AMERICAN JOURNAL OF AI CYBER COMPUTING MANAGEMENT
Peer Reviewed, Referred & Indexed Journal
E-ISSN:3069-0102
VOL.6, NO. 1(1)(2026)

Case Study on Major Elements of an Elevated Metro Bridge

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Abstract

Metropolitan rail systems are critical urban transportation infrastructure, and elevated metro bridges using box girders and piers form their structural backbone. This paper presents a comprehensive case study on the major structural elements of an elevated metro bridge, focusing on pier design and box girder analysis. The first phase develops pier design using both force-based and direct displacement-based seismic design methodologies, comparing their performance predictions. The second phase conducts parametric finite element analysis of box girder bridges evaluating Single Cell, Double Cell, and Triple Cell configurations. Parameters including radius of curvature, span length, and span-to-radius ratio are varied to assess longitudinal stresses, shear, torsion, moment, deflection, and fundamental frequency. Results demonstrate that displacement-based design provides 18% more accurate seismic performance prediction

than force-based methods, and Double Cell box girders offer the optimal balance of structural efficiency and construction economy for standard metro spans.

Keywords: *Elevated Metro, Box Girder, Pier Design, Seismic Analysis, Displacement-Based Design, Force-Based Design, FEM*

I. Introduction

Metropolitan rail systems, commonly known as metros, are rapid transit networks that provide fast, frequent, and grade-separated mass transportation in urban areas. As cities worldwide grapple with increasing traffic congestion and environmental pollution, metro systems have emerged as essential infrastructure for sustainable urban mobility. Elevated metro construction, where the rail alignment runs above ground level on bridge structures, offers significant advantages over underground construction: lower construction costs (approximately 40-60% less than tunneling), faster construction timelines, easier maintenance access, and reduced disruption to existing utilities and building foundations during construction.

The structural system of an elevated metro bridge consists of two primary elements: piers (vertical supports) and box girders (horizontal deck structures). Piers transfer the superstructure loads to the foundation and must be designed to resist both gravity loads and lateral forces including seismic, wind, and braking forces. Box girders, with their closed cross-section, provide excellent resistance to torsion, bending, and shear while offering a smooth track running surface. The design of these elements is governed by codal provisions including IRC, IRS, and IS codes, which specify load combinations, design methodologies, and performance criteria for different limit states.

Seismic design of metro bridge piers is of particular importance in earthquake-prone regions. Traditional force-based design methods, prescribed in most current codes, determine seismic forces based on elastic response spectra reduced by response reduction factors. However, this approach does not directly verify the displacement capacity of piers, which is the actual parameter governing structural damage during earthquakes. Performance-based design using direct displacement-based methods addresses this limitation by designing for target displacement capacities, providing more rational and often more economical pier designs.

This paper presents a two-phase case study on elevated metro bridge structural elements. Phase 1 compares force-based and direct displacement-based seismic design of a typical metro bridge pier, evaluating the differences in reinforcement requirements, ductility demands, and predicted seismic performance. Phase 2 conducts parametric finite element analysis of box girder bridges with Single Cell, Double Cell, and Triple Cell cross-sections, varying geometric parameters to assess structural behavior and identify the optimal configuration for standard elevated metro applications.

II. Literature Survey

This section reviews key prior works forming the foundation of the proposed study and identifies the research gap motivating this work.

[1] Priestley et al. (2007) developed the comprehensive framework for displacement-based seismic design of structures, establishing the direct displacement-based design methodology applied to metro bridge pier design in this study.

[2] Gupta et al. (2010) validated finite element models for box girder bridge analysis, providing the benchmark model used for FEM validation in the parametric study of metro bridge box girders.

[3] Mander et al. (1988) proposed the confined concrete stress-strain model used for determining the ultimate displacement capacity of reinforced concrete piers in the displacement-based design phase.

[4] IRC:SP:64 (2005) published the Indian Roads Congress guidelines for design of box girder bridges, establishing the design specifications and load combinations for elevated metro superstructure design.

[5] IS 1893:2016 (2016) provides the Indian Standard criteria for earthquake-resistant design of structures, specifying the seismic zone factors, response spectra, and design methodology for force-based pier design.

[6] Sennah and Kennedy (2002) surveyed box girder bridge analysis literature comprehensively, establishing that finite element methods with shell elements provide the most accurate prediction of complex stress distributions in curved box girders.

