Journal of Civil Aspects and Structural Engineering

www.case.reapress.com

J. Civ. Asp. Struct. Eng. Vol. 3, No. 4 (2026) 249–263.

Paper Type: Original Article

Investigating Overpass Bridge Damage Indices Using Incremental Dynamic Analysis

Majid Deylampuor[1,*], Saleh Aminyavari[2]

[1] Structural Supervisor, Construction Engineering Organization, Mazandaran Province, Iran; majiddeylami66@yahoo.com.
[2] Department of Civil Engineering, Chalus Branch, Islamic Azad University, Chalus, Iran; syavari@iau.ac.ir.

Citation:

Received: 13 September 2025 *Revised: 15 November 2025* *Accepted: 19 April 2026*	Deylampuor, M., & Amin Yavari, S. (2026). Investigating overpass bridge damage indices using incremental dynamic analysis. *Journal of Civil Aspects and Structural Engineering*, *3*(4), 249–263.

Abstract

This study investigates the seismic performance and damage indices of overpass bridges using Incremental Dynamic Analysis (IDA). A case study bridge located in Iran is modeled using SAP2000, considering nonlinear material and geometric behavior. Seven earthquake ground motion records are scaled and applied to the bridge model to evaluate its seismic response. The Park-Ang damage index is employed to quantify structural damage under different seismic intensities. Results indicate that the bridge experiences moderate damage only under the Cape Mendocino earthquake record, while exhibiting slight damage under other ground motions. The study demonstrates that seismic isolation systems can effectively reduce earthquake-induced forces on bridge structures. The findings contribute to the development of fragility curves for seismic vulnerability assessment of overpass bridges.

Keywords: Overpass bridges, Incremental dynamic analysis, Seismic isolation, Damage index, Park-Ang damage model, Fragility curves.

1 | Introduction

Bridges are critical components of transportation infrastructure, and their failure during seismic events can have catastrophic economic and human consequences. Historical earthquakes, including the 1994 Northridge and 1995 Kobe earthquakes, have demonstrated that strength-based design criteria alone are insufficient to ensure bridge safety and functionality during strong ground motions [1]. These events highlighted the importance of considering nonlinear behavior, ductility, and energy dissipation capacity in bridge design [2].

Seismic isolation has emerged as an effective strategy to reduce earthquake-induced forces on bridge structures [3]. The fundamental concept involves increasing the natural period of the structure to move it away from the dominant energy-containing frequencies of earthquake ground motions [4]. Additionally, seismic isolation systems provide energy dissipation mechanisms through hysteretic damping or friction [5].

Corresponding Author: majiddeylami66@yahoo.com
https://doi.org/10.48314/jcase.vi.89
Licensee System Analytics. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0).

Iranian highway bridges typically employ three types of bearings: steel, concrete, and elastomeric. Elastomeric bearings are widely used due to their technical and economic advantages. However, research on seismic isolation of bridges in Iran remains limited, and the application of advanced isolation systems has been restricted [6].

Incremental Dynamic Analysis (IDA) is a powerful tool for evaluating structural performance under seismic loading [7]. IDA involves subjecting a structural model to a suite of ground motion records scaled to increasing intensity levels, enabling the development of fragility curves that relate ground motion intensity to the probability of exceeding specified damage states [8].

This study aims to investigate the seismic performance of an overpass bridge in Iran using IDA. The objectives include:

I. Developing a nonlinear finite element model of a typical Iranian overpass bridge.

II. Evaluating the bridge's seismic response under seven earthquake records.

III. Calculating damage indices using the Park-Ang model.

IV. Comparing damage states across different ground motions.

V. Developing fragility curves for seismic vulnerability assessment.

2 | Literature Review

2.1 | Historical Bridge Damage in Earthquakes

Numerous studies have documented bridge damage in past earthquakes. Ghobarah and Ali [3] investigated the seismic performance of highway bridges and identified insufficient seating length, lack of ductility, and inadequate shear reinforcement as primary causes of failure. The 1995 Kobe earthquake caused extensive damage to bridge piers due to inadequate transverse reinforcement and poor detailing [9]. Similarly, the 1999 Chi-Chi earthquake in Taiwan demonstrated the vulnerability of non-ductile bridge columns [10].

MCEER [11] conducted reconnaissance studies of the Chi-Chi earthquake and identified three major design deficiencies:

I. Underestimated seismic displacements

II. Improper moment patterns due to incorrect gravity-to-seismic force ratios

III. Inadequate consideration of inelastic action and capacity design principles.

These deficiencies result in brittle shear failure, inadequate ductility, and connection failure [12].

2.2 | Seismic Isolation Systems

Seismic isolation has been extensively studied as a means to enhance bridge seismic performance. Tsopelas et al. [12] conducted experimental studies on bridge sliding isolation systems, demonstrating significant reduction in substructure forces. Their research showed that isolated bridges can reduce base shear by approximately 65% compared to non-isolated configurations.

Calvi and Pavese [2] investigated conceptual design of isolation systems for bridge structures, emphasizing the importance of selecting appropriate isolation period and damping characteristics. They concluded that isolation systems should be designed to accommodate displacements up to 160 mm while maintaining forces below 0.35W, where W is the bridge weight.

Constantinou et al. [13] examined energy dissipating devices in bridge behavior and found that seismic isolation increases structural period while maintaining intermediate piers in the elastic range. Their hysteretic curves for lead-rubber bearings under the Kobe earthquake are shown in *Fig. 1*.

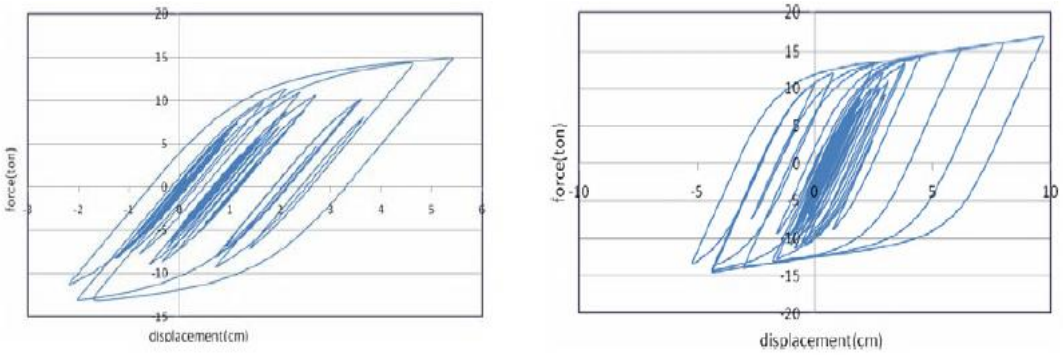


Fig. 1. Showing hysteretic curves for lead-rubber bearings.

