}$) and length ($L_{top}$) are both equal to 1294 mm. Additionally, the thickness of these plates ($T_{top}$ = $T_{bot}$) measures 44 mm. The thickness of the steel shim is determined to be 3 millimeters ($t_s$ = 3 mm). The rubber layer for the outermost layer shall have a thickness of 38 mm, with a total of 2 layers. The inner rubber layer has a thickness of 36 mm and consists of a total of 10 layers. The bearing diameter, denoted as $D_b$, is measured at 1194 millimeters, while the core diameter, referred to as Dvoid, is measured at 100 millimeters. The steel core dimensions are as follows: the top diameter ($D_{ctop}$) measures 20 mm, the bottom diameter ($D_{cbot}$) measures 30 mm, and the height ($H_{cs}$) measures 280 mm.

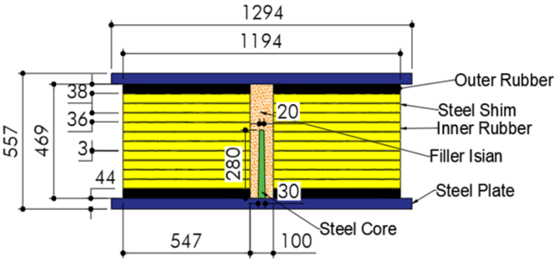

**Figure 1:** Dimension of component in elastomeric bearing equipped with proposed core filler system

### 2.2. *Rubber Material*

The bearing material utilized in accordance with the findings from the experimental study conducted by Tavio & Wijaya comprises Isoprene, a type of Indonesian natural rubber. The proposed rubber exhibits a hardness of 60 International Rubber Hardness Degrees (IRHD), while concurrently possessing a shear modulus of 0.9 ± 0.15 Newtons per square millimeter (N/mm2) [22]. A variety of hyperelastic models can be found within the ABAQUS software package [23]. In this study, Ogden's model has been selected from a range of hyperelastic models. The Ogden hyperelastic model has demonstrated commendable reliability in accurately predicting the behavior of rubber materials. Equation 1 exhibits the strain function, denoted as the energy W, pertaining to Ogden's hyperelastic model.

$$W=\sum_{i=1}^{N}\frac{2\mu_i}{\alpha_i^2}\left[\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3\right] \tag{1}$$

Where $\lambda_1$, $\lambda_2$, and $\lambda_3$ adalah principal stress, N is the order of the energy strain function. While μi and αi material constants are shown in Table 1.

**Table 1:** Material constants of Ogden hyperelastic model

| Model Ogden N=3 | |
|---|---|
| μ | α |
| 0.3326 | 2.4466 |
| 0.3326 | 2.4466 |
| 0.3326 | 2.4466 |

### 2.3. *Material HDPE & Lead*

Materials Table 2 shows the mechanical properties of each material, namely HDPE taken from the research by Rueda et al and Lead taken from the research by Tan et al [21,24]. Used in elastomeric bearing core simulation using the finite element modeling method.

**Table 2:** Mechanical properties of HDPE and Lead

| Material | Model | Properties |
|---|---|---|
| HDPE | General elasticity | $E$ = 496.3 MPa |
| | General plasticity | $\nu$ = 0.44 |
| | | $\sigma_y$ = 26.1 MPa |
| Lead | General elasticity | $E$ = 18 MPa |
| | General plasticity | $\nu$ = 0.3 |
| | | $\sigma_y$ = 10 MPa |

### 2.4. *Model Meshing*

Material designated region into individual elements. In the case of the rubber layer and the core filled with rubber, the model employs the C3D8RH meshing technique. This technique utilizes solid hexahedral linear elements that consist of eight nodes and possess three degrees of freedom. These elements are subjected to hourglass control and are hybrid in nature. Additionally, constant pressure is applied to the rubber layer. The C3D8R meshing type is utilized for the steel plate, steel core, and shim materials. This particular meshing type consists of a linear hexahedral solid element with eight nodes and three degrees of freedom. It is designed to effectively control hourglass effects while applying constant pressure, excluding rubber materials. Figure 2 depicts a meshing representation of the PCLRB (HDPE Core Rubber Bearing).

