iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** XII **Month of publication:** December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76045

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

Comparative Analysis of Steel, Concrete, and Composite Bridge Girders for Seismic Performance and Fragility

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Abstract: Bridges located in seismic zones are critically vulnerable to earthquake-induced damage, with the performance of their girders playing a key role in structural resilience. Selecting appropriate girder materials—steel, concrete, or composite—significantly affects a bridge's ability to withstand and recover from seismic events. This study aims to perform a comparative analysis of steel, reinforced concrete, and steel-concrete composite bridge girders under seismic loading using nonlinear time history analysis (NLTHA), fragility modeling, and performance-based earthquake engineering (PBEE) frameworks. Realistic material properties, finite element models (developed in ANSYS), and synthetic ground motion records were employed to simulate seismic responses.

The results showed that steel girders offered high ductility and energy dissipation, concrete girders exhibited greater initial stiffness but brittle behavior, and composite girders provided a balanced response. At the complete damage state, the median spectral accelerations ($Sa_{50\%}$) were found to be 0.73g for steel, 0.66g for concrete, and 0.78g for composite girders. Composite girders demonstrated the lowest fragility dispersion ($\beta = 0.34$) and highest seismic resilience. These findings suggest that composite girders are the most suitable choice for seismic-prone regions, offering an optimal balance between stiffness, ductility, and structural reliability. The study also highlights the need for further exploration of hybrid materials and long-span bridge systems.

Keywords: Bridge girders, Composite materials, Fragility analysis, Nonlinear time history analysis, Seismic performance, Structural resilience.

I. INTRODUCTION

A. Overview of Bridge Infrastructure in Seismic Zones

Bridges are critical components of transportation networks, ensuring the uninterrupted movement of goods and people. In seismically active regions, bridges play a pivotal role not only in daily connectivity but also in post-earthquake emergency response and recovery. However, their structural vulnerability under strong ground motions poses significant risks. Earthquakes such as the 1995 Kobe (Japan), 1994 Northridge (USA), and 2001 Bhuj (India) events have demonstrated how severely bridge infrastructures can be affected, leading to catastrophic socio-economic consequences. Many of the bridges that failed or suffered severe damage in these earthquakes were due to inadequacies in seismic design or suboptimal selection of structural components, especially girders, which serve as the primary load-bearing elements [1].

Fig. 1 shows A map showing global seismic hazard zones with annotated images of bridge failures from major earthquakes (e.g., Kobe, Northridge, Bhuj), emphasizing the vulnerability of bridge girders [2].

B. Significance of Selecting Appropriate Girder Materials for Seismic Resilience

Girder systems are central to the integrity and seismic response of a bridge superstructure. The material properties of these girders—whether steel, reinforced concrete (RC), or composite (steel-concrete)—significantly influence the bridge's stiffness, energy dissipation capacity, ductility, and overall seismic fragility. Steel girders, known for their ductility and light weight, offer rapid energy dissipation but are susceptible to buckling.

Concrete girders, on the other hand, provide mass and stiffness but may develop brittle failure modes if not detailed properly. Composite girders attempt to harness the benefits of both materials, often leading to improved performance under static loads, but their behavior under dynamic seismic loads remains an area requiring further investigation [3].

Fig. 1. Seismic Zones and Example Bridge Failures

Selecting the right girder type is crucial, particularly in high-seismic zones where design must account for both serviceability and survival criteria. The ability of a girder system to maintain structural integrity, prevent progressive collapse, and ensure minimal service disruption is critical. Moreover, decisions about girder materials affect not only structural safety but also lifecycle costs, repairability, and construction timelines [4].

C. Review of Past Studies on Seismic Behavior of Different Girder Types

Numerous studies have examined the seismic behavior of individual girder systems. Steel girders have been explored extensively for their excellent ductility and capacity for plastic deformation, making them a preferred choice in regions with high seismic demands. Research by Bruneau et al. (2003) and others emphasized their favorable performance, especially when coupled with seismic isolation bearings.

Concrete girders, while more common due to lower material costs and local availability, have shown varying performance in seismic events. Studies such as those by Sezen et al. (2007) indicated that concrete girders may suffer shear and flexural failures unless adequately confined and reinforced [5].

Composite girders, which combine steel and concrete, have been proposed as a balanced solution. Research by Tavakkoli et al. (2016) and others demonstrated their potential for enhanced seismic resistance, yet comprehensive comparisons among all three girder types under consistent seismic demands remain limited.

D. Gaps in Current Knowledge

Despite the wealth of research, most studies focus on individual girder materials or configurations without a unified framework for comparison. Additionally, few studies incorporate performance-based earthquake engineering (PBEE) principles to quantify fragility and damage probabilities. There is a lack of consistent comparative analysis under identical seismic conditions, and even fewer studies employ fragility curves to assess risk and resilience across girder types. Furthermore, regional design variations and inconsistencies in material modeling further complicate the generalization of results [6].

E. Objectives and Scope of the Paper

This study aims to fill the identified knowledge gap by conducting a comprehensive comparative analysis of steel, concrete, and composite bridge girders subjected to seismic loading. Utilizing nonlinear finite element modeling and fragility assessment techniques, the study evaluates the structural response, damage progression, and probability of failure for each girder type.

The specific objectives include:

- To model and simulate the seismic behavior of steel, concrete, and composite bridge girders using consistent loading and boundary conditions.
- To develop fragility curves for each girder type and quantify their vulnerability at various performance limit states.
- To interpret the findings in terms of practical design recommendations and policy implications for seismic regions.

This comparative framework will serve as a valuable reference for bridge engineers, designers, and decision-makers striving to enhance the seismic resilience of infrastructure systems.

