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Comparison of Peak Seismic Displacement Obtained from Simplified Analysis for Lead Rubber Bearing (LRB) Isolators with Nonlinear Response History Analysis

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Abstract

Seismic isolation systems are widely used to reduce earthquake-induced structural demands by increasing the fundamental period and providing additional energy dissipation. Among available isolation devices, Lead Rubber Bearings (LRBs) are commonly employed because they combine lateral flexibility with hysteretic damping. Simplified displacement-based design procedures are frequently used in practice to estimate the effective properties and displacement demands of LRB systems; however, their accuracy relative to nonlinear dynamic analysis remains an important concern. This study evaluates the accuracy of a simplified iterative design procedure for LRB isolation systems through comparison with nonlinear time-history analyses performed in OpenSeesPy. The isolated structure was modeled as an equivalent single-degree-of-freedom (SDOF) system. A parametric investigation was conducted using six characteristic strength ratios ($\mu = 0.03–0.30$) and ten post-yield stiffness ratios ($\alpha = 0.05–0.50$), resulting in sixty isolator configurations. Effective mechanical properties were first determined using the displacement-based iterative procedure. Nonlinear time-history analyses were then performed using 44 FEMA P695 ground-motion records scaled to the design earthquake spectrum for downtown Los Angeles. Peak displacement demands obtained from nonlinear analyses were statistically evaluated and compared with the design displacements predicted by the simplified procedure. Results showed that the simplified method consistently underestimated displacement demands, particularly for low characteristic strength ratios. The average prediction error exceeded 100% for $\mu = 0.03$ and decreased to approximately 29% for $\mu = 0.30$. The characteristic strength ratio was identified as the primary factor affecting prediction accuracy, while the influence of the post-yield stiffness ratio was relatively small. The findings indicate that simplified procedures are useful for preliminary design, but nonlinear time-history analysis is necessary for reliable estimation of displacement demands in seismically isolated structures.

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Keywords: Lead Rubber Bearing (LRB), Seismic Isolation, Nonlinear Time-History Analysis, OpenSeesPy, Displacement-Based Design, FEMA P695 Ground Motions, Effective Period, Hysteretic Damping, Seismic Response, Performance Assessment

1. Introduction

The primary objective of this study is to evaluate the accuracy of the simplified displacement-based design procedure for lead rubber bearings by comparing the design displacement predicted through the iterative spectral approach with the maximum displacement demands obtained from nonlinear time-history analyses. For each of the 60 LRB configurations, the displacement response was evaluated using a suite of 44 FEMA P-695 (FEMA, 2009; Zamani et al., 2024) ground motions, and the resulting displacement demands were statistically compared with the corresponding design displacement predictions.

Seismic isolation has become one of the most effective strategies for mitigating earthquake-induced demands on structures. By introducing a flexible isolation layer between the superstructure and the foundation, seismic isolation systems significantly lengthen the fundamental vibration period of the structure and reduce the transmission of seismic energy. As a result, structural accelerations, interstory drifts, and damage potential can be substantially reduced compared with conventional fixed-base systems (Chopra, 2007).

Among the various isolation technologies currently available, lead rubber bearings (LRBs) are one of the most widely implemented devices in practical engineering applications. LRBs combine the flexibility provided by laminated rubber layers with the hysteretic energy dissipation generated by a yielding lead core. This combination enables the isolation system to simultaneously achieve period shift and supplemental damping, resulting in improved seismic performance under a broad range of earthquake intensities. Owing to their reliability, durability, and proven effectiveness, LRBs have been extensively adopted in buildings, bridges, and critical infrastructure worldwide (Kelly, 1993).

The seismic response of isolated structures depends strongly on the mechanical characteristics of the isolation system. Parameters such as characteristic strength, post-yield stiffness, effective period, and equivalent damping ratio govern the displacement demand and energy dissipation capacity of the isolation layer. Consequently, accurate estimation of these parameters is essential for achieving reliable seismic performance. To facilitate practical design, several displacement-based procedures have been incorporated into modern design standards and guidelines. These simplified methodologies estimate the effective properties of isolation systems through iterative calculations and are commonly used during preliminary and final design stages (Skinner et al., 1993).