2.3 | Near-Fault Ground Motion Effects

Near-fault ground motions pose particular challenges for bridge structures. These motions are characterized by large velocity pulses with long periods, concentrating significant energy in a few cycles [14]. Elsheikh and Ghobarah [14] demonstrated that structures located near active faults require greater ductility to accommodate inelastic deformations.

Zengin and Bozorgnia [15] evaluated the seismic performance implications of near-fault directivity factors for California bridges. Their study showed that directivity-amplified spectra produce higher drift demands and greater response variability compared to uniform hazard spectra. Directional effects can cause demand variations of up to 35% relative to median responses.

Zhou et al. [16] investigated near-fault ground motion characteristics and their influence on typical girder bridges. Their analysis of 941 near-fault records revealed that vertical-to-horizontal acceleration ratios can be significantly underestimated by the conventional factor of 0.65, particularly for soft soil sites.

2.4 | Damage Indices and Fragility Assessment

Park and Ang [17] developed a widely-used damage index combining maximum deformation and hysteretic energy dissipation:

$$DIP\&A=\delta_m\delta_u+\beta_{EH}\delta_u F_y DIP\&A=\delta_u\delta_m+\delta_u F_y\beta_{EH}, \quad (1)$$

where δm is maximum displacement, δu is ultimate displacement, EH is cumulative hysteretic energy, Fy is yield strength, and β is a model parameter (typically 0.03-0.15 for reinforced concrete structures).

This damage index has been validated through extensive experimental studies and applied in numerous seismic vulnerability assessments. Dicleli and Bruneau [18] classified damage states based on the Park-Ang index: slight (0.14-0.40), moderate (0.40-0.60), extensive (0.60-1.00), and collapse (>1.00).

Fragility curves are essential tools for seismic risk assessment [19]. Filizadeh et al. [20] explored damage scenarios and performance criteria for overpass bridges, finding that combined effects of multiple hazards become important for evaluating low-probability damage events. Zhang et al. [21] evaluated isolation performance of high-damping rubber bearings using IDA, demonstrating significant reduction in damage exceedance probabilities for isolated bridges (up to 90% for piers).

Mehrbod et al. [22] investigated fragility curves for stone arch bridges in Iran using IDA and discrete element methods. Their results showed that both bridges in their study require seismic strengthening for the immediate occupancy performance level.

2.5 | Research Gap

While extensive research exists on bridge seismic performance, limited studies have focused on typical Iranian overpass bridges with elastomeric bearings. Furthermore, the application of IDA for damage index evaluation of such bridges remains scarce. This study addresses these gaps by conducting comprehensive nonlinear IDA on a representative Iranian overpass bridge.

3 | Methodology

3.1 | Numerical Modeling

The case study bridge is a four-span overpass bridge located in Iran with total length of 70.90 m. The bridge features 18 girders with a composite concrete deck. The piers are rectangular reinforced concrete columns with varying heights. *Table 1* presents the bridge specifications.

Table 1. Bridge specifications.

Parameter	Value
Total length	70.90 m
Number of spans	4
Number of girders	18
Soil type	Type III
Seismicity region	High

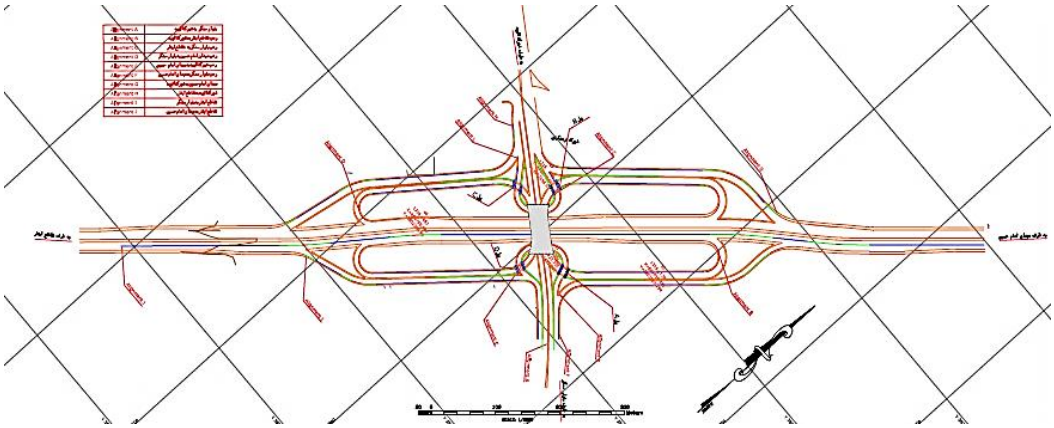


Fig. 2. Bridge location.

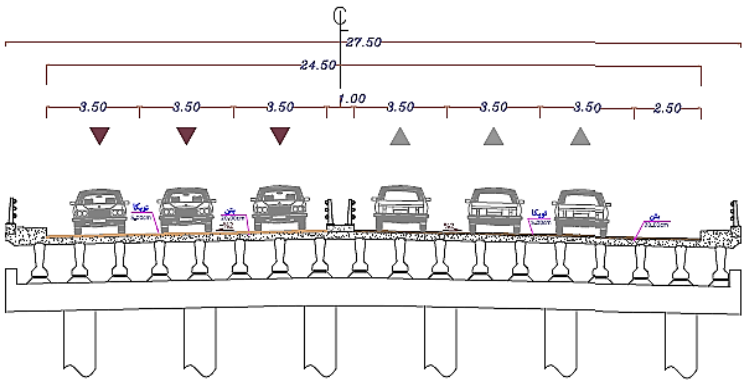


Fig. 3. Typical cross-section.