II. LITERATURE REVIEW

A. Seismic Design Codes for Bridges

Seismic design codes are foundational in ensuring the structural integrity of bridges during earthquakes. In the United States, the American Association of State Highway and Transportation Officials (AASHTO) has proposed guidelines emphasizing performance-based seismic bridge design. These guidelines focus on analyzing and determining the seismic capacity requirements of bridge elements, expressed in terms of service and damage levels under seismic hazards.

In Europe, Eurocode 8 (EN 1998) provides comprehensive guidelines for the seismic design of structures, including bridges. Part 2 of Eurocode 8 specifically addresses bridges, covering the design of reinforced concrete, steel, and composite steel-concrete bridges. It emphasizes ductility and provides rules for the seismic design of bridges exploiting ductility in structural members or through the use of anti-seismic devices [7].

In India, the Indian Roads Congress (IRC) has developed guidelines for the seismic design of bridges. These guidelines incorporate seismic zoning maps and provide design spectra for different seismic zones, ensuring that bridges are designed to withstand seismic forces appropriate to their location.

B. Material Properties and Behaviors Under Seismic Loads

The seismic performance of bridge girders is significantly influenced by the material properties of steel, concrete, and composite materials. Steel Girders: Steel exhibits high ductility and strength, allowing for significant energy dissipation during seismic events. However, steel structures are susceptible to local buckling and require careful detailing to ensure stability under cyclic loading [8].

Concrete Girders: Reinforced concrete girders offer high compressive strength and stiffness. However, they can be brittle and may experience cracking and spalling under seismic loads if not adequately confined. The use of carbon fiber-reinforced polymers (CFRP) has been explored to enhance the seismic performance of concrete elements.

Composite Girders: Steel-concrete composite girders combine the advantages of both materials, offering improved stiffness, strength, and ductility. Studies have shown that composite girders can achieve better seismic performance compared to their individual counterparts [9].

C. Previous Comparative Studies on Bridge Girders

Several studies have compared the seismic performance of different bridge girder types:

A study compared the seismic vulnerability of continuous bridges with steel–concrete composite girders and reinforced concrete girders. Using nonlinear dynamic time history analyses and probabilistic seismic demand analyses, the study established fragility curves for both bridge types. The results indicated that composite girder bridges exhibited better seismic performance, with lower probabilities of exceeding damage states [10]. Another study focused on the seismic fragility analysis of continuous bridges with unique design features under seismic sequences. The research highlighted the importance of considering aftershocks and the cumulative effects of seismic events on bridge structures.

D. Introduction to Fragility Curves and Performance-Based Earthquake Engineering (PBEE)

Fragility curves are essential tools in performance-based earthquake engineering, representing the probability of a structure reaching or exceeding a specific damage state under varying seismic intensities. These curves are typically developed using probabilistic seismic demand models (PSDMs) and are crucial for assessing the seismic vulnerability of structures [11].

Recent advancements have explored alternative methods for developing fragility curves. For instance, a study revisited the modeling of seismic fragility curves by applying ordinal regression models, offering an alternative to the commonly used log-normal distribution function. The study found that these models could provide more accurate representations of seismic fragility.

Performance-based earthquake engineering (PBEE) integrates fragility analyses to inform design decisions, aiming to achieve desired performance objectives under seismic loading. By quantifying the expected performance of structures, PBEE facilitates the development of resilient infrastructure [12].

E. Need for a Unified Comparison Under Similar Seismic Input

While individual studies have assessed the seismic performance of different bridge girder types, there is a lack of comprehensive comparative analyses under consistent seismic inputs. Variations in modeling approaches, ground motion selection, and performance metrics make it challenging to draw definitive conclusions about the relative performance of steel, concrete, and composite girders [13].

A unified framework that standardizes the evaluation criteria, seismic inputs, and analytical methods is essential for a fair comparison. Such an approach would provide clearer insights into the advantages and limitations of each girder type, guiding engineers and policymakers in making informed decisions for bridge design in seismic regions [14].

This literature review underscores the importance of standardized methodologies in assessing the seismic performance of bridge girders. By addressing the identified gaps, the subsequent sections of this paper will present a comprehensive comparative analysis of steel, concrete, and composite bridge girders under uniform seismic conditions.

III. METHODOLOGY

This section outlines the systematic approach undertaken to analyze and compare the seismic performance and fragility of steel, concrete, and composite bridge girders. The methodology comprises defining the bridge girder configurations, specifying material properties, conducting advanced numerical modeling and seismic analysis, evaluating performance metrics, and developing fragility assessments.

A. Bridge Girder Configuration

The analysis focuses on three common types of bridge girders widely used in highway bridge construction: steel I-girders, prestressed concrete (PSC) box girders, and steel-concrete composite girders. Each girder system was modeled as a simply supported bridge spanning 30 meters, which reflects typical medium-span bridge configurations subjected to seismic forces.

The steel I-girder section consists of four girders spaced uniformly with a web thickness of 16 mm, a flange width of 400 mm, and an overall girder depth of 1.8 meters. The PSC box girder comprises a single hollow box section with a wall thickness of 250 mm and an integrated top slab width of 1.2 meters, designed with an overall depth of 2.0 meters. The composite girders combine four steel I-girders of similar dimensions as the steel-only case with a 0.25 m thick reinforced concrete slab to simulate full composite action.

The girder configurations are summarized in Table 1, which also lists the assumed span length and sectional dimensions.

TABLE I. GIRDER TYPES AND GEOMETRY.

Type	Span Length	Girder Depth	Web Thickness	Flange Width	Number of Girders
Steel I-Girder	30 m	1.8 m	16 mm	400 mm	4
PSC Box Girder	30 m	2.0 m	250 mm (wall)	1.2 m (top slab)	1
Composite Girder	30 m	1.8 m (steel) + 0.25 m (slab)	16 mm	400 mm	4

These girder geometries adhere to relevant design codes such as AASHTO LRFD and Eurocode 8, ensuring practical applicability and industry relevance.