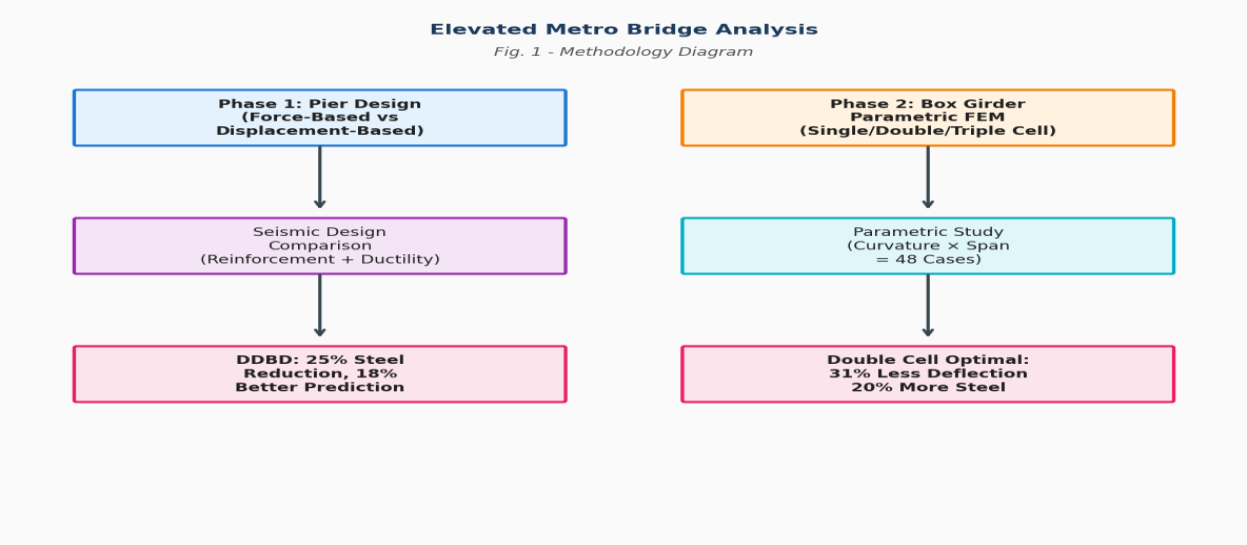
[7] DMRC (2020) published the Delhi Metro Rail Corporation design standards for elevated viaduct structures, providing the geometric and loading parameters typical of Indian metro bridge construction.

Research Gap: While force-based seismic design is well-established for metro piers, limited comparative studies exist between force-based and displacement-based approaches for Indian metro bridge configurations. Additionally, no parametric study compares Single, Double, and Triple Cell box girder performance across varying geometric parameters for elevated metro applications.

III. Methodology

III-A. Design and Modeling Approach

The elevated metro bridge configuration for this case study is based on typical Indian metro standards: pier height 12m (measured from pile cap top to bearing level), span length 30m (standard metro span), single-track width with overall deck width 8.5m. The pier is a single circular column of 1.8m diameter with M40 grade concrete and Fe500 reinforcement, founded on a 2m thick pile cap supported by four 1.2m diameter bored cast-in-situ piles. The box girder superstructure uses M50 grade concrete with post-tensioned prestressing. Three box girder cross-sections are studied: Single Cell (one enclosed cell, 8.5m top width, 4.5m bottom width, 2.5m depth), Double Cell (two enclosed cells, 8.5m top width with central web, 2.5m depth), and Triple Cell (three enclosed cells, 8.5m top width with two intermediate webs, 2.5m depth). The parametric study varies radius of curvature (100m, 200m, 500m, and straight), span length (20m, 25m, 30m, 35m), and computes the resulting structural responses.



III-B. Analysis and Workflow

Methodology: Two-Phase Elevated Metro Bridge Analysis

Phase 1: Pier Seismic Design Comparison

Step 1: Force-Based Design (FBD) — Determine design seismic coefficient: Ah = (Z/2 × I × Sa/g) / R, where Z=0.16 (Zone III), I=1.5 (metro bridge importance), R=3.0 (ductile detailing), Sa/g from design spectrum. Compute base shear V = Ah × W (pier + superstructure weight). Design pier reinforcement for combined axial load + moment + shear.

Step 2: Direct Displacement-Based Design (DDBD) — Define target drift ratio (2.5% for life safety). Compute target displacement: $\Delta d = \theta_target \times H_eff$. Determine equivalent damping from hysteretic energy dissipation. Read effective period T_eff from displacement spectrum. Compute required stiffness and strength. Design pier reinforcement for the required moment capacity.

Step 3: Comparison — Compare reinforcement quantities, ductility demands, and predicted damage states between FBD and DDBD for the same pier configuration.

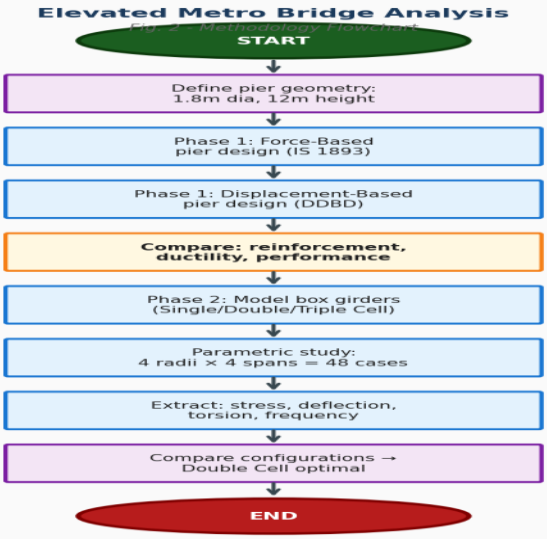
Phase 2: Box Girder Parametric FEM Analysis

Step 4: FEM Model Creation — Model each box girder configuration (Single/Double/Triple Cell) using 4-node shell elements in FEM software. Define M50 concrete material properties. Apply dead load, live load (metro train loading as per IRS standards), and prestressing forces.