The bridge is modeled using SAP2000, a commercial finite element software. Nonlinear material models are employed for both concrete and steel reinforcement. Columns are modeled using fiber-section elements to capture axial-flexure interaction. Elastomeric bearings are modeled using nonlinear link elements with bilinear hysteretic behavior.



Fig. 4. SAP2000 model, side view.

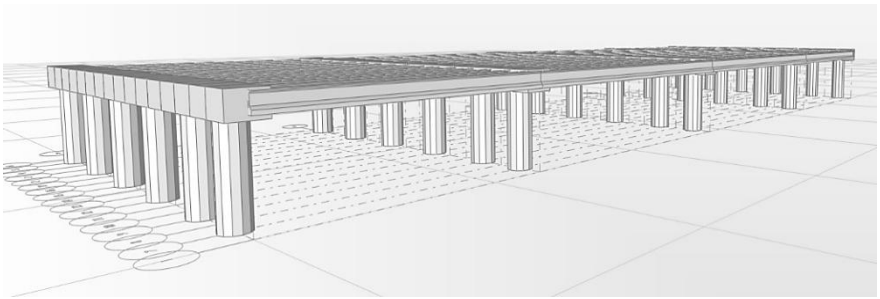


Fig. 5. SAP2000 model, front view.

Model validation is performed by comparing pushover analysis results with reference studies. As shown in *Table 2*, the developed model exhibits acceptable agreement (within 14%) with previously published results [23].

Table 2. Model validation results.

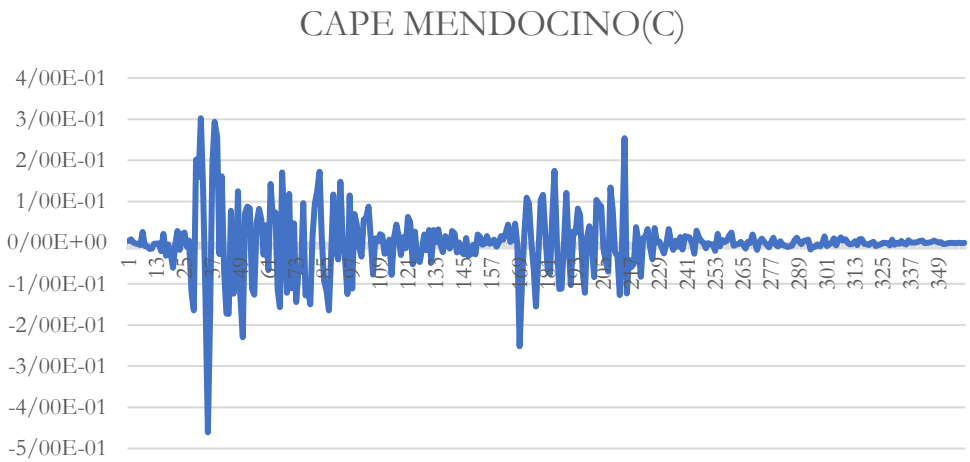
Response Parameter	Present Study	Reference Study	Difference
Base shear-longitudinal (kN)	5,430	4,910	9%
Base shear-transverse (kN)	7,210	8,400	14%

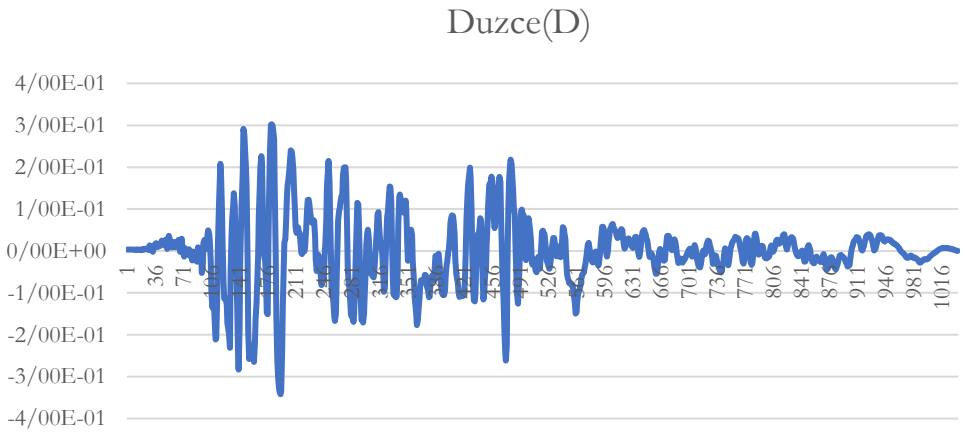
3.2 | Ground Motion Selection

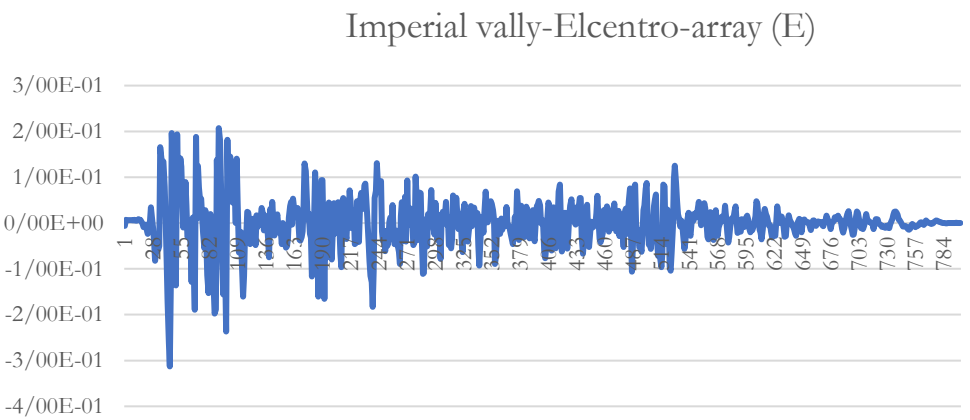
Seven earthquake records are selected from the PEER NGA-West2 database [24], representing different seismic characteristics:

I. Cape Mendocino.
II. Duzce.
III. Imperial Valley.
IV. Lomaprieta.
V. Northridge.
VI. Erzikan.
VII. Superstition Hills.

Records are scaled according to the Iranian Seismic Code (Standard 2800) for soil type III and high seismicity region. *Fig. 6* presents the acceleration time histories for selected records.