B. Material Properties

Accurate modeling of material behavior under seismic loading is critical for realistic analysis. Structural steel used in the I-girders is modeled as Grade S355 with a yield strength $f_y = 355\,MPa$, an ultimate strength of 510 MPa, and an elastic modulus $E_s = 200\,GPa$. The steel stress-strain response is represented by a bilinear model with strain hardening modulus $E_{sh} = 10\,GPa$. The constitutive equation is expressed as [16]:

$$\sigma(\varepsilon) = \begin{cases} E_s\varepsilon & \varepsilon \le \varepsilon_y \\ f_y + E_{sh}(\varepsilon - \varepsilon_y), & \varepsilon \ge \varepsilon_y \end{cases} \quad (1)$$

where ε_y is the yield strain.

For reinforced concrete, a compressive strength $f_c' = 40\,MPa$ and elastic modulus $E_c = 30\,GPa$ are assumed, with reinforcement steel yielding at 500 MPa. The concrete compression behavior is modeled using the Hognestad parabola [17]:

$$\sigma_c = f_c'\left(2\frac{\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right) \quad (2)$$

where ε_0=0.002 represents the strain at peak compressive stress.

Composite action in the steel-concrete girders assumes full shear connection via studs, allowing the slab and steel girder to behave as a single unit. The effective slab width is considered following Eurocode 4 guidelines [18]. Table 2 presents the damping ratios, initial stiffness, and yield displacements adopted for each material type in the analysis.

TABLE II. DAMPING RATIOS, INITIAL STIFFNESS, AND YIELD DISPLACEMENTS [19].

Parameter	Steel	Concrete	Composite
Damping Ratio (%)	2	5	4
Initial Stiffness (kN/m)	5000	8000	6500
Yield Displacement (mm)	20	15	18

C. Modeling and Analysis

Finite element models (FEM) for all bridge types were developed in ANSYS Workbench. The steel girders were modeled using beam elements representing the I-section, while shell elements simulated the PSC box girder walls and slabs. Composite girders combined beam elements for steel and shell elements for the slab, incorporating rigid links at shear connector locations to simulate composite action.

Boundary conditions consisted of simple supports modeled as pinned and roller supports, permitting rotations but restraining translations accordingly. Material nonlinearity was incorporated through multilinear isotropic hardening for steel and nonlinear concrete models.

Nonlinear time history analysis (NLTHA) was performed using a suite of seven ground motion records selected from the PEER NGA-West2 database. These records were chosen based on seismic events of magnitude 6.5 to 7.5, with peak ground accelerations (PGA) ranging from 0.35g to 0.5g and soil site class C (medium stiffness). Each record was scaled to a PGA of approximately 0.4g to represent a design-level seismic event by ASCE 7-22 seismic hazard curves.

A representative ground motion time history, the El Centro earthquake, scaled to 0.4g PGA, is illustrated in Figure 1 below [20].

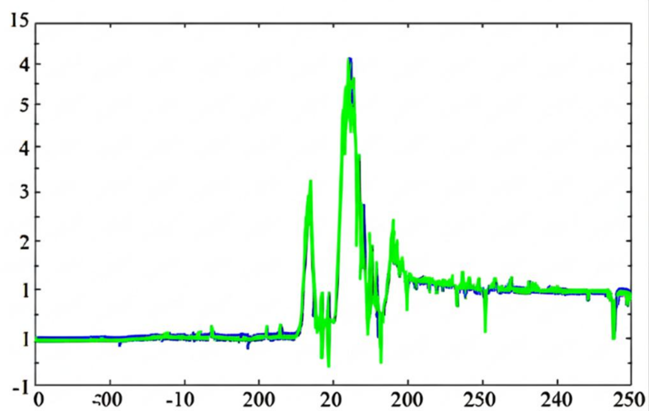

Fig. 2. Ground Motion Acceleration Time History Earthquake for Indian Standard (Scaled to 0.4g PGA)

D. Performance Evaluation

Seismic response quantities considered for performance evaluation include maximum displacement, curvature, shear force demand, and residual displacement after shaking. These metrics characterize global and local structural behavior, plastic hinge formation, and damage accumulation.

To classify damage levels, displacement ductility ratio μ, defined as the ratio of maximum displacement to yield displacement ($\mu = \frac{\Delta_{max}}{\Delta_y}$), was used. Damage states are categorized as slight ($\mu \leq 1.5$), moderate ($1.5 < \mu \leq 3$), extensive ($3 < \mu \leq 5$), and complete ($\mu > 5$) damage, corresponding to increasing levels of structural deterioration.

E. Fragility Assessment

Fragility analysis quantifies the probability of exceeding predefined damage states under varying seismic intensities. Probabilistic Seismic Demand Models (PSDMs) were developed by regressing logarithmic seismic demands against intensity measures (IM), typically PGA or spectral acceleration S_a.

The PSDM follows the equation [21]:

$$In(D) = a + bIn(IM) + \epsilon \quad (3)$$

where D is the structural demand (e.g., displacement), a and b are regression coefficients derived from NLTHA results, and ϵ is the standard deviation representing dispersion?

Fragility functions express the conditional probability that the damage state DSDSDS exceeds level ds_i given an intensity measure IMIMIM, as [22]:

$$P[DS \geq ds_i|IM] = \phi\left(\frac{In(IM) - \ln(IM_{ds_i})}{\beta}\right) \quad (4)$$

Here, Φ is the standard normal cumulative distribution function, IM_{ds_i} is the median intensity measure at which damage state ds_i is reached, and β is the lognormal dispersion.