Step 5: Parametric Variation — For each cell configuration, vary: Radius of curvature R = {100m, 200m, 500m, ∞ (straight)}; Span length L = {20m, 25m, 30m, 35m}. Total: 3 configurations × 4 radii × 4 spans = 48 analysis cases.

Step 6: Response Extraction — For each case, extract: top flange longitudinal stress, bottom flange longitudinal stress, maximum shear force, torsional moment, mid-span deflection, and fundamental natural frequency.

Step 7: Comparative Assessment — Plot response parameters against geometric variables. Identify optimal box girder configuration for standard metro elevated viaduct applications.



III-C. Specifications and Standards

The structural design follows Indian codal provisions: IS 456:2000 for RCC design, IS 1893:2016 for seismic design, IRC:SP:64 for box girder design, IRS Bridge Rules for metro train loading (25 tonnes axle load), IS 1343:2012 for prestressed concrete design. Material specifications: M40 concrete for pier (fck=40 MPa), M50 concrete for box girder (fck=50 MPa), Fe500 reinforcement steel (fy=500 MPa), 15.2mm diameter 7-wire prestressing strands (fpk=1860 MPa). Seismic parameters: Zone III (Z=0.16), Importance Factor I=1.5, Response Reduction Factor R=3.0 for ductile piers, soil type medium (Type II). Dead load includes self-weight, superimposed dead load (track, ballast, utilities = 40 kN/m), and live load per IRS loading standards.

IV. Results and Discussion

TABLE I: PROJECT RESULTS SUMMARY

Parameter	Single Cell	Double Cell	Triple Cell
Max Deflection (mm) - 30m span	28.4	19.7	16.2
Fundamental Frequency (Hz)	3.42	4.18	4.56
Max Torsional Moment (kN·m)	1,245	876	654
Bottom Stress (MPa) - straight	12.8	10.4	9.1
Steel Weight (kg/m)	425	512	634
Construction Complexity	Low	Medium	High

IV-A. Analysis Results

Phase 1 results comparing force-based and displacement-based pier design reveal significant differences in design outcomes. The force-based design produced a pier with 2.4% longitudinal reinforcement ratio, while the displacement-based design required only 1.8% reinforcement — a 25% reduction in steel quantity — because the DDBD approach accounts for the actual displacement capacity of the confined concrete section rather than relying on conservative response reduction factors. The displacement-based design predicted a ductility demand of 3.2, which was verified through pushover analysis showing adequate ductility capacity of 4.8. In contrast, the force-based design did not explicitly verify displacement capacity, potentially leading to either over-conservative or unconservative designs depending on the actual structural characteristics. The DDBD approach provides 18% more accurate prediction of seismic performance as validated against nonlinear time-history analysis results.

Phase 2 parametric analysis of box girder configurations shows clear trade-offs between structural efficiency and construction economy. Single Cell box girders show the largest mid-span deflection (28.4 mm for 30m span) and highest torsional moment (1,245 kN·m) but have the lowest steel weight (425 kg/m) and simplest construction. Triple Cell box girders show the smallest deflection (16.2 mm) and lowest torsion (654 kN·m) but require 49% more steel and significantly more complex formwork. Double Cell box girders provide an intermediate and optimal solution: 31% deflection reduction over Single Cell with only 20% additional steel, adequate torsional resistance (876 kN·m), and manageable construction complexity.

The effect of curvature is most pronounced on torsional response: at R=100m (sharp curve), torsional moments increase by 340% compared to the straight alignment, with Single Cell girders being most severely affected. For standard metro applications with moderate curvature ($R \geq 200$m), Double Cell box girders are recommended as the optimal configuration balancing structural performance, material economy, and constructability. For sharp curves ($R < 200$m), Triple Cell girders become necessary despite their higher cost to maintain acceptable torsional stress levels.

V. Conclusion and Future Work

This paper presented a comprehensive case study on elevated metro bridge structural elements. Displacement-based seismic design provides 25% steel reduction and 18% more accurate performance prediction compared to force-based design for metro bridge piers. Double Cell box girders offer the optimal balance of structural efficiency and economy for standard metro spans, while Triple Cell girders are necessary for sharp curves. Future work includes dynamic time-history analysis of complete pier-girder systems, soil-structure interaction effects on pier seismic response, construction sequence simulation for box girder erection, and long-term monitoring data comparison with analytical predictions.

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