Despite their widespread use, simplified design procedures inherently rely on idealized assumptions regarding structural behavior, damping characteristics, and seismic demand. In many cases, these methods neglect important nonlinear dynamic effects and record-to-record variability that may influence the actual response of isolated structures. As performance-based earthquake engineering increasingly emphasizes the behavior of structures under severe earthquake loading, the adequacy of simplified design approaches has become an important research topic. Assessing the accuracy and limitations of these procedures is therefore essential for determining when more advanced nonlinear analyses are required (Naeim & Kelly, 1999).

Numerous studies have investigated the behavior and modeling of LRB isolation systems. Previous research has demonstrated that simplified bilinear representations can adequately reproduce the primary hysteretic characteristics of LRBs for many engineering applications. However, discrepancies may arise when simplified design assumptions are compared with nonlinear dynamic analyses conducted under suites of realistic earthquake records. In particular, the influence of key isolator properties, such as characteristic strength and post-yield stiffness, on displacement prediction accuracy remains an area requiring further investigation (Park et al., 1986).

The objective of this study is to evaluate the capability of a displacement-based simplified design procedure to predict the displacement demands of lead rubber bearing isolation systems. A comprehensive parametric study is conducted by varying the characteristic strength ratio and post-yield stiffness ratio over a practical range of design values. The effective properties obtained from the simplified procedure are subsequently used to develop nonlinear numerical models in *OpenSeesPy*. Nonlinear time-history analyses are then performed using a suite of 44 FEMA P-695 ground-motion records scaled to a design earthquake spectrum representative of downtown Los Angeles (Iervolino & Cornell, 2005).

The primary focus of the investigation is the comparison between the design displacement predicted by the simplified methodology and the displacement demand obtained from nonlinear dynamic analysis. Statistical measures including mean displacement, median displacement, standard deviation, coefficient of variation, displacement ratio, and prediction error are used to quantify the level of agreement between the two approaches. Through this comparison, the study aims to identify the range of isolator properties for which the simplified design procedure provides reliable estimates and to determine the conditions under which nonlinear dynamic analysis becomes necessary for accurate performance assessment (Rashvand et al., 2025).

2. Ground Motion Selection and Scaling

For the purpose of this study, it will be assumed that the selected building is located in downtown Los Angeles (Latitude: 34.1°, Longitude: -118.2°) with S_{D1}=1.16g and S_{DS}=1.56g.

A set of 44 ground motion records used in this study was selected and scaled according to the

FEMA P695 methodology. FEMA P695 introduces a scaling method where records are first normalized by the geometric mean of their peak ground velocities (PGV) in perpendicular horizontal components. Here Design Earthquake (DE) spectrum is selected as the target spectral acceleration. Normalization by peak ground velocity is a simple way to remove unwarranted variability between records due to inherent differences in event magnitude, distance to source, source type and site conditions, while still maintaining the inherent aleatory (i.e., record-to-record) variability (Baker, 2011; Iervolino & Cornell, 2005; Somerville, 2003). Table 1 lists summary of earthquake event and recording station data for the selected ground motion set.