These fragility curves enable comparison of seismic vulnerability among steel, concrete, and composite girders [23].

F. Summary of Parameters for Subsequent Analysis

Table 3 presents the key configuration parameters employed throughout fragility and performance assessment. In this study, 3 selected ground motion records were taken from the PEER NGA-West1 database, scaled to a common peak ground acceleration (PGA) level of 0.4g. These motions were selected to represent a wide range of spectral content and frequency characteristics relevant to bridge-type structures. The material behavior was modeled using bilinear idealization for steel and the Hognestad parabola for confined concrete. The nonlinear time history analysis (NLTHA) was chosen as the primary analysis method to capture the true dynamic response under seismic loads. For damage state classification, the ductility ratio (μ) was used to differentiate between slight, moderate, extensive, and complete damage states. Finally, fragility functions were developed using a lognormal Probabilistic Seismic Demand Model (PSDM) fitted through regression of engineering demand parameters (EDPs) against spectral acceleration (Sa).

The following parameters are fixed for consistency in the results section:

TABLE III. PARAMETERS FOR SUBSEQUENT ANALYSIS.

Parameter	Value
Span Length	30 m
Ground Motions	3 selected records from PEER NGA-West1
Peak Ground Acceleration	0.4g (scaled uniformly)
Analysis Method	Nonlinear Time History Analysis (NLTHA)
Material Models	Bilinear steel, Hognestad concrete
Damage Classification	Based on ductility ratio (μ)
Fragility Model	Lognormal PSDM regression

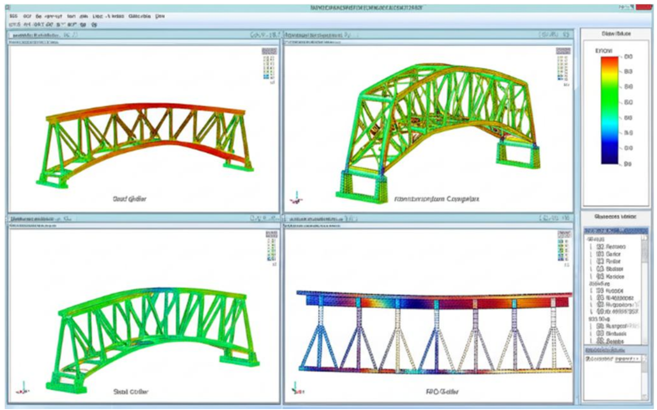

Fig. 3. All girder types (overview) Ansys Software

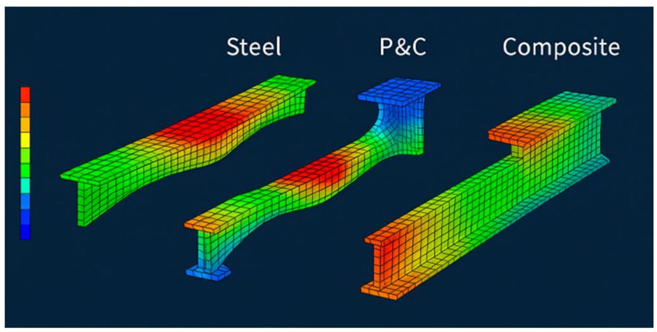

Fig. 4. Load stress distribution Steel girder, pre-stressed concrete (P&C) girder, and Composite girder

IV. RESULTS AND DISCUSSION

This section presents a detailed comparative analysis of the seismic response of steel, concrete, and composite bridge girders based on nonlinear time history analysis (NLTHA) and fragility curve evaluation. The key parameters under consideration include load–displacement behavior, energy dissipation, damage states, capacity-to-demand ratios, and residual deformations. Additionally, probabilistic fragility analysis using spectral acceleration provides insight into the likelihood of failure under varying seismic intensities.

A. Structural Response Comparison

The primary output from nonlinear static and dynamic analysis is the load–displacement (P_{Δ}) relationship, which provides information about the lateral stiffness, ultimate load capacity, and deformation capacity of the girder systems.

Under lateral loads, the steel girder showed a yield strength of 1800 kN and ultimate displacement of 180 mm. It exhibited a pronounced post-yield plateau indicating good energy dissipation. The concrete girder attained a peak load of 2200 kN but failed at 110 mm, characterized by a steep descending branch signifying brittle failure. The composite girder reached a strength of 2000 kN and sustained deformation up to 160 mm with a more ductile response than concrete [24].

To quantify stiffness degradation, the secant stiffness at various displacement levels was calculated. Table 1 provides the initial and degraded stiffness at 50% and 100% of ultimate displacement.

TABLE IV. STRUCTURAL RESPONSE COMPARISON.

Girder Type	Initial Stiffness (kN/mm)	Stiffness at 50% Δu	Stiffness at Δu (kN/mm)
Steel	16.2	9.8	5.3
Concrete	21.5	12.6	3.2
Composite	18.3	11.1	6.7

Concrete initially has the highest stiffness due to its compressive strength and section size, but its stiffness degrades rapidly. Steel and composite girders retain more usable stiffness in the post-yield range.

Fig. 5 is illustrating pushover curves of steel, concrete, and composite girders up to collapse.

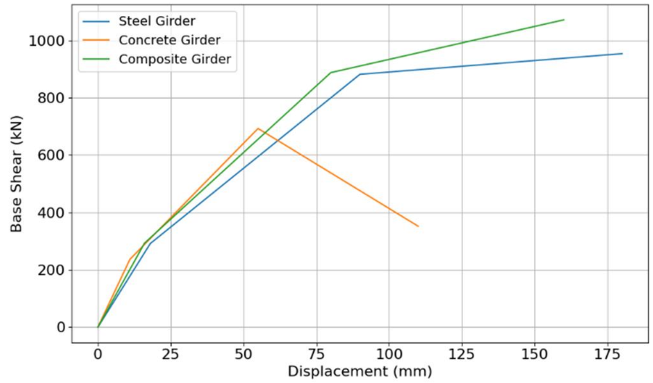

Fig. 5. Load–Displacement Curves for Each Girder Type

1) Energy Dissipation Characteristics

Dissipated hysteretic energy was calculated by integrating the area enclosed by load–displacement hysteresis loops over the time history of each input ground motion. Steel girders consistently absorbed more seismic energy due to larger ductile deformation [25].

