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# Seismic performance Assessment of prestressed concrete Box girder in elevated Metro Structures - A Review

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**Abstract:** - In recent years, rapid urbanization and increasing transportation demand have led to the development of elevated metro systems across major cities. These systems rely heavily on prestressed concrete (PSC) box girder bridges due to their high strength, durability, and efficiency for long-span structures. However, these bridges are highly vulnerable to seismic forces due to their elevated configuration, slender geometry, and dynamic loading conditions. This review paper presents a comprehensive analysis of previous research studies related to seismic performance of PSC box girder bridges, elevated metro structures, and advanced analysis techniques. The study covers various aspects such as structural behavior, dynamic response, prestressing techniques, material performance, and design methodologies including force-based design (FBD) and displacement-based design (DDBD). The literature indicates that trapezoidal and multi-cell box girder configurations provide better structural performance compared to conventional rectangular sections due to improved load distribution and torsional rigidity. Advanced analysis methods such as nonlinear time history analysis and pushover analysis provide more realistic results compared to conventional response spectrum methods. The review also highlights the importance of considering factors such as soil-structure interaction, corrosion effects, residual prestress loss, and train-bridge interaction for accurate evaluation of structural behavior.

**Keywords:** - Prestressed Concrete, Box Girder Bridge, Seismic Analysis, Elevated Metro, Response Spectrum, FEM, SAP2000.

## I. INTRODUCTION

The development of modern transportation infrastructure has become extremely important in recent years due to rapid population growth, urban expansion, and increasing demand for efficient mobility systems. Metropolitan cities are facing serious challenges such as traffic congestion, longer travel time, air pollution, and pressure on existing road networks. Conventional transportation systems are no longer sufficient to handle the growing number of vehicles and passengers. Therefore, there is a strong need for advanced, reliable, and high-capacity public transportation systems that can efficiently cater to the needs of urban populations. In this context, metro rail systems have emerged as one of the most effective solutions for urban transportation, offering fast, safe, economical, and environmentally friendly travel.

Among different types of metro systems, elevated metro bridge systems are widely adopted in urban areas due to their practical advantages. These systems are constructed above ground level, which eliminates the need for extensive land acquisition and reduces interference with existing traffic. Compared to underground metro systems, elevated structures are relatively easier and faster to construct, and they involve lower construction costs and fewer technical difficulties. As a result, many metro rail projects in India and across the world are based on elevated viaduct systems.

An elevated metro bridge is essentially a continuous structural system consisting of piers, pier caps, bearings, and superstructure elements. The most critical component of the superstructure is the prestressed concrete (PSC) box girder, which carries the metro track and transfers loads to the supporting piers. PSC box girders are widely preferred in bridge construction due to their excellent structural properties, such as high strength, reduced self-weight, improved load distribution, high torsional rigidity, and durability. The hollow box section allows efficient use of material while maintaining high stiffness, making it suitable for long-span bridges and curved alignments commonly found in metro systems.

Prestressing is a technique in which internal compressive stresses are introduced into the concrete using high-strength steel tendons. This helps in counteracting tensile stresses caused by external loads, thereby reducing cracking and improving the load-carrying capacity of the structure. As a result, PSC box girders provide better performance compared to conventional reinforced concrete structures, especially under heavy loads and dynamic conditions.

However, despite these advantages, elevated metro bridge systems are subjected to complex loading conditions throughout their service life. These include dead load (self-weight of the structure), live load (moving train loads), wind load, temperature effects, creep and shrinkage, and most importantly, seismic loads. Among these, seismic loading is one of the most critical factors, particularly in earthquake-prone regions. During an earthquake, the ground motion induces dynamic forces in the structure, leading to vibrations, displacement, and internal stresses. If not properly designed, these forces can cause severe damage to structural components such as piers, bearings, and girders, and may even lead to collapse of the structure.

Elevated metro bridges are especially vulnerable to seismic effects due to their height, slenderness, and flexibility. The dynamic interaction between the superstructure and substructure plays a crucial role in determining the overall seismic response of the system. The natural frequency and time period of the structure are important parameters that influence how the bridge responds to earthquake excitation. If the frequency of the structure matches with the frequency of ground motion or moving loads, resonance may occur, leading to excessive vibrations and potential structural failure.