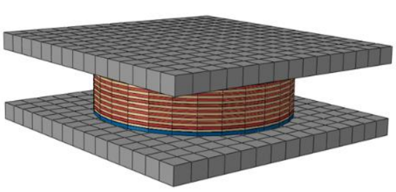

**Figure 2**: The proposed meshing model for elastomeric bearings

### 2.5. *Loading and Interaction*

The elastomeric bearings being considered for implementation must undergo thorough testing in accordance with the specifications outlined in SNI 1726-2019. The utilization of a specific section, namely Article 12.8, within the SNI 1726-2019 code serves as a point of reference when conducting examinations on elastomeric bearings [25]. The bearings undergo a total of three complete shear cycles in conjunction with the state of full engagement. In this study, the design compressive load was derived based on the axial force-bearing reaction results of the dead, live, and earthquake loads during the analysis of the Aster Inpatient Building, located at Tidar Hospital and spanning 6 floors. The vertical loading of the test specimen was altered through adjustments in the PCLRB (HDPE Core Local Rubber Bearing) core material, resulting in a uniform vertical load of 2.75 MPa. The connectivity between all nodes located on the upper surface is established by employing beam-type multi-point constraints, a feature conveniently provided within the ABAQUS software. A cyclic lateral displacement of 200 mm is implemented as a design lateral displacement at the specific loading location. Three sinusoidal cycles of horizontal displacement have been defined. and applied laterally, with a frequency of 0.1012 Hz, or 0.636 rad/s in circular frequency can be seen in figure 3.

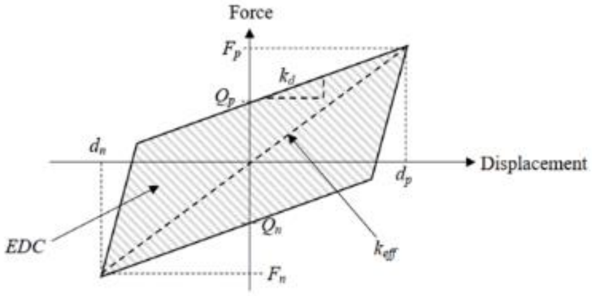

**Figure 3**: Sinusoidal lateral displacement cycles applied during finite element

### 2.6. *Characteristics of Elastomeric Bearing*

The Isolation system is typically characterized by parameters such as the effective stiffness keff, the damping ratio ξ, the characteristic strength Q, and the post-melting stiffness kd. The aforementioned parameter is derived through the analysis of the lateral displacement force curve, which is obtained by conducting cyclic shear testing. The methodology for determining this particular attribute is elucidated through equations 2, 3, 4, and 5.

$$k_{eff} = \frac{F_p - F_n}{d_p - d_n} \tag{2}$$

$$\xi = \frac{2EDC}{\pi k_{eff}\left(d_p - d_n\right)^2} \tag{3}$$

$$Q = \frac{1}{2}\left(Q_p - Q_n\right) \tag{4}$$

$$k_d = \frac{1}{2}\left(\frac{F_p - Q_p}{d_p} - \frac{F_n - Q_n}{d_n}\right) \tag{5}$$

where dp and dn represent the utmost magnitudes of positive and negative displacements, respectively, which are applied during the test. The forces $F_p$ and $F_n$ are the respective counterparts of the forces dp and dn. The EDC, or Total Energy Dissipated in Each Cycle, is ascertained by quantifying the hysteresis loop area of the force-side displacement curves. The points $Q_p$ and $Q_n$ represent the locations where the curve intersects the vertical axis, with $Q_p$ denoting the positive intersection and $Q_n$ representing the negative intersection. Figure 4 presents a graphical representation elucidating the parameters and characteristics that can be ascertained from the curve depicting horizontal displacement forces.