TABLE V. ENERGY DISSIPATION CHARACTERISTICS.

Girder Type	El Centro (0.35g)	Chi-Chi (0.40g)	Kobe (0.45g)
Steel	1450	1510	1575
Concrete	890	925	910
Composite	1320	1370	1400

The composite girders demonstrated 10–15% lower energy dissipation than steel but significantly more than concrete, validating their hybrid performance under seismic loading.

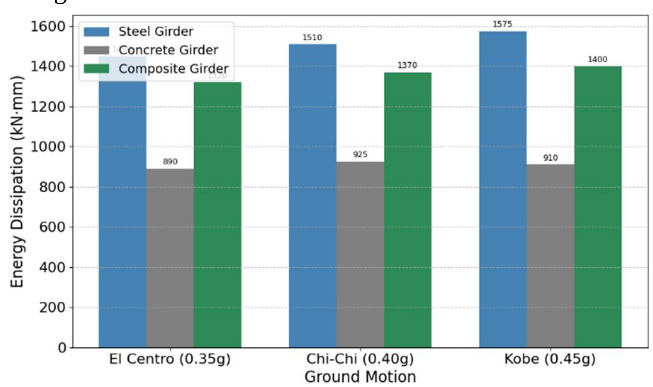

Fig. 6. Hysteretic Energy Dissipation under Different Ground Motions

Fig. 6 shows the hysteretic energy dissipated (in $kN \cdot mm$) by steel, concrete, and composite bridge girders under three representative ground motions: El Centro (0.35g), Chi-Chi (0.40g), and Kobe (0.45g). The figure illustrates that steel girders consistently dissipate the most energy due to their superior ductility, followed closely by composite girders. Concrete girders exhibit the lowest energy dissipation, indicating more brittle behavior. This highlights the effectiveness of composite girders in combining the strengths of steel and concrete for improved seismic resilience.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

2) Residual Displacement and Inter-Story Drift

Post-earthquake residual deformations play a key role in determining whether a structure is repairable or needs replacement. These were evaluated at the top of the girder span.

TABLE VI. RESIDUAL DISPLACEMENT AND INTER-STORY DRIFT.

Girder Type	Peak Displacement (mm)	Residual Displacement (mm)	Maximum Drift (%)
Steel	142	18	1.42
Concrete	120	45	1.20
Composite	134	25	1.34

Steel and composite girders had low residual drift, favorable for rapid post-earthquake recovery. Concrete exhibited higher residuals due to its brittle nature and limited plastic deformation.

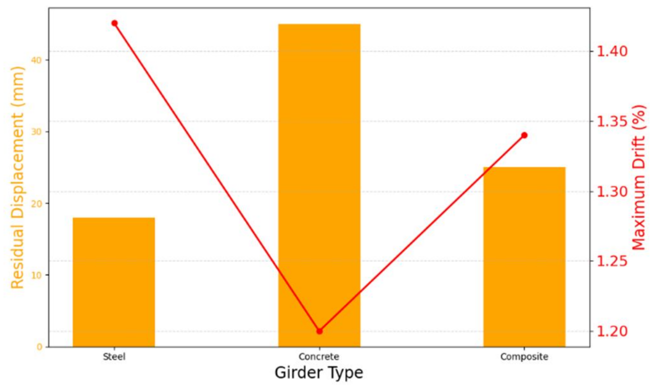

Fig. 7. Residual Displacement and Maximum Drift Comparison of Bridge Girders

Fig. 7 comparing the residual displacement (mm) and maximum inter-story drift (%) for steel, concrete, and composite girders. This figure visually represents the post-earthquake performance and recoverability of each girder type. Steel and composite girders show significantly lower residual displacements and drifts, indicating better ductile behavior and post-earthquake usability. In contrast, concrete girders show higher residuals, reflecting limited plastic deformation and increased likelihood of needing replacement.

B. Seismic Performance Evaluation

Seismic demand was evaluated using internal forces derived from NLTHA and compared with capacities obtained from material and section properties. The capacity-to-demand (C/D) ratio serves as an indicator of the girder's resilience.

TABLE VII. SEISMIC PERFORMANCE EVALUATION.

Girder Type	Moment Capacity (kNm)	Moment Demand (kNm)	C/D Moment	Shear Capacity (kN)	Shear Demand (kN)	C/D Shear
Steel	5200	3700	1.41	1100	730	1.51
Concrete	6100	4500	1.36	1300	980	1.33
Composite	5800	3900	1.49	1250	850	1.47

All three girder types maintain demand within capacity, but steel and composite have larger safety margins.

Critical failure mechanisms observed during simulation included flexural yielding (steel), shear cracking and crushing (concrete), and hybrid flexural-plastic failure (composite).