In addition to structural safety, serviceability requirements such as deflection limits, vibration control, and passenger comfort are also very important in metro bridge design. Excessive deflection or vibration can affect the smooth operation of trains and reduce passenger comfort. Therefore, it is necessary to carefully analyze and design the structure to ensure that all performance criteria are satisfied.

With advancements in computational tools and software such as SAP2000, ETABS, and STAAD Pro, engineers can now perform detailed analysis of bridge structures using the Finite Element Method (FEM). These tools allow accurate modeling of complex geometries and loading conditions, and help in evaluating important parameters such as bending moment, shear force, stress distribution, displacement, natural frequency, and time period. Among different analysis methods, response spectrum analysis is commonly used for seismic evaluation, while advanced methods like nonlinear time history analysis provide more realistic results.

Another important aspect in modern bridge engineering is the selection of appropriate girder configuration. Different types of box girders, such as rectangular and trapezoidal sections, exhibit different structural behavior. The trapezoidal section, due to its inclined webs and optimized geometry, often provides better load distribution, reduced self-weight, and improved seismic performance compared to rectangular sections. Therefore, comparative studies are necessary to identify the most efficient girder configuration for elevated metro bridges.

Furthermore, elevated metro bridges are subjected to continuous dynamic loading due to moving trains, which creates additional challenges such as fatigue, vibration, and long-term deformation. Factors like creep, shrinkage, and prestress loss also affect the performance of PSC structures over time. Environmental effects such as corrosion and temperature variations further influence the durability and safety of the structure.

Considering all these aspects, it becomes essential to carry out a detailed study on the seismic performance of prestressed concrete box girder bridges used in elevated metro systems. Such studies help in understanding the behavior of the structure under different loading conditions, identifying critical parameters, and improving design practices. Proper seismic analysis ensures that the bridge structure can withstand earthquake forces, minimize damage, and continue to function safely after seismic events.

## II. LITERATURE REVIEW

A large number of researchers have studied the seismic performance of prestressed concrete box girder bridges, focusing on different parameters such as structural behavior, dynamic response, material performance, and design methods.

The study by Bozza et al. (2026) focused on seismic evaluation of curved prestressed box girder bridges using nonlinear time history analysis. It was observed that components like bearings and joints are highly vulnerable under seismic loading and require proper retrofitting measures.

Sridhar et al. (2026) conducted a detailed study on elevated metro bridge components and compared FBD and DDBD methods. It was found that displacement-based design provides nearly 18% more accurate results compared to conventional force-based methods.

Gyawali et al. (2025) emphasized the importance of nonlinear time history analysis for accurate prediction of displacement in box girder bridges. Their study highlighted that simplified models often underestimate seismic demand.

Misar et al. (2024) analyzed PSC box girder bridges and concluded that trapezoidal girders perform better than rectangular girders in terms of deflection, stress distribution, and overall stability.

Hangad et al. (2024) studied post-tensioning techniques and found that double-stage post-tensioning improves structural performance for longer spans.

Agredo Chávez et al. (2024) focused on residual prestress in existing bridges and highlighted that actual prestress values may differ from theoretical predictions due to environmental effects and aging.

Xu et al. (2023) studied the effect of corrosion on prestressed concrete beams and concluded that corrosion significantly reduces seismic performance and energy dissipation capacity.

Singh and Maru (2023) compared PSC box girder and I-girder bridges and concluded that box girders provide better torsional rigidity and seismic resistance.

Wei et al. (2022) conducted experimental studies on prefabricated subway structures and found that such systems show good ductility and energy dissipation under seismic loading.

Tanmane et al. (2022) compared FBD and DDBD methods and concluded that displacement-based design is more reliable for seismic performance evaluation.

Sawant et al. (2022) highlighted the importance of precast construction techniques for faster and more efficient metro bridge construction.

Rhee (2012) conducted experimental analysis on box girders and confirmed their superior dynamic performance and structural efficiency.

Abdel-Mohti and Pekcan (2013) studied skew bridges and found that skew angle significantly affects seismic response due to torsional effects.