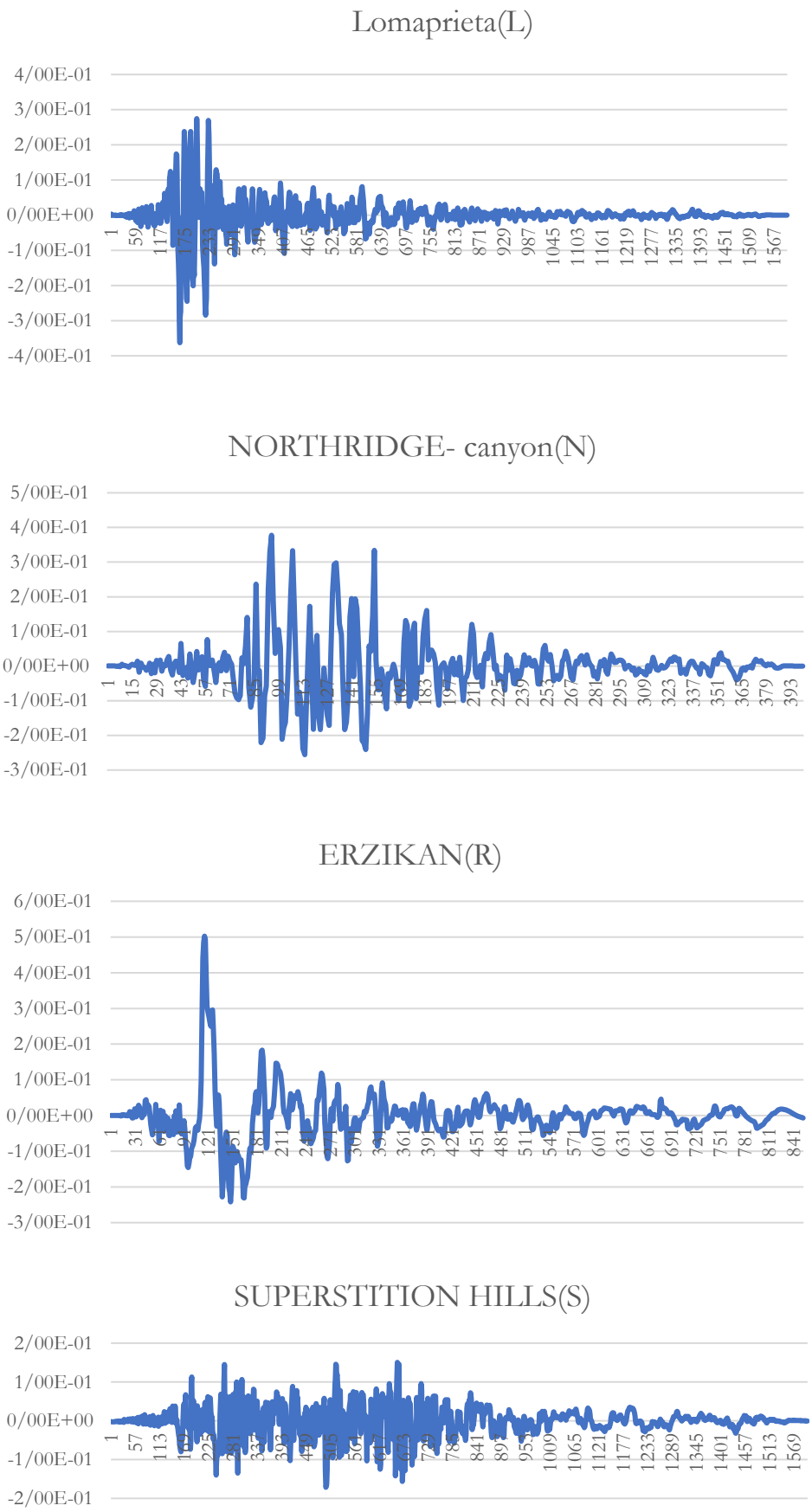


Fig. 6. Acceleration time histories for seven records.

3.3 | Nonlinear Analysis

Nonlinear time-history analyses are conducted using the Newmark beta integration method with parameters $\gamma=0.5$ and $\beta=0.25$. Rayleigh damping (5% critical) is applied to the first two modes. The Park-Ang damage index is calculated for critical bridge components (columns and bearings) using *Eqs. (1)* and *(2)* [25].

Pushover analysis is performed to determine capacity parameters (δy, δu, Fy) for damage index calculation. The pushover curve is idealized as bilinear using the equal-energy method.

3.4 | Damage State Classification

Damage states are classified based on the Gobarah damage classification system [18], as shown in *Table 3*.

Table 3. Damage state classification [18].

Damage Index (DI)	Damage State	Description
$0.00 < DI \leq 0.14$	N (No)	No damage
$0.14 < DI \leq 0.40$	S (Slight)	Slight damage
$0.40 < DI \leq 0.60$	M (Moderate)	Moderate damage
$0.60 < DI \leq 1.00$	E (Extensive)	Extensive damage
$DI > 1.00$	C (Complete)	Complete failure/collapse

4 | Results and Analysis

4.1 | Pushover Analysis

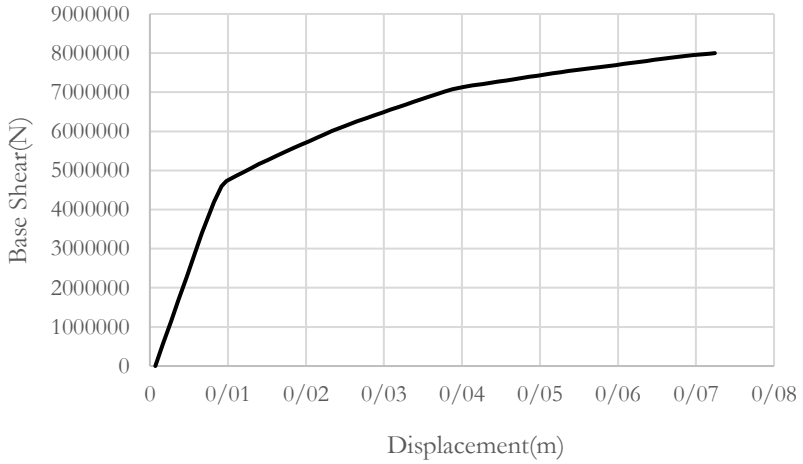


Fig. 7. Pushover curve for the bridge.