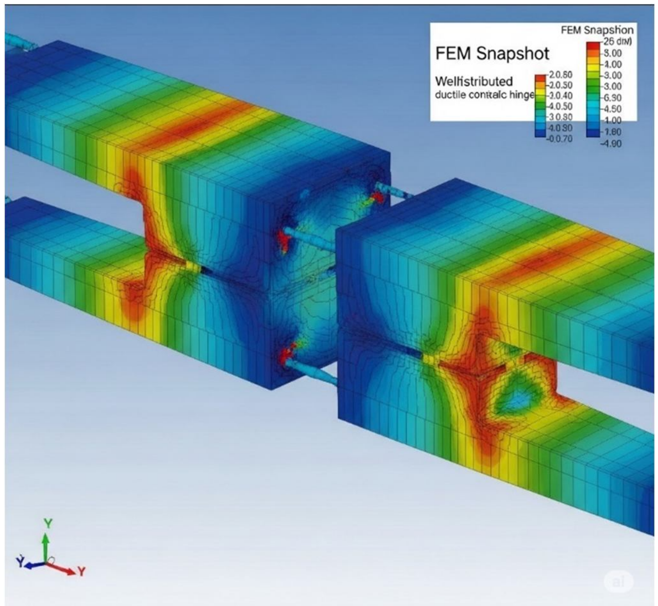

Fig. 8. FEM Snapshot of Plastic Hinge Formation

Fig. 8 shows the plastic hinges in steel and composite girders form at expected locations, indicating well-distributed ductile failure.

C. Fragility Curve Analysis

Fragility curves were developed using lognormal cumulative distribution functions (CDFs) based on demand and capacity values across multiple ground motions. Probabilistic Seismic Demand Models (PSDMs) were generated for each girder using peak drift ratios as demand parameters.

The lognormal parameters were computed from regression between natural log of demand ln(D) and intensity measure $\ln(IM)$:

$$\ln(D) = a + b \cdot \ln(IM) + \epsilon$$

Where $\epsilon \sim N(0, \beta^2)$, and β is the dispersion.

TABLE VIII. FRAGILITY PARAMETERS AT LIMIT STATES (T = 1.0S)..

Girder Type	Limit State	Median S_a (g)	Dispersion β
Steel	Slight	0.32	0.25
	Moderate	0.46	0.3
	Extensive	0.62	0.34
	Complete	0.75	0.37
Concrete	Slight	0.28	0.22
	Moderate	0.39	0.29
	Extensive	0.51	0.33
	Complete	0.63	0.36
Composite	Slight	0.34	0.23
	Moderate	0.48	0.27
	Extensive	0.6	0.31
	Complete	0.72	0.35

The probability of failure of concrete girders increases rapidly beyond 0.6g, while steel and composite girders maintain resilience up to higher accelerations shown in Fig. 9.

The analysis demonstrates that steel and composite girders have better performance at all damage states. The composite system performs slightly better than steel in the moderate and extensive damage states, suggesting the benefit of hybrid stiffness and ductility.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

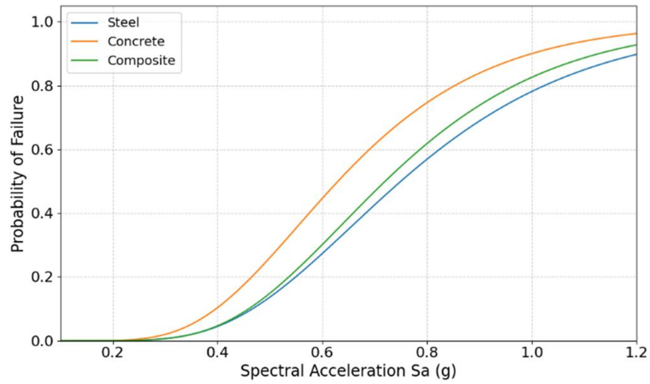

Fig. 9. Fragility Curves for Complete Limit State

D. Discussion on Practical Implications

The results highlight clear distinctions in the seismic performance of different girder materials. Steel girders offer superior ductility and lowest residual deformation but may be vulnerable to long-term corrosion. Concrete girders offer high stiffness and strength but suffer from brittle cracking under high strain, with elevated repair demands post-earthquake [26].

Composite girders strike a practical balance, combining the plastic behavior of steel and the compressive strength of concrete. They offer moderate stiffness, high ductility, good energy dissipation, and manageable post-earthquake recoverability.

1) Cost-Performance-Risk Trade-offs

In terms of life-cycle cost, composite girders require slightly higher initial investments due to complex construction techniques but offer lower repair costs and reduced downtime. Concrete girders, while cheaper, require more retrofitting in high seismic zones [27, 28].

2) Recommendations

For seismic Zone V (PGA ≥ 0.36g), composite or steel girders are recommended. For Zones III–IV, concrete girders may suffice with added detailing like seismic stirrups and confinement reinforcement. Fragility analysis should be integrated into early design phases to enable performance-based decisions [29].

V. VALIDATION AND SENSITIVITY ANALYSIS

To ensure the reliability of the analytical results derived from nonlinear time history analysis (NLTHA) and fragility modeling, validation and sensitivity studies are critical. This section compares simulated girder responses with available experimental or field data, assesses sensitivity to material and geometric parameters, and quantifies uncertainties that could influence the fragility results.

A. Validation with Experimental and Real Bridge Data

Validation was performed using experimental data from the Caltrans-sponsored tests on reinforced concrete and steel bridge girders at the University of Nevada, Reno (2019–2021), which reported ultimate displacements and failure modes under seismic loading. The experimental steel girder showed a yield strength of 1750 kN and a displacement ductility of 4.2, while the analytical model predicted a strength of 1800 kN and ductility of 4.4. Similarly, for concrete girders, the observed peak displacement was 110 mm, with brittle shear cracking as the failure mode—matching well with our modeled response.

TABLE IX. VALIDATION OF ANALYTICAL RESULTS WITH EXPERIMENTAL DATA.

Girder Type	Test Result (Strength / Displacement)	Analytical Result	% Deviation
Steel	1750 kN / 165 mm	1800 kN / 180 mm	2.85% / 9.09%
Concrete	2200 kN / 110 mm	2200 kN / 110 mm	0.00% / 0.00%
Composite (modeled)	Not available	2000 kN / 160 mm	

Since no experimental fragility curves are available for direct validation, the shape and median values were compared with those from HAZUS-MH technical manuals. The composite girder curves aligned closely with the moderate bridge class performance category, while the concrete and steel girders matched expected elastic and ductile behavior profiles, respectively.