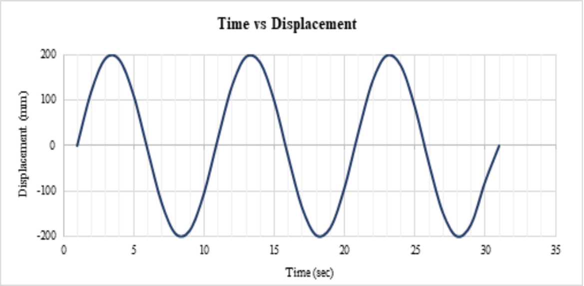

**Figure 4**: Parameters and characteristics of elastomeric bearing in the lateral force-displacement curve

## 3. Result and Discussion

### 3.1. *Numerical Result Local Core Rubber Bearing with Material Variation*

The finite element analysis modeling has yielded the outcomes for the development of the PCLRB (HDPE Core Local Rubber Bearing) model, incorporating the utilization of local Indonesian rubber for each layer of the bearing pad. The assessment of the progress made in the advancement of insulator core material holds ‘significant value in the quest for identifying suitable alternatives to copper lead plugs that align with sustainable and eco-friendly principles. The provided information includes a hysteric loop graph derived from the assessment of different material variations, as depicted in Figure 5 and Table 3.

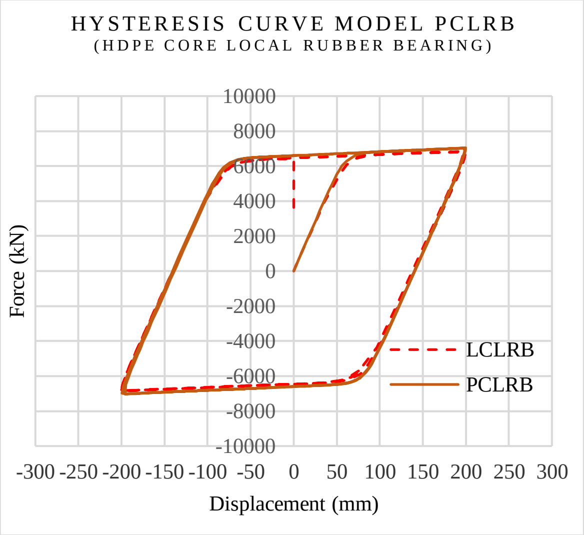

**Figure 5:** Result of hysteresis loops model PCLRB

**Table 3:** Comparison of FCLRB mechanical behavior characteristics with core material variations

| Model | $W_d$ (kNmm) | $K_{eff}$ (kN/mm) | $\xi$ (%) | Q (kN) | $K_d$ (kN/mm) |
|---|---|---|---|---|---|
| LCLRB | 3512399.84 | 34.36 | 40.88 | 6296.48 | 2.81 |
| PCLRB | 3657771.24 | 34.74 | 42.27 | 6599.14 | 1.61 |
| $\Delta_{P-L}$ (%) | 4.14% | 1.12% | 3.41% | 4.81% | -42.77% |

Based on the findings derived from the finite element numerical analysis, as depicted by the hysteresis curve illustrated in Figure 5, it is evident from the curve's magnitude that the PCLRB (HDPE Core Local Rubber Bearing) model exhibits a higher energy dissipation capacity compared to the LCLRB (Lead Core Local Rubber Bearing) model. Upon reviewing the summarized outcomes of the comparative assessment of mechanical properties presented in Table 3, it is observed that the energy dissipation, stiffness, and damping ratio values are provided for every variant of the rubber-bearing insulator core filler material. The investigation demonstrates the viability of utilizing High-Density Polyethylene (HDPE) as a potential alternative to ecologically sustainable copper lead plugs in the context of core filling materials. Based on the selection of materials for the replacement of the insulator core, it is advisable to opt for materials exhibiting shape-memory alloy characteristics and hyperelastic properties. These materials possess superior flexibility, enabling them to effectively dissipate energy. Additionally, they exhibit considerable stiffness and excellent damping capabilities when compared to alternative materials. Regarding material maintenance, it is worth noting that HDPE material exhibits remarkable superiority in enhancing post-melting stiffness. This particular attribute plays a crucial role in effectively regulating the displacement of base isolation and superstructures.

### 3.2. *Numerical Result Local Core Rubber Bearing with Material Variation*

The assessment of the impact of the HDPE core rubber bearing filling material encompasses an examination of its mechanical characteristics as well as an evaluation of the maximum stress experienced by the base isolation model. The maximum stress is indicated in Figures 6 and 7, corresponding to each base isolator model.