Table 1. Summary of ground motion data used in this study

ID No.	Earthquake			Name of Recording	1-Sec Spec. Acc. (g)		Median of PGV	Normalization	PGA max	PGV max
	M	Year	Name	Station	Comp. 1	Comp.2	(in/sec)	Factor	(g)	(in/sec)
1	6.7	1994	Northridge	BeverlyHills-Mulhol	1.02	0.94	22.5	0.65	0.34	16.4
2	6.7	1994	Northridge	CanyonCountry-WLC	0.38	0.63	17.6	0.83	0.4	15.2
3	7.1	1999	Duzce,	TurkeyBolu	0.72	1.16	23.3	0.63	0.52	15.6
4	7.1	1999	Hector Mine	Hector	0.35	0.37	13.4	1.09	0.37	18.4
5	6.5	1979	Imperial Valley	Delta	0.26	0.48	11.2	1.31	0.46	17.2
6	6.5	1979	Imperial Valley	ElCentroArray#11	0.24	0.23	14.4	1.01	0.39	17.2
7	6.9	1995	Kobe, Japan	Nishi-Akashi	0.31	0.29	14.2	1.03	0.53	15.6
8	6.9	1995	Kobe, Japan	Shin-Osaka	0.33	0.23	13.3	1.1	0.26	16.8
9	7.5	1999	Kocaeli, Turkey	Duzce	0.43	0.61	21.3	0.69	0.25	16.4
10	7.5	1999	Kocaeli, Turkey	TurkeyArcelik	0.11	0.11	10.8	1.36	0.3	21.6
11	7.3	1992	Landers	YermoFireStation	0.5	0.33	14.8	0.99	0.24	20.4
12	7.3	1992	Landers	Coolwater	0.2	0.36	12.8	1.15	0.48	19.6
13	6.9	1989	Loma Prieta	Capitola	0.46	0.28	13.5	1.09	0.58	15.2
14	6.9	1989	Loma Prieta	GilroyArray#3	0.27	0.38	16.7	0.88	0.49	15.6
15	7.4	1990	Manjil, Iran	Abbar	0.35	0.54	18.6	0.79	0.4	17.2
16	6.5	1987	Superstition Hills	ElCentroImp.Co.	0.31	0.25	16.9	0.87	0.31	16
17	6.5	1987	Superstition Hills	PoeRoad(temp)	0.33	0.34	12.5	1.17	0.53	16.8
18	7	1992	Cape Mendocino	RioDellOverpass	0.54	0.39	17.9	0.82	0.45	14.4
19	7.6	1999	Chi-Chi, Taiwan	CHY101	0.49	0.95	35.7	0.41	0.18	18.8
20	7.6	1999	Chi-Chi, Taiwan	TCU045	0.3	0.43	15.3	0.96	0.49	15.2
21	6.6	1971	San Fernando	LA-HollywoodStor	0.25	0.15	7.0	2.1	0.44	16
22	6.5	1976	Friuli, Italy	Tolmezzo	0.25	0.3	10.2	1.44	0.5	17.6

3. Lead Rubber Bearing Isolators

The use of lead rubber bearings (LRB) for seismic isolation was proposed in 1974 in New Zealand by Skinner et al. (1974) (Skinner et al., 1974), and since then they have been the subject of various research studies. They were developed in detail by Robinson and Tucker

(1977) (Robinson & Tucker, 1977) experimentally demonstrating that the isolation system performed as anticipated. Since then, LRBs have become one of the most widely applied devices for seismic isolation. The LRB consists of alternating thin rubber layers and steel shims that allow for horizontal flexibility while the steel shims prevent bulging of the rubber and produce a high vertical stiffness. The lead is typically placed at the center of the bearing as a form of hysteretic energy dissipation. The lead core's material makeup allows for the mechanical properties of the lead to be recovered within minutes of previous excitations and allows for repeated use of the LRB under multiple earthquakes. The rubber shims are made of an unfilled elastomer typically known as natural rubber. The mechanical behavior of the elastomer is well established at low to intermediate strains, and because of its low damping properties, it is often simplified as an elastic material (Constantinou et al., 2007).

Although the behavior of LRBs have been heavily researched, one persistent challenge is capturing the exact response of bearings due to various factors such as scragging, rate effects, contamination, temperature, initial lead hardening, and distance travelled. Current design codes conservatively account for these complex behaviors in an estimated sense, using property modification factors such as in ASCE 7-22 (ASCE/SEI, 2022). Furthermore, simple models currently implemented in software and widely used by practicing engineers seem to capture the response of LRBs accurately for design level earthquake shaking. However, a recent emphasis of examining the response of seismically isolated buildings under extreme earthquake shaking requires more advanced models that capture the aforementioned behaviors.

Ideally, a mathematical model for LRBs should capture all the various nonlinear behaviors observed at small to large strains: scragging, rate effects, initial lead hardening, contamination, temperature, and distance travelled. Modeling all these behaviors is impractical, therefore being able to strategically select the features that are most important towards determining key response parameters is critical. The most practical approach to pinpointing the contributions of the complex behavior demonstrated by LRBs is to separate the main components and understand their key material properties (Marquez, 2021).

3.1. Simplified Design Procedure for Lead Rubber Bearings (LRBs)

To focus exclusively on the behavior of the isolation system, the superstructure was assumed to behave as a rigid body relative to the isolation layer. Consequently, the seismic response of the isolated structure was represented using an equivalent single-degree-of-freedom (SDOF) model.