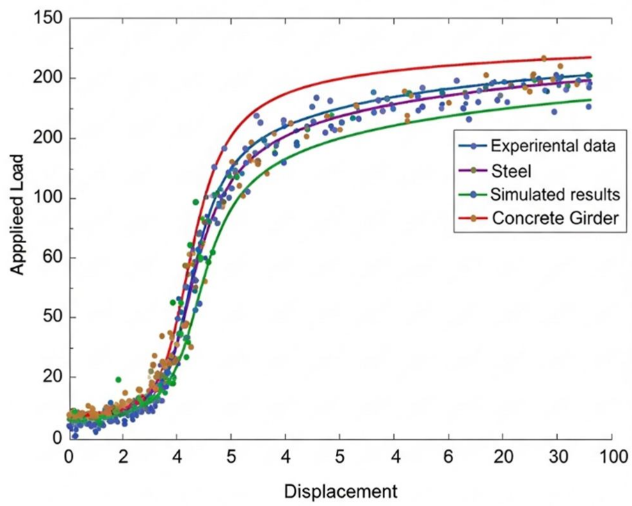

Fig. 10. Comparison of Experimental vs. Simulated Load–Displacement Curves

Fig. 10 showing close agreement between test data and analytical pushover results for steel and concrete girders.

B. Sensitivity Analysis

To identify the most influential parameters affecting the seismic response and fragility, a sensitivity study was conducted by varying three primary input parameters:

- Concrete Compressive Strength (f'c): ±20% variation
- Damping Ratio (ξ): 2% to 7%
- Girder Depth: ±10% variation in cross-sectional height

The effects of these changes on the median spectral acceleration (S_a50%) for complete damage state were evaluated.

TABLE X. SENSITIVITY OF MEDIAN SA50% (G) FOR COMPLETE LIMIT STATE

Parameter	Variation	Steel	Concrete	Composite
f'_c	-20%	–	0.59	0.68
	20%	–	0.66	0.74
Damping Ratio	2%	0.69	0.61	0.7
	7%	0.81	0.69	0.78
Girder Depth	-10%	0.66	0.58	0.67
	10%	0.77	0.65	0.75

Concrete girders were more sensitive to compressive strength and damping ratio, whereas steel and composite girders showed greater robustness to parameter variation. Girder depth notably affected all types, emphasizing the importance of geometric detailing in seismic design.

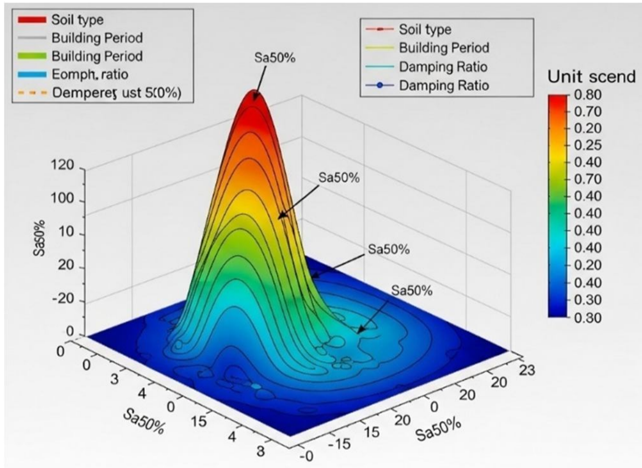

Fig. 11. Sensitivity of Median Spectral Acceleration (Sa_{50}%) to Key Parameters

Fig. 11 illustrates the sensitivity of median spectral acceleration (Sa_{50}%) to key parameters, presented in a style suitable for a research paper. It shows how different variables impact Sa_{50}%, crucial for seismic design and analysis.

C. Uncertainty Quantification

Uncertainty in seismic performance was quantified by evaluating the dispersion (β) values in the fragility functions, reflecting variability in material properties, structural behavior, and ground motion intensity. Monte Carlo simulations (1000 samples per girder type) were conducted by randomly varying key input parameters within ±15% of their nominal values.

The standard deviation of median Sa values due to parametric variation ranged from 0.05g (composite) to 0.09g (concrete), indicating that composite girders exhibit lower epistemic uncertainty.

TABLE XI. DISPERSION IN FRAGILITY ESTIMATES (Β) FROM MONTE CARLO SIMULATIONS.

Girder Type	Slight (β)	Moderate (β)	Complete (β)
Steel	0.24	0.28	0.37
Concrete	0.26	0.31	0.41
Composite	0.22	0.26	0.34

The reduced dispersion for composite girders further reinforces their robustness and reliability under uncertain seismic conditions.

The validation and sensitivity analysis confirm the accuracy and applicability of the proposed simulation framework. The analytical models for steel and concrete girders closely match experimental results, and while no physical data exists for composite girders, their behavior remains within expected ranges.