**Figure 6:** Maximum Stress Contours Model LCLRB

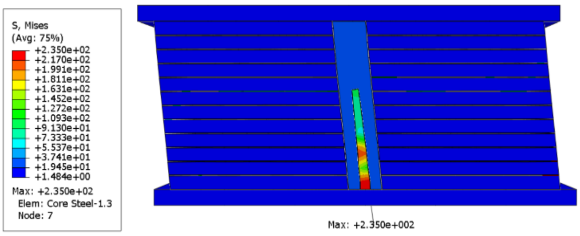

**Figure 7:** Maximum Stress Contours Model PCLRB

The determination of the maximum stress in the HDPE local core rubber bearing is achieved by considering the maximum stress and yield value within the steel core region, which is measured at 235 MPa. This stress is primarily induced by shear forces resulting from the presence of filler and isolator materials, as well as the stress distribution originating from the top plate and extending towards the steel core. Ultimately, this stress accumulation leads to failure at the termination point of the steel core. The LCLRB (Lead Core Local Rubber Bearing) model exhibits its maximum stress and first yield within the shim area, with a magnitude of 235 MPa. The peak stress experienced within the shim region manifests at the periphery of the steel him layer, resulting from the thermal effects induced by the frictional interaction between the rubber material and the compromised leads. In the rubber layer, it is observed that the maximum stress experienced remains consistent at 10.24 MPa.

## 4. Conclusion

Based on the findings of this study, it is possible to derive the following conclusions regarding the utilization of local rubber elastomeric bearings with HDPE filling systems:

1. Based on the analysis conducted on the mechanical behavior of the modified core rubber bearing filler material, utilizing the local rubber model PCLRB (HDPE Core Local Rubber Bearing), it has been determined that the HDPE-filled model exhibits superior performance and optimal efficiency in effectively dissipating seismic energy.
2. Based on the stress behavior analysis, it has been determined that the steel core within the PCLRB (HDPE Core Local Rubber Bearing) model experiences the highest magnitude of stress. In the structural system, it is observed that the steel core undergoes shear forces resulting from the presence of the filler and insulator materials. Additionally, the stress distribution originating from the top plate and extending towards the steel core leads to failure occurring at the termination point of the steel core.

## 5. Acknowledgement(s)

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

## References

[1] U. Wijaya, R. Soegiarso, and Tavio, "Numerical Study of Potential Indonesian Rubber for Elastomeric Base Isolators in Highly-Seismic Zones," in *Journal of Physics: Conference Series*, vol. 1477, 2020, pp. 1–7.

[2] A. Jaya, O. Nishikawa, and S. Jumadil,

“Distribution and morphology of the surface ruptures of the 2018 Donggala–Palu earthquake, Central Sulawesi, Indonesia,” *Earth, Planets Sp.*, vol. 71, no. 1, 2019, pp. 1–13.

[3] W. Pawirodikromo, *Engineering Seismology and Seismic Engineering*, 1st ed. yogyakarta: Pustaka Pelajar, 2012.

[4] F. Habieb, Ahmad Basshofi and Milani, Gabriele and Tavio, Tavio and Milani, “Low cost frictional seismic base-isolation of residential new masonry buildings in developing countries: A small masonry house case study,” *Open Civ. Eng. J.*, vol. 11, no. Suppl-5, M2, 2017, pp. 1026–1035.

[5] E. Ozer, M. Inel, and B. T. Cayci, “Seismic Performance Comparison of Fixed and Base-Isolated Models,” *Iran. J. Sci. Technol. - Trans. Civ. Eng.*, vol. 47, no. 1, 2022, pp. 1007–1023.

[6] A. B. Habieb, G. Milani, and T. Tavio, “Two-step advanced numerical approach for the design of low-cost unbonded fiber reinforced elastomeric seismic isolation systems in new masonry buildings,” *Eng. Fail. Anal.*, vol. 90, 2018, pp. 380–396.

[7] R. L. Mayes, L. R. Jones, T. E. Kelly, and M. R. Butto, “Design Guidelines for Base-Isolated Buildings with Energy Dissipators:,”, vol. 1, no. 1, 2019, pp. 41–74.