### III. RESEARCH GAP

From the detailed review of all the above literature related to elevated metro bridges, prestressed concrete box girder bridges, seismic analysis, dynamic behavior, and advanced construction techniques, it is clearly observed that although a significant amount of research work has been carried out in this field, still many important aspects remain unexplored or partially addressed. Most of the studies have focused on individual components of the bridge system such as pier, girder, or deck separately, but very limited research has been conducted on the combined behavior of the entire metro bridge system, where interaction between pier, girder, bearings, joints, and foundation plays a crucial role during seismic loading. In practical conditions, especially in elevated metro structures, all these components act together under dynamic loads, and neglecting their interaction may lead to inaccurate prediction of structural performance. Another major gap identified is that most of the research is based on analytical modeling and simulation using software tools like ETABS, STAAD Pro, SAP2000, and ABAQUS, while there is a lack of sufficient field validation and real-time experimental data, which creates a difference between theoretical results and actual structural behavior under earthquake conditions. Furthermore, many international studies are based on foreign standards such as AASHTO and Eurocode, and do not fully consider Indian site conditions, IRC codes, climatic variations, soil conditions, and urban construction challenges, which are very important for metro projects in India. In addition to this, although some researchers have compared Force-Based Design (FBD) and Displacement-Based Design (DDBD) methods, the comparison is not comprehensive as it does not include variations in seismic zones, soil conditions, and structural configurations. Similarly, studies on box girder bridges have analyzed different configurations such as single cell, double cell, and triple cell sections, but there is a lack of detailed research that combines structural performance, cost analysis, construction feasibility, and optimization together, which is essential for practical project implementation. Another important gap is that most of the studies consider only one type of loading condition such as seismic load or dynamic load, whereas in real-life conditions bridges are subjected to combined effects of seismic forces, wind loads, moving loads, creep, shrinkage, and temperature variations simultaneously, and this multi-hazard effect is not adequately studied. Moreover, limited attention has been given to aging and existing bridge structures, where issues such as residual prestress loss, corrosion, material degradation, and retrofitting requirements are very important for long-term performance and safety. Further, although advanced materials like Ultra High-Performance Concrete (UHPC), Fibre Reinforced Polymer (FRP), and Self-Compacting Concrete (SCC) have been discussed in some studies, their practical implementation, cost effectiveness, and long-term performance in metro bridge construction are not fully evaluated. In terms of analysis techniques, most studies rely on linear methods such as response spectrum analysis, while advanced methods like nonlinear time history analysis and pushover analysis, which provide more realistic results for seismic performance, are not widely used. Another critical gap is related to skew and curved bridges, where individual effects have been studied, but their combined influence along with seismic loading has not been fully explored, even though such conditions are very common in urban metro alignments. Additionally, the effect of train-bridge interaction, especially for metro systems with high frequency loading and strict serviceability requirements, has not been studied in sufficient detail, particularly in relation to passenger comfort and operational safety.

Moreover, most of the existing studies focus mainly on structural safety and strength parameters, while economic factors such as cost optimization, construction time, and resource efficiency are not considered together, which is essential for large-scale infrastructure projects. There is also a lack of a comprehensive design framework or guidelines that integrates all important parameters such as structural configuration, material selection, seismic performance, and construction methodology specifically for elevated metro bridges. Therefore, it can be concluded that there exists a significant research gap in developing an integrated approach that combines system-level analysis, advanced seismic evaluation methods, multi-parameter optimization, Indian standard considerations, and practical construction aspects. The present study aims to address these gaps by providing a detailed and comprehensive analysis of elevated metro bridge systems, considering both structural performance and practical implementation aspects, which will contribute towards safer, more efficient, and economical metro bridge design.

## CONCLUSION

From the overall review, it can be concluded that prestressed concrete box girder bridges are highly efficient and suitable for elevated metro structures. They provide better load distribution, high torsional rigidity, and improved seismic performance. Trapezoidal box girders are found to be more efficient compared to rectangular girders. Advanced analysis methods and proper design approaches are essential for ensuring structural safety. Future research should focus on system-level analysis, multi-hazard loading, and use of advanced materials for improving performance.

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