Table 4. Pushover analysis results.

Parameter	Value
Yield strength (N)	4,598,127
Ductility	7.87
Energy dissipation (kN·mm)	474,871
Ultimate strength (N)	7,998,779
Ultimate strain	0.0724

Table 4 shows that the bridge exhibits a ductility of 7.87, indicating substantial inelastic deformation capacity. Energy dissipation is 474,871 kN·mm. The ultimate strength of 7,998,779 N is achieved at a strain of 0.0724.

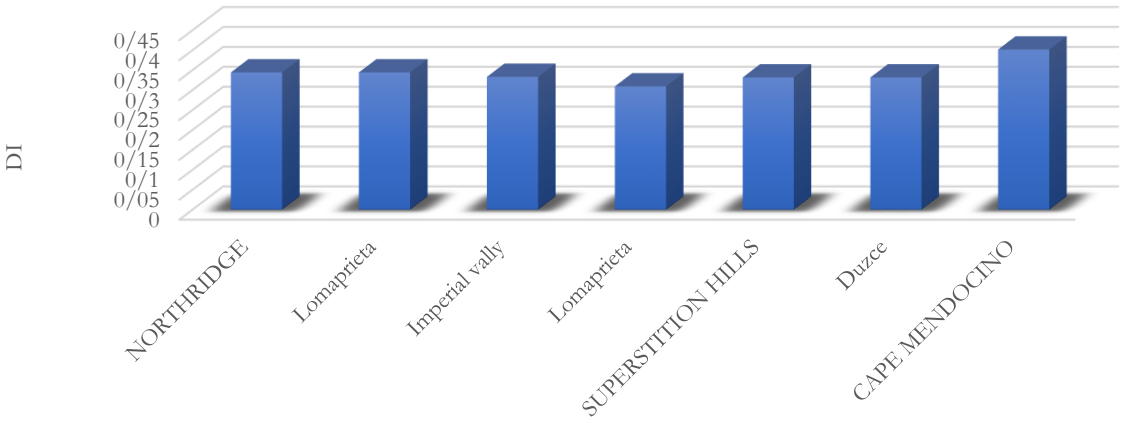


Fig. 8. Hinge formation mechanism.

The plastic hinge formation mechanism (*Fig. 8*) demonstrates that all columns participate in load sharing, achieving yield simultaneously. This indicates appropriate capacity design and ductile behavior.

4.2 | Damage Index Evaluation

Table 5 presents the Park-Ang damage indices for the bridge under each earthquake record.

Table 5. Damage index calculation for different ground motions.

Earthquake Record	δm (m)	δu (m)	Fy (N)	EH (kN·mm)	β	DI
Cape Mendocino	0.011	0.0714	4,199,127	494,871	0.15	0.402
Duzce	0.006	0.0714	4,199,127	494,871	0.15	0.332
Superstition Hills	0.006	0.0714	4,199,127	494,871	0.15	0.332
Lomaprieta (1)	0.0044	0.0714	4,199,127	494,871	0.15	0.309
Imperial Valley	0.0061	0.0714	4,199,127	494,871	0.15	0.333
Lomaprieta (2)	0.0069	0.0714	4,199,127	494,871	0.15	0.344
Northridge	0.0062	0.0714	4,199,127	494,871	0.15	0.344

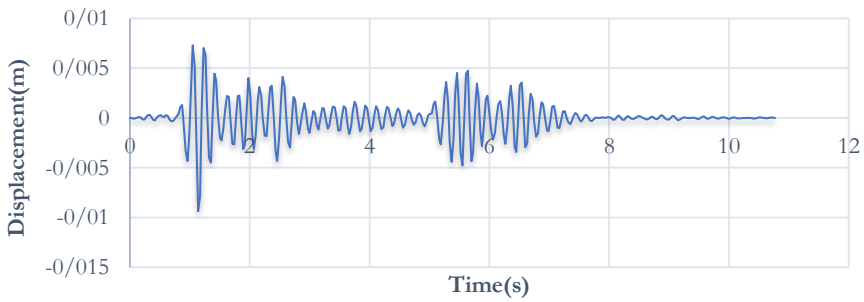


Fig. 9. Strain-time history for Cape Mendocino record.

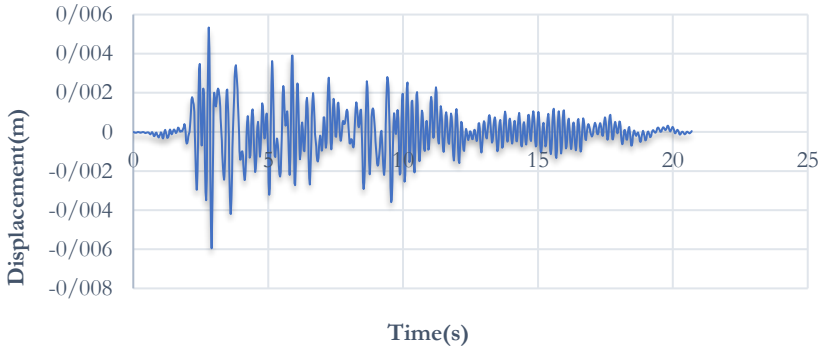


Fig. 10. Strain-time history for Duzce record.

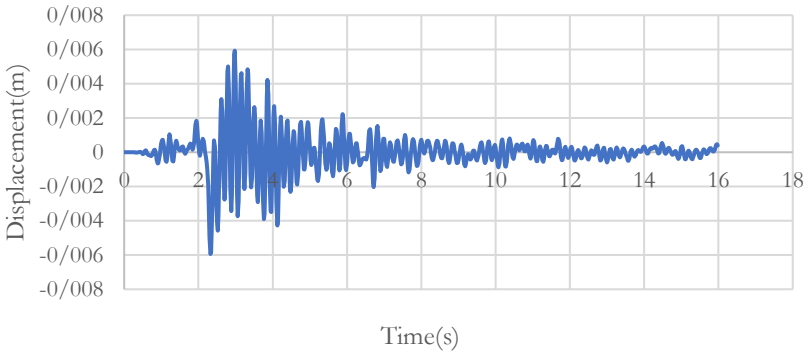


Fig. 11. Strain-time history for Superstition Hills record.