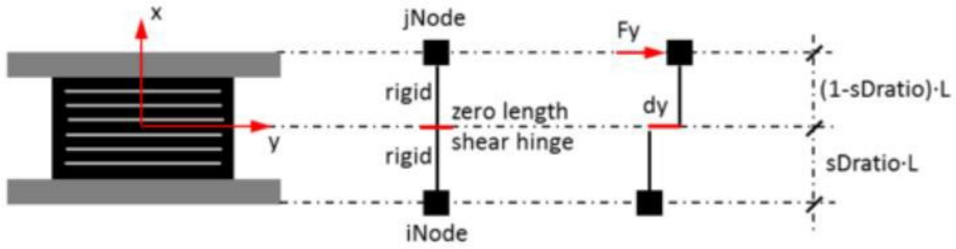

Figure 1. Bouc-Wen Hardening Element (Schellenberg et al. 2015) (Schellenberg et al., 2015)

Figure 1 shows a section of lead rubber bearing isolator. As shown in Figure 2, the mechanical behavior of a lead rubber bearing can be characterized with two important parameters: post-yield stiffness ratio (α) and the ratio of the characteristic strength to weight (μ). 6 ratio of the characteristic strength to weight of 0.03, 0.06, 0.12, 0.18, 0.24 and 0.3 are considered in this study.

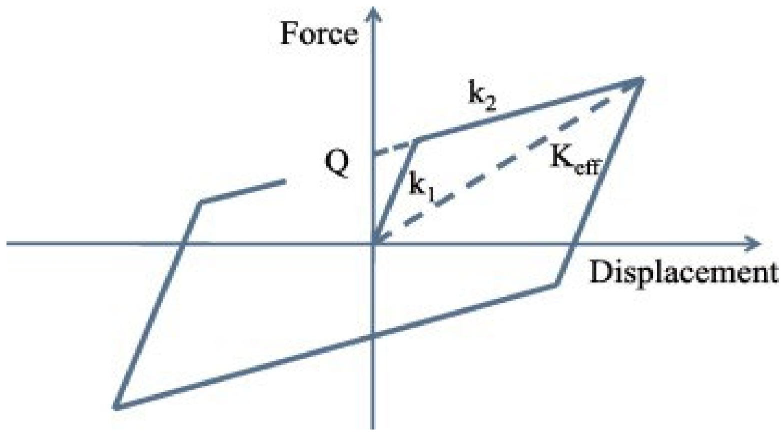

Figure 2. Hysteretic Behavior of Lead Rubber Bearing (LRB)

A displacement-based iterative design procedure was developed to determine the effective mechanical properties of Lead Rubber Bearings (LRBs) prior to nonlinear dynamic analysis. The total seismic weight of the isolated structure was assumed as (W = 5092 kips), and the yield displacement of the lead core was taken as (D_y = 1 inch). To investigate the influence of isolator properties on seismic performance, a parametric study was conducted using two design parameters: the characteristic strength ratio (μ) and the post-yield stiffness ratio (α). 6 values of (μ) ranging from 0.03 to 0.30 and 10 values of (α) ranging from 0.05 to 0.50 were considered. The characteristic strength of the isolator was defined as

$$Q_d = \mu W$$

while the post-yield stiffness was calculated as

$$K_d = \frac{Q_d \alpha}{D_y}$$

resulting in a total of 60 LRB configurations. For each configuration, the effective stiffness of the isolation system was evaluated using

$$K_{eff} = K_d + \frac{Q_d}{D_D}$$

where (D_D) denotes the design displacement. The corresponding effective period of the isolated structure was calculated as

$$T_{eff} = 2\pi \sqrt{\frac{W}{gK_{eff}}}$$

The equivalent viscous damping ratio was estimated from the hysteretic energy dissipation of the lead core according to

$$\beta_{eff} = \frac{2Q_d(D - y)}{\pi K_{eff} D^2}$$

with an upper limit of 30%. A damping modification factor was computed as to account for damping levels greater than the conventional 5% critical damping.

The iterative procedure continued until convergence was achieved. The final converged values of (Q_d), (K_d), (K_{eff}), (T_{eff}), (ξ_{eff}), and (D) were subsequently used to construct the numerical models employed in the nonlinear dynamic analyses.

3.2. Nonlinear Time-History Analysis of the Isolated System

The seismic performance of each LRB configuration was evaluated using nonlinear time-history analysis in OpenSeesPy (McKenna, 2011). The isolated structure was represented by an equivalent single-degree-of-freedom (SDOF) system in which the superstructure was assumed to behave as a rigid mass relative to the isolation layer. The lumped mass was calculated and assigned to the isolated node.