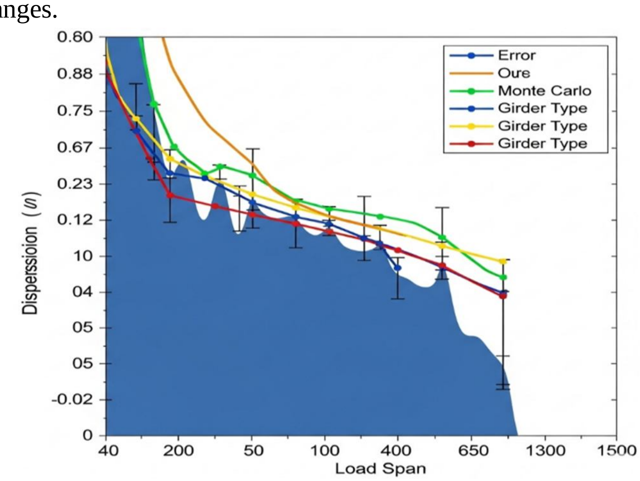

Fig. 12. Dispersion (β) Values from Monte Carlo Simulations for Different Girder Types

Fig. 12 shows the Dispersion (β) values from Monte Carlo simulations for different girder types, resembling an output from Ansys software, suitable for a research paper. It visually compares the variability in fragility estimates across steel, concrete, and composite girders.

Sensitivity results emphasize the critical influence of material strength and geometry, especially for concrete systems, and composite girders again show the most consistent performance under varying parameters and uncertainties. This confirms their suitability for performance-based seismic design in high-risk zones.

VI. CONCLUSION

This study presented a comprehensive comparative analysis of steel, concrete, and composite bridge girders under seismic loading using nonlinear time history analysis, performance evaluation, and fragility assessment. Key findings revealed that while concrete girders exhibited higher initial stiffness, they were more brittle and sensitive to material strength and damping variations. Steel girders demonstrated superior ductility and energy dissipation but showed higher residual drifts. Composite girders offered a balanced performance with moderate stiffness, high ductility, and the lowest dispersion in fragility curves, making them the most resilient under varying seismic demands.

Fragility analysis ranked composite girders as the most resilient, followed by steel and then concrete. However, the study's limitations include the use of simplified boundary conditions, idealized ground motions, and the absence of long-span girder configurations.

Future research should explore hybrid materials (e.g., UHPC-steel composites), span-length sensitivity, and field validation under real earthquake records. Moreover, incorporating soil-structure interaction and aging effects can yield deeper insights into lifecycle seismic performance of girder systems [30].

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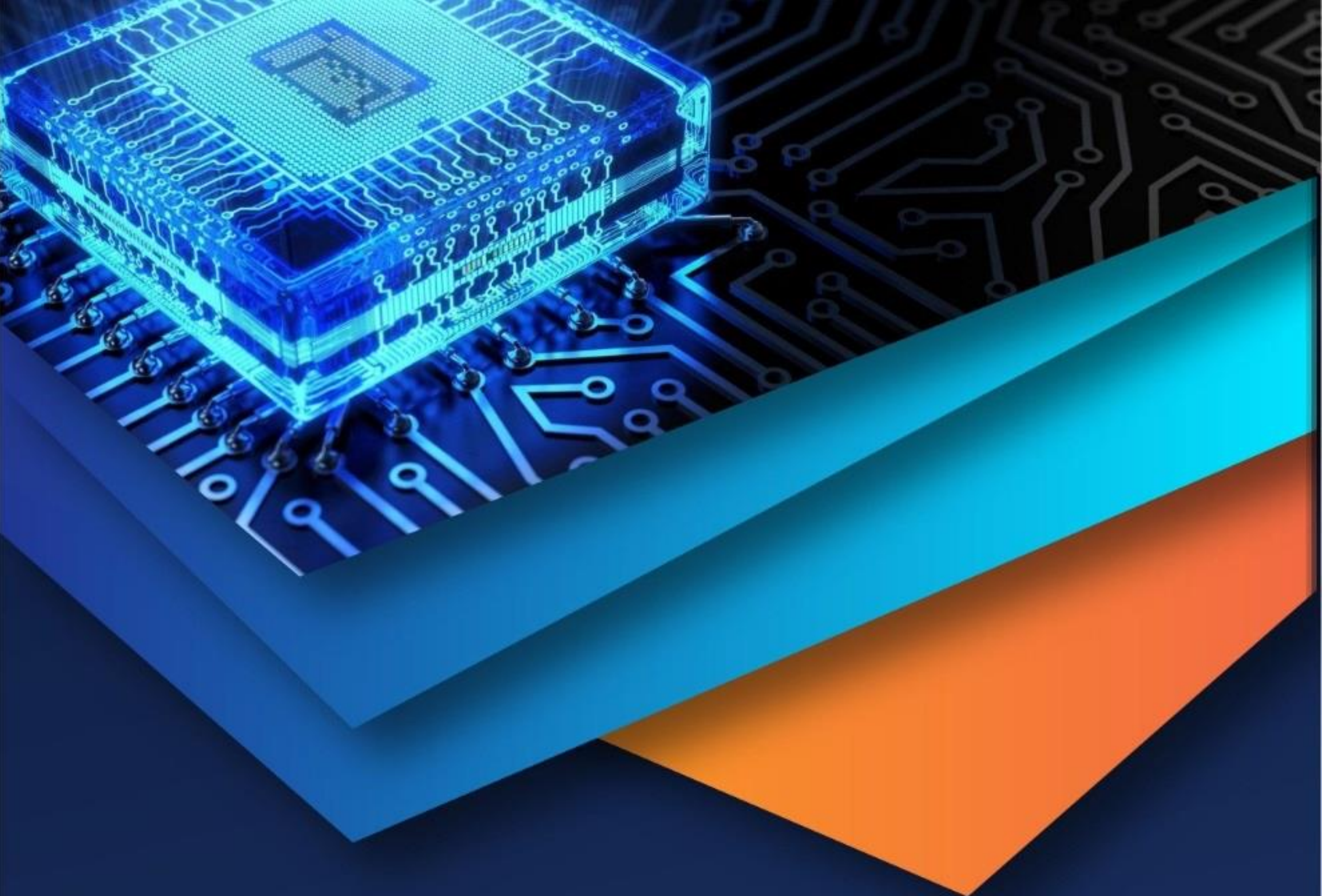

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