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Study & Analysis on Major Elements of an Elevated Metro Bridge

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ABSTRACT: A metro system is a railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. Metro System is used in cities, agglomerations, and metropolitan areas to transport large numbers of people. An elevated metro system is more preferred type of metro system due to ease of construction and also it makes urban areas more accessible without any construction difficulty. An elevated metro system has two major elements pier and box girder. The present study focuses on two major elements, pier and box girder, of an elevated metro structural system.

Conventionally the pier of a metro bridge is designed using a force based approach. During a seismic loading, the behaviour of a single pier elevated bridge relies mostly on the ductility and the displacement capacity. It is important to check the ductility of such single piers. Force based methods do not explicitly check the displacement capacity during the design. The codes are now moving towards a performance-based (displacement-based) design approach, which consider the design as per the target performances at the design stage. Performance of a pier designed by a Direct Displacement Based Design is compared with that of a force-based designed one. The design of the pier is done by both force based seismic design method and direct displacement based seismic design method.

KEYWORDS: Elevated Metro Structure, Bridge Pier, Box Girder Bridge, Direct Displacement Based Seismic Design, Performance Based Design, Force Based Design

I. INTRODUCTION

1.1 OVERVIEW

A metro system is an electric passenger railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. Metro System is used in cities, agglomerations, and metropolitan areas to transport large numbers of people at high frequency. The grade separation allows the metro to move freely, with fewer interruptions and at higher overall speeds. Metro systems are typically located in underground tunnels, elevated viaducts above street level or grade separated at ground level. An elevated metro structural system is more preferred one due to ease of construction and also it makes urban areas more accessible without any construction difficulty. An elevated metro structural system has the advantage that it is more economic than an underground metro system and the construction time is much shorter.

An elevated metro system has two major components pier and box girder. Viaduct or box girder of a metro bridge requires pier to support the each span of the bridge and station structures. Piers are constructed in various cross sectional shapes like cylindrical, elliptical, square, rectangular and other forms. The piers considered for the present study are in rectangular cross section and it is located under station structure.

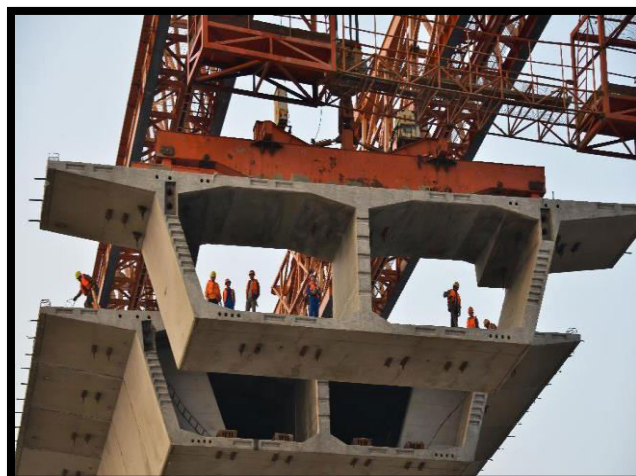
Box girders are used extensively in the construction of an elevated metro rail bridge and the use of horizontally curved in plan box girder bridges in modern metro rail systems is quite suitable in resisting torsional and warping effects induced by curvatures. The torsional and warping rigidity of box girder is due to the closed section of box girder. The box section also possesses high bending stiffness and there is an efficient use of the complete cross section. Box girder cross sections may take the form of single cell, multi spine or multi cell.



(Fig.1.1 : A typical elevated metro bridge model)



(Fig.1.2 : Typical Pier)



(Fig.1.3 : Box Girders)



(Fig.1.4 : Construction of the girders using a launching truss)



(Fig.1.5 : External prestressing tendons in the box girders)



(Fig.1.6 : Post-tensioning of a bundle with strands)

II. LITERATURE REVIEW

In the past three decades, the finite element method of analysis has rapidly become popular and effective technique for the analysis of box girder bridges. So many researchers conducted studies on Box girder bridges by using finite element method. Khaled et al. (2001, 2002) have conducted detailed literature review on analysis of box girder bridges. Based on Khaled et al.(2001, 2002), the following literature review has been done and presented. Malcolm and Redwood (1970) and Moffatt and Dowling (1975) studied the shear lag phenomena in steel boxgirder bridges. Sisodiya et al. (1970) approximated the curvilinear boundaries of finite elements used to model the curved box-girder bridges by a series of straight boundaries using parallelogram elements. This approximation would require a large number of elements to achieve a satisfactory solution. Such an approach is impractical, especially for highly curved box bridges. Komatsu and Nakai (1966,1970) presented several studies on the free vibration and forced vibration of horizontally curved single, and twin boxgirder bridges using the fundamental equation of motion along with Vlasov's thin-walled beam theory. Field tests on bridges excited either by a shaker or by a truck travelling at various speeds showed reasonable agreement between the theory and experimental results. Chu and Pinjarkar (1971) proposed a finite element formulation of curved box-girder bridges, consisting of horizontal sector plates and vertical cylindrical shell elements. The method can be applied only to simply supported bridges without intermediate diaphragms. Chapman et al. (1971) carried out a finite element analysis on steel and concrete box-girder bridges to study the effect of intermediate diaphragms on the warping and distortional stresses. Lim et al. (1971) proposed an element that has a beam-like-in-plane displacement field. The element is trapezoidal in shape, and hence, can be used to analyse right, skew, or curved box-girder bridges with constant depth and width. William and Scordelis (1972) presented an elastic analysis of cellular structures of constant depth with arbitrary geometry in the plane using quadrilateral elements. Cheung and Cheung (1972) described the application of the finite-strip method for the determination of the natural frequencies and mode shapes of vibration of straight and curved beam-slab or boxgirder bridges. Tabba (1972) utilized the thin-walled beam theory to estimate the natural modes and frequencies of a curved simply supported girder of asymmetric multi cell section. Results from testing two curved cellular plexiglass models were used to verify the proposed method. Fam (1973) studied the behaviour of curved box-girder bridges using the finiteelement method for applied dynamic loads. Results from testing a single-cell plexiglass model having high curvature were used to verify the proposed method. Armstrong and Landon (1973) and Greig and Armstrong (1973