The isolation system was modeled using a zero-length element connecting the fixed base to the isolated mass. To reproduce the bilinear hysteretic behavior of a lead rubber bearing (LRB), a parallel material formulation was adopted. The lead core was represented using the Steel01 material model with a yield strength equal to Q_d and an initial elastic stiffness defined as $\frac{F_y}{D_y}$. A zero strain-hardening ratio (b = 0) was assigned, resulting in an elastic-perfectly plastic response after yielding. The rubber component was modeled as a linear elastic material with stiffness equal to K_d. These two components were combined in parallel to reproduce the characteristic bilinear force–displacement behavior of the isolation system. The resulting model captures the primary stiffness contribution of the rubber layers together with the hysteretic energy dissipation provided by the yielding lead core (Dolatshahi et al., 2019; Mazzoni et al., 2006; Zahrai & Hamidia, 2010).

It should be noted that the adopted model represents a simplified bilinear approximation of LRB behavior and does not explicitly account for rate dependency, temperature effects, scragging, or lead-core hardening phenomena.

A suite of 44 FEMA earthquake ground-motion records was employed to evaluate the seismic response. Each record was scaled to the target design spectrum using where ($S_a Target$) is the target spectral acceleration obtained from the design spectrum and ($S_a GM$) is the spectral acceleration associated with the considered ground motion at the effective isolation period. Record-specific normalization factors were incorporated into the final scaling procedure.

The scaled accelerograms were applied through a uniform excitation pattern, and nonlinear dynamic analyses were performed over the entire duration of each record. This procedure was repeated for all 60 isolator configurations and 44 ground motions, providing a comprehensive database of seismic responses for subsequent evaluation.

3.3. Response Evaluation and Comparison Methodology

Following completion of the nonlinear time-history analyses, the displacement response of the isolation system was extracted for each ground-motion record and isolator configuration. Since the primary objective of this study is to evaluate the accuracy of the simplified displacement-based design procedure, the peak displacement demand obtained from nonlinear dynamic analysis was selected as the principal response parameter for comparison.

For each analysis, the maximum absolute displacement of the isolation layer was determined from the displacement time-history record as the peak isolator displacement demand. Consequently, each of the 60 LRB configurations produced a set of 44 peak displacement values corresponding to the 44 FEMA P695 ground-motion records. This resulted in a total of 2640 nonlinear dynamic analysis results available for statistical evaluation.

To obtain a representative displacement demand for each isolator configuration, the mean value of the 44 peak displacement responses was calculated. In addition, the median, maximum, minimum, and standard deviation of the displacement demands were evaluated to quantify the record-to-record variability associated with the selected ground-motion set. The coefficient of variation (COV) was also computed as a normalized measure of dispersion.

The displacement demand predicted by the simplified design procedure, denoted as the design displacement, was then compared with the corresponding mean displacement obtained from nonlinear time-history analysis. To quantify the level of agreement between the two approaches, a displacement ratio was defined as the ratio of the mean nonlinear displacement demand to the design displacement. A ratio close to unity indicates excellent agreement between the simplified procedure and nonlinear dynamic analysis, whereas values greater than or less than unity indicate unconservative or conservative predictions, respectively.

Furthermore, the percentage error between the two methods was calculated to evaluate the accuracy of the simplified procedure across the entire range of isolator properties considered in the study. The influence of the characteristic strength ratio (μ) and post-yield stiffness ratio (α) on the displacement prediction accuracy was subsequently investigated through a series of statistical comparisons and graphical evaluations.

The resulting dataset enabled a comprehensive assessment of the capability of the simplified displacement-based design methodology to predict the displacement demands of lead rubber bearing isolation systems subjected to design-level earthquake ground motions.

4. Results and Discussion

The accuracy of the proposed simplified design procedure was evaluated by comparing the design displacement predicted by the iterative displacement-based method with the mean peak displacement obtained from nonlinear time-history analyses (THA). A total of 60 LRB configurations, defined by 6 characteristic strength ratios (μ) and ten post-yield stiffness ratios (α), were subjected to 44 FEMA P695 ground-motion records.