[8] W. H. Robinson and A. G. Tucker, “A lead-rubber shear damper,” *Bull. New Zeal. Soc. Earthq. Eng.*, vol. 10, no. 3, 1977, pp. 151–153.

[9] A. B. Habieb, M. Valente, and G. Milani, “Effectiveness of different base isolation systems for seismic protection: Numerical insights into an existing masonry bell tower,” *Soil Dyn. Earthq. Eng.*, vol. 125, 2019, p. 105752.

[10] E. Kazeminezhad, “Effect of lead core size and arrangement on the shear and axial behavior of the lead rubber bearings,” *Reasearch Sq.*, vol. 1, no. 1, 2023, pp. 1–32.

[11] G. C. Marano and R. Greco, “Efficiency of base isolation systems in structural seismic protection and energetic assessment,” *Earthq. Eng. Struct. Dyn.*, vol. 32, no. 10, 2003, pp. 1505–1531.

[12] C. Yaşar, V. Karuk, E. Cavdar, and Gokhan Ozdemir, “Variation in Mechanical Properties of a Lead–Rubber Bearing Exposed to Low Temperature,” *ASCE*, vol. 37, no. 3, 2023, pp. 687–698.

[13] W. H. Robinson, “Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes,” *Earthq. Eng. Struct. Dyn.*, vol. 10, no. 4, 1982, pp. 593–604.

[14] K. Ryan, J. Kelly, and Anil K. Chopra, “Nonlinear model for lead–rubber bearings including axial-load effects,” in *ASCE*, vol. 131, no. 12, 2005, p. 1270.

[15] G. B. Dhumal, P. M. Ghude, P. V Jaybhaye, N. S. Neve, and D. D. Raskar, “Study of Lead Rubber Bearing and Friction Pendulum Base Isolation System for G+ 20 High Rise Building in Seismic Zone III,” *tijer.org*, vol. 10, no. 5, 2023, pp. 553–558.

[16] M. C. Nagar, M. L. Dotaniya, A. Sharma, C. K. Dotaniya, R. K. Doutaniya, and J. K. Saha, “Pressmud overcome lead toxicity by improving spinach biomass in lead-contaminated soils,” *Environ. Monit. Assess.*, vol. 195, no. 1, 2023, p. 107.

[17] D. R. Juberg, C. F. Kleiman, and S. C. Kwon, “Position paper of the American Council on Science and Health: lead and human health,” *Ecotoxicol. Environ. Saf.*, vol. 38, no. 3, 1997, pp. 162–180.

[18] A. A. Katsamakas, G. Belser, M. F. Vassiliou, and M. Blondet, “Experimental investigation of a spherical rubber isolator for use in low income countries,” *Eng. Struct.*, vol. 250, 2022, p. 113522.

[19] K. C. Tan and F. Hejazi, “Rubber bearing isolator with granular and polymer filler

core and application on a building," in *Structures*, vol. 42, 2022, pp. 309–332.

[20] H. I. Rofiq, Tavio, and D. Iranata, "Model validation of carbon-fiber and glass-fiber reinforced elastomeric isolators using finite element method," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1116, no. 1, 2022, p. 12001.

[21] F. Rueda, J. P. Torres, M. Machado, P. M. Frontini, and J. L. Otegui, "External pressure induced buckling collapse of high density polyethylene (HDPE) liners: FEM modeling and predictions," *Thin-Walled Struct.*, vol. 96, 2015, pp. 56–63.

[22] U. Wijaya, R. Soegiarso, and Tavio, "Mechanical properties of Indonesian hyperelastic low-grade rubber for low-cost base isolator," *MATEC Web Conf.*, vol. 276, 2019, p. 01017.

[23] A. U. Manual, *Abaqus theory guide. Version 6.14*. 2014.

[24] K. C. Tan, F. Hejazi, H. Mohammadi Esfahani, and T. Chong, "Development of Elastomeric Rubber Bearing Utilizing Core-and-Filler System," *Structures*, vol. 37, 2022, pp. 125–139.

[25] BSN, "Planning procedures for the seismic resistance of buildings and non-building structures (1729-2019)," 1st ed., BSN, Ed. Jakarta: BSN, 2019, pp. 188–192.