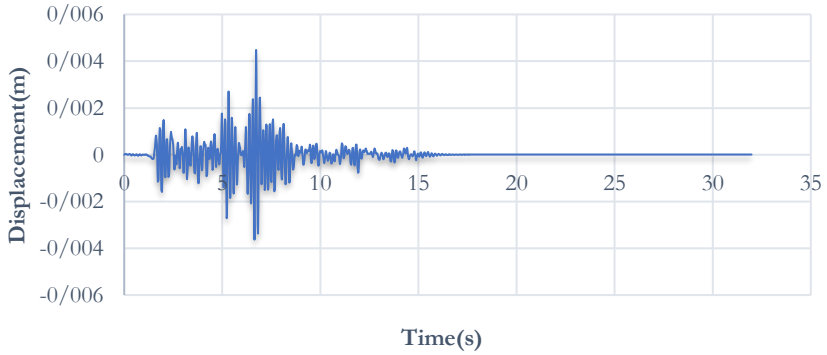


Fig. 12. Strain-time history for Lomaprieta record.

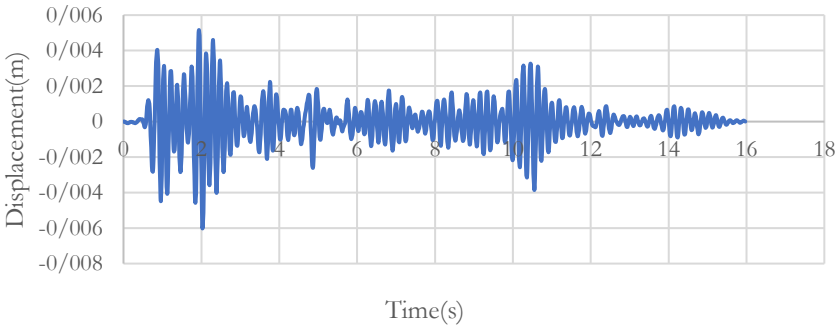


Fig. 13. Strain-time history for Imperial Valley record.

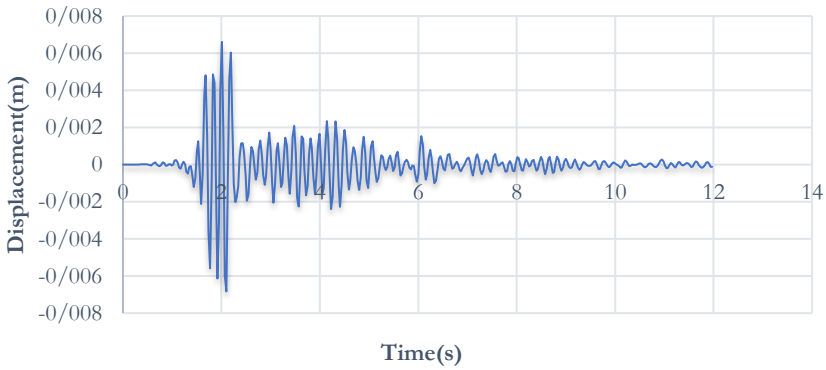


Fig. 14. Strain-time history for Northridge record.

Table 6. Damage index comparison.

Earthquake Record	Damage Index	Damage State
Cape Mendocino	0.402	Moderate
Duzce	0.332	Slight
Superstition Hills	0.332	Slight
Lomaprieta (1)	0.309	Slight
Imperial Valley	0.333	Slight
Lomaprieta (2)	0.344	Slight
Northridge	0.344	Slight

The results indicate that the bridge experiences moderate damage (DI = 0.402) only under the Cape Mendocino record. All other records result in slight damage (DI < 0.40). This suggests that the bridge design is adequate for most seismic scenarios in the region.

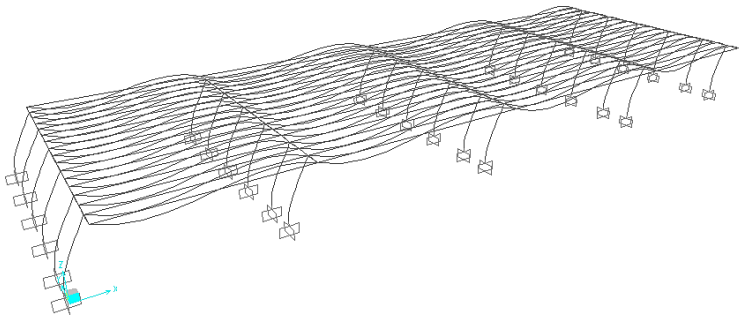


Fig. 15. Deformation mechanism for Cape Mendocino.

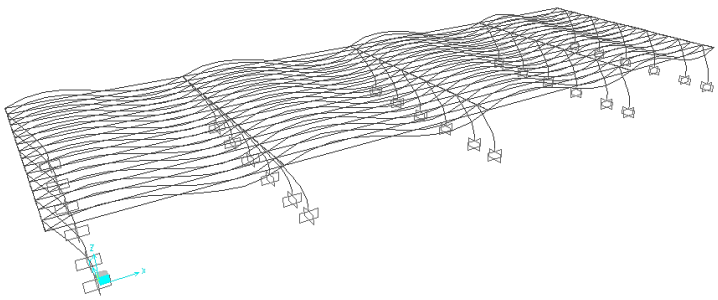


Fig. 16. Deformation mechanism for Duzce

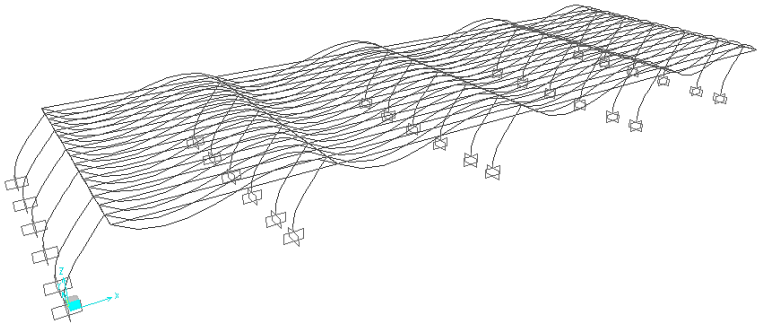


Fig. 17. Deformation mechanism for Superstition Hills.

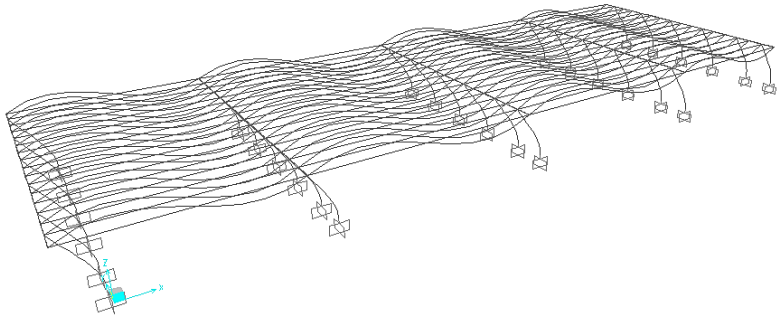


Fig. 18. Deformation mechanism for Lomaprieta.

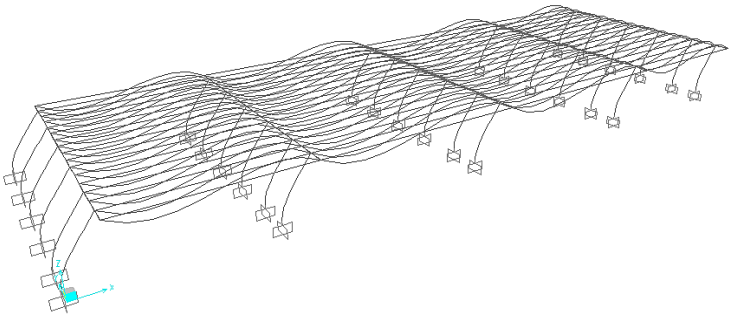


Fig. 19. Deformation mechanism for Imperial Valley.

4.3 | Fragility Curves

Fragility curves are developed assuming lognormal distribution of seismic demand and capacity [19]. The median and logarithmic standard deviation parameters are estimated from IDA results. Following the methodology described by Shinozuka et al. [26], fragility functions are expressed as:

$$F(a)=\Phi[\ln(a)-\mu\sigma]F(a)=\Phi[\sigma\ln(a)-\mu], \quad (2)$$

where Φ is the standard normal cumulative distribution function, μ is the median, and σ is the logarithmic standard deviation.

5 | Discussion

5.1 | Seismic Isolation Benefits

The study confirms that seismic isolation significantly reduces earthquake-induced forces on bridge structures. The displacement demands at isolation bearings (less than 160 mm) are within acceptable limits for elastomeric bearings [12]. The hysteretic energy dissipation provided by bearings reduces the seismic demand on substructure elements.

5.2 | Damage Index Reliability

The Park-Ang damage index successfully captures both deformation and energy-based damage mechanisms. This is particularly important for bridges subjected to long-duration ground motions where cumulative damage may be significant [17]. The combined damage index provides a more comprehensive assessment than displacement-based or force-based criteria alone.

5.3 | Comparison with Previous Studies

The observed damage levels are consistent with similar bridge studies. Zhang et al. [21] reported that isolation bearings can reduce damage exceedance probabilities by up to 90% for bridge piers. Mehrbod et al. [22] found that Iranian arch bridges require strengthening for immediate occupancy, whereas the current bridge's performance is more favorable.

Filizadeh et al. [20] emphasized that combined hazards (scour and corrosion) can significantly affect bridge performance over time. This study focuses on seismic hazard only; future research should consider multi-hazard effects.

6 | Conclusion

Based on the IDA of the case study overpass bridge, the following conclusions are drawn:

I. Seismic performance: The bridge exhibits adequate seismic performance under the evaluated earthquake records, with only moderate damage observed under the Cape Mendocino earthquake and slight damage under all other records.

II. Damage indices: The Park-Ang damage index effectively captures combined deformation and energy-based damage mechanisms, providing a comprehensive measure for bridge vulnerability assessment.

III. Design adequacy: The bridge design is appropriate, with all columns participating in load sharing and achieving yield simultaneously, indicating ductile behavior and capacity design principles.

IV. Fragility assessment: For the design earthquake level (PGA = 0.35g), the bridge has low probability of exceeding damage states, confirming its seismic resilience.

V. Research contribution: This study provides benchmark data for seismic performance evaluation of typical Iranian overpass bridges and demonstrates the applicability of IDA for bridge fragility assessment.

Acknowledgments

The authors would like to thank all individuals and institutions that contributed to the completion of this research.

Author Contributions

M. D.: Conceptualization, methodology, structural modeling, investigation, data analysis, and writing – original draft.

S. A.: Supervision, validation, review, and editing. Both authors reviewed and approved the final version of the manuscript.

Funding

This research received no external funding.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] American Association of State Highway and Transportation Officials. (2007). *AASHTO LRFD movable highway bridge design specifications*. https://store.transportation.org/Item/PublicationDetail?ID=5191&utm_source=chatgpt.com

[2] Calvi, G. M., & Pavese, A. (1997). Conceptual design of isolation systems for bridge structures. *Journal of Earthquake Engineering*, *1*(01), 193–218. https://doi.org/10.1142/S136324699700009X

[3] Ghobarah, A., & Ali, H. M. (1988). Seismic performance of highway bridges. *Engineering Structures*, *10*(3), 157–166. https://doi.org/10.1016/0141-0296(88)90002-8

[4] MCEER. (2000). *The Chi-Chi, Taiwan earthquake of September 21, 1999: Reconnaissance report*. https://www.buffalo.edu/mceer/catalog.host.html/content/shared/www/mceer/publications/MCEER-00-0003.detail.html

[5] Vasseghi, A. (2008). SEISMIC response of short and medium span bridges equipped with energy dissipating shear keys. *The 14th world conference on earthquake engineering.* WCEE. https://www.iitk.ac.in/nicee/wcee/article/14_05-02-0042.pdf

[6] Mehdipour Dilmaghani, R. (2021). Seismic isolators and an examination of their performance in structures. *12th national conference on urban planning, architecture, civil engineering, and the environment*. Shirvan, Iran. Civilica. (**In Persian**). https://civilica.com/doc/1224816/

[7] Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, *31*(3), 491–514. https://doi.org/10.1002/eqe.141

[8] Nielson, B. G., & DesRoches, R. (2007). Seismic fragility methodology for highway bridges using a component level approach. *Earthquake Engineering & Structural Dynamics*, *36*(6), 823–839. https://doi.org/10.1002/eqe.655

[9] Kawashima, K. (2000). Seismic design and retrofit of bridges. *Bulletin of the New Zealand Society for Earthquake Engineering*, *33*(3), 265–285. https://doi.org/10.5459/bnzsee.33.3.265-285

[10] Lee, G. C., Kitane, Y., & Buckle, I. G. (2001). Literature review of the observed performance of seismically isolated bridges. *Research progress and accomplishments: Multidisciplinary center for earthquake engineering research* (pp. 51–62). University at Buffalo New York. https://nehrpsearch.nist.gov/static/files/NSF/PB2004101677.pdf

[11] Lee, G. C., Kitane, Y., & Buckle, I. G. (2001). Literature review of the observed performance of seismically isolated bridges. *Research progress and accomplishments: 2000–2001* (pp. 51–62). Multidisciplinary Center for Earthquake Engineering Research (MCEER). https://nehrpsearch.nist.gov/static/files/NSF/PB2004101677.pdf

[12] Tsopelas, P., Constantinou, M. C., Okamoto, S., Fujii, S., & Ozaki, D. (1996). Experimental study of bridge seismic sliding isolation systems. *Engineering Structures*, *18*(4), 301–310. https://doi.org/10.1016/0141-0296(95)00147-6

[13] Constantinou, M. C., Kartoum, A., Reinhorn, A. M., & Bradford, P. (1992). Sliding isolation system for bridges: Experimental study. *Earthquake Spectra*, *8*(3), 321–344. https://doi.org/10.1193/1.1585684

[14] Elsheikh, A. H., & Ghobarah, A. (2004). Response of RC structures to near-fault records. *Emirates Journal for Engineering Research*, *9*(2), 45–51. http://www.engg.uaeu.ac.ae/ejer/issues/v9/pdf_iss2_9/p7_Sheikh.pdf

[15] Zengin, E., & Bozorgnia, Y. (2026). Structural implications of near-fault directivity representations for bridges. *Earthquake Spectra*, *42*(4), e70113. https://doi.org/10.1002/esp4.70113

[16] Zhou, L., Zhang, J., Wang, X., Zhang, Y., Jiang, X., Chen, L., & Zheng, C. (2025). An investigation into near-fault ground motion characteristics and their influence on the seismic response of typical girder bridges. *Buildings*, *15*(22), 4067. https://doi.org/10.3390/buildings15224067

[17] Park, Y. J., & Ang, A. H. S. (1985). Mechanistic seismic damage model for reinforced concrete. *Journal of Structural Engineering*, *111*(4), 722–739. https://doi.org/10.1061/(ASCE)0733-9445(1985)111:4(722)

[18] Dicleli, M., & Bruneau, M. (1997). A quantitative approach for rapid seismic vulnerability assessment of steel highway bridges. *Proceedings of the second national seismic conference on bridges and highways* (pp. 15–29). METU. https://trid.trb.org/view/498426

[19] Shinozuka, M., Feng, M. Q., Lee, J., & Naganuma, T. (2000). Statistical analysis of fragility curves. *Journal of Engineering Mechanics*, *126*(12), 1224–1231. https://doi.org/10.1061/(ASCE)0733-9399(2000)126:12(1224)

[20] Filizadeh, R., Hernandez, E., & Rosowsky, D. (2023). Time-dependent damage evolution of reinforced concrete bridge piers: Implications for multihazard analysis. *ASCE-Asme Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *9*(1), 4022066. https://doi.org/10.1061/AJRUA6.RUENG-953

[21] Zhang, Q., Wang, X., & Huang, J. (2024). Seismic vulnerability analysis of concrete-filled steel tube tied arch bridges using symmetrically arranged high-damping rubber bearings. *Symmetry*, *16*(8), 1056. https://doi.org/10.3390/sym16081056

[22] Mehrbod, A., Behnamfar, F., Aziminejad, A., & Hashemol-Hosseini, H. (2025). Fragility curves of stone arch bridges by incremental dynamic analysis method and DEM. *International Journal of Architectural Heritage*, *19*(11), 2805–2824. https://doi.org/10.1080/15583058.2025.2465440

[23] Amani, A. (2007). An examination of the destructive effects of earthquakes on bridges and methods to prevent such damage. *The 2nd national conference on improvement and retrofitting of Iran.* Kerman, Iran. Civilica. (**In Persian**). https://civilica.com/l/3222/

[24] Ancheta, T. D., Darragh, R. B., Stewart, J. P., Seyhan, E., Silva, W. J., Chiou, B. S. J., ..., & Donahue, J. L. (2014). NGA-West2 database. *Earthquake Spectra*, *30*(3), 989–1005. https://doi.org/10.1193/070913EQS197M

[25] Islam, A. B. M. S., Jameel, M., & Jumaat, M. Z. (2011). Seismic isolation in buildings to be a practical reality: behavior of structure and installation technique. *Journal of Engineering and Technology Research*, *3*(4), 99–117. https://doi.org/10.5897/JETR.9000075

[26] Shinozuka, M., Feng, M. Q., Kim, H. K., & Kim, S. H. (2000). Nonlinear static procedure for fragility curve development. *Journal of Engineering Mechanics*, *126*(12), 1287–1295. https://doi.org/10.1061/(ASCE)0733-9399(2000)126:12(1287)