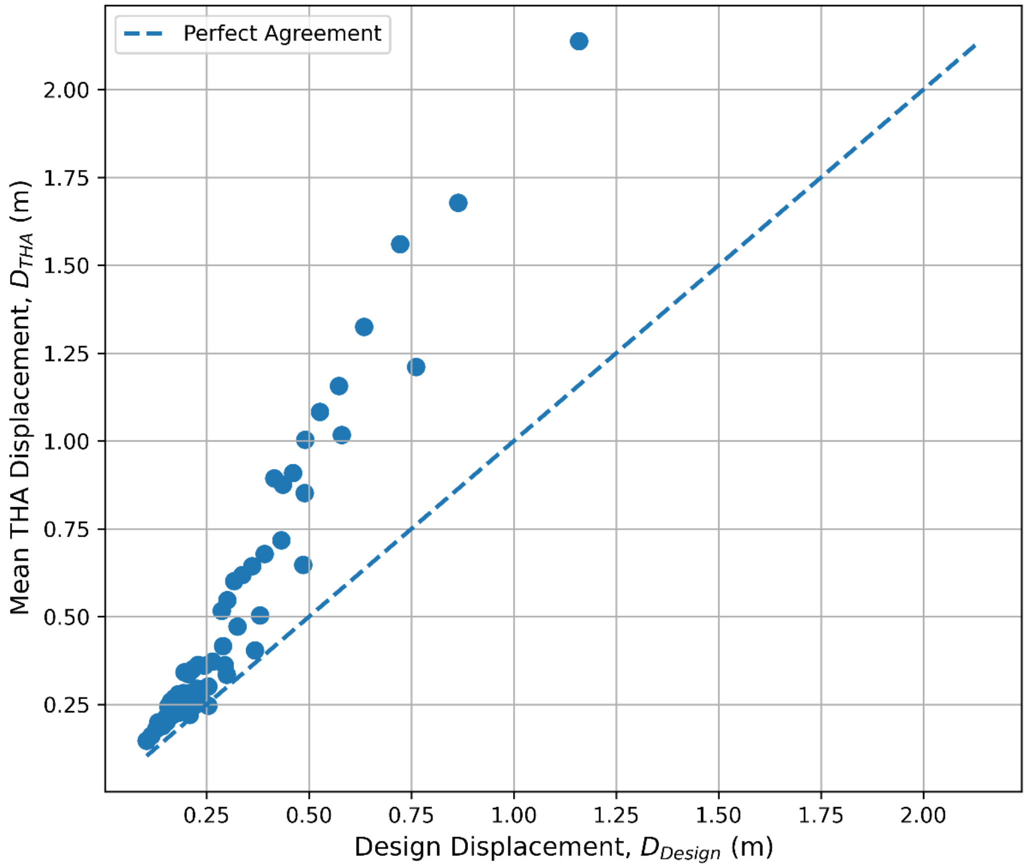

Figure 3. Comparison of simplified-design displacement predictions and mean peak displacement demands obtained from nonlinear time-history analyses

4.1. Comparison between Simplified and Nonlinear Dynamic Responses

Figure 3 compares the design displacement obtained from the simplified procedure with the mean peak displacement computed from nonlinear time-history analyses. The dashed diagonal line represents perfect agreement between the two approaches.

It can be observed that nearly all data points lie above the line of equality, indicating that the nonlinear dynamic analyses consistently produced larger displacement demands than those predicted by the simplified design procedure. Therefore, the simplified method generally underestimates the actual isolator displacement demand.

The discrepancy is particularly pronounced for systems with small characteristic strength ratios, where the difference between the predicted and simulated displacements becomes significant. As the characteristic strength ratio increases, the data points move closer to the line of equality, suggesting improved agreement between the simplified and nonlinear approaches.

These results indicate that the simplified design methodology captures the overall displacement trend but may not fully represent the dynamic amplification and record-to-record variability associated with low-strength isolation systems.

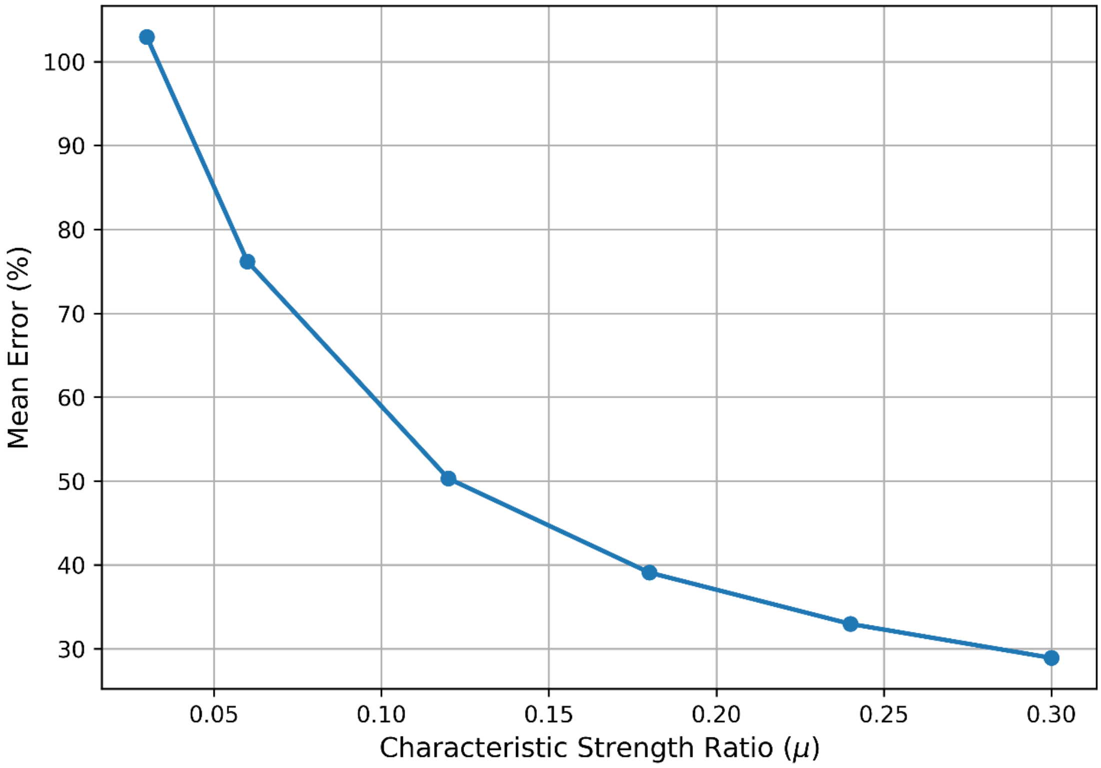

Figure 4. Effect of characteristic strength ratio (μ) on the displacement prediction error of the simplified design procedure

4.2. Influence of Characteristic Strength Ratio

Figure 4 illustrates the variation of the average displacement prediction error as a function of the characteristic strength ratio (μ).

A clear decreasing trend can be observed. The average prediction error exceeds 100% for μ = 0.03 and gradually decreases as μ increases. For μ = 0.30, the average error is reduced to approximately 29%.

This behavior suggests that increasing the characteristic strength of the lead core improves the consistency between simplified predictions and nonlinear dynamic responses. Larger values of μ provide greater hysteretic energy dissipation and reduce the sensitivity of the isolation system to record-to-record variations, resulting in more reliable displacement estimates.

The results also indicate that the simplified procedure is most conservative for high-strength isolators and least accurate for low-strength systems.

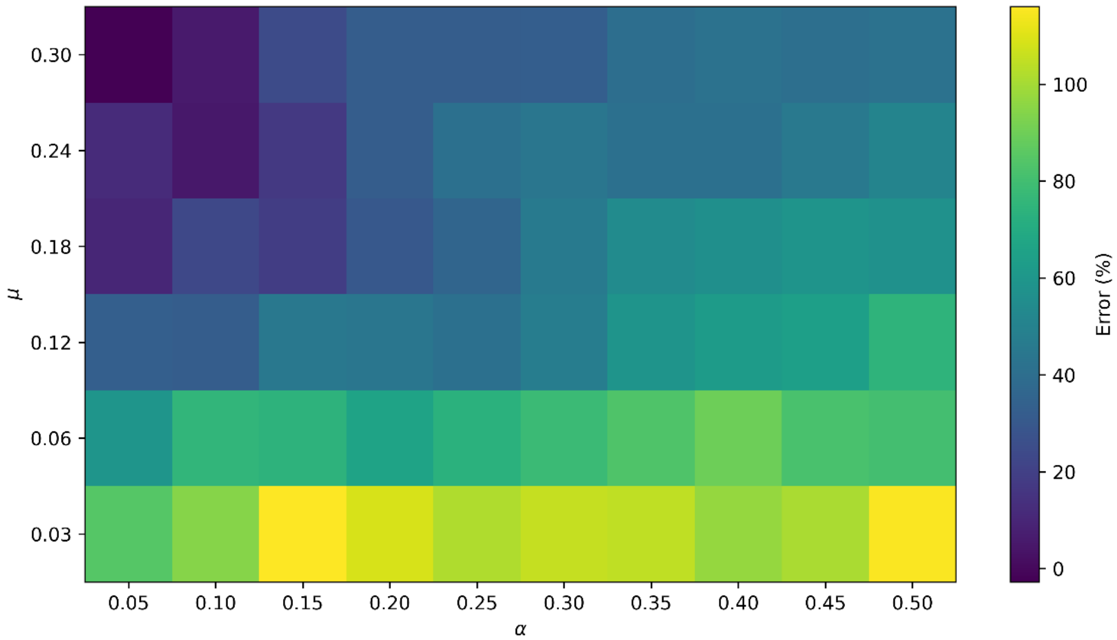

Figure 5. Relationship between post-yield stiffness ratio (α) and displacement demand ratio ($\frac{D_{THA}}{D_{Design}}$) for different values of characteristic strength ratio (μ).

4.3. Combined Effect of μ and α

The combined influence of the characteristic strength ratio and post-yield stiffness ratio on prediction accuracy is illustrated in Figure 5.

Several important observations can be made:

1. The largest prediction errors occur for μ = 0.03 regardless of α.
2. Increasing μ systematically reduces the prediction error.
3. The influence of α is secondary compared with μ.
4. For low values of μ, changes in α have limited ability to improve prediction accuracy.
5. For moderate and large values of μ, the error remains within a relatively narrow range.

The heat map demonstrates that the characteristic strength ratio is the dominant parameter controlling the accuracy of displacement predictions. In contrast, the post-yield stiffness ratio mainly affects local variations within each μ level.

The lowest prediction error was observed for μ = 0.30 and α = 0.05, where the difference between the simplified procedure and nonlinear dynamic analysis was less than 3%. Conversely, the largest errors occurred for μ = 0.03, where the mean displacement demand obtained from THA exceeded the simplified prediction by more than 100%.

4.4. Engineering Implications

The results suggest that simplified displacement-based design procedures may not always provide sufficiently accurate estimates of displacement demand, particularly for isolation systems with low characteristic strength ratios.

For preliminary design applications, the simplified approach remains useful because it rapidly provides effective stiffness, effective period, damping ratio, and design displacement. However, when low values of μ are selected or when performance under strong earthquake excitation is of interest, nonlinear time-history analysis becomes necessary to accurately estimate displacement demand.

The findings also demonstrate the importance of considering record-to-record variability, which is not explicitly captured by the simplified procedure but significantly influences the nonlinear response.

5. Conclusions

This study investigated the accuracy of a displacement-based simplified design procedure for Lead Rubber Bearing (LRB) isolation systems through comparison with nonlinear time-history analyses conducted in OpenSeesPy. Sixty LRB configurations were generated using combinations of characteristic strength ratio (μ) and post-yield stiffness ratio (α), and each configuration was evaluated using 44 FEMA P695 ground-motion records.

Based on the results obtained, the following conclusions can be drawn:

1. The simplified design procedure systematically underestimates the displacement demand of LRB isolation systems when compared with nonlinear time-history analysis results.
2. The discrepancy between the two methods strongly depends on the characteristic strength ratio (μ).
3. The average prediction error decreases significantly as μ increases, reducing from approximately 103% for $\mu = 0.03$ to about 29% for $\mu = 0.30$.
4. The characteristic strength ratio is the dominant parameter affecting prediction accuracy, whereas the influence of the post-yield stiffness ratio (α) is comparatively less significant.
5. For low-strength isolation systems, nonlinear dynamic effects and record-to-record variability become increasingly important and cannot be adequately represented by the simplified procedure alone.
6. The best agreement between the simplified and nonlinear analyses was achieved for high characteristic strength ratios, where the prediction error was reduced to less than 5% for some configurations.
7. Although the simplified methodology provides an efficient preliminary design tool, nonlinear time-history analysis remains necessary for accurate assessment of

displacement demand, particularly when evaluating the performance of isolated structures subjected to severe earthquake ground motions.

Overall, the study demonstrates that the reliability of simplified displacement-based design procedures depends strongly on the mechanical characteristics of the isolation system, and their application should be accompanied by nonlinear verification when accurate performance assessment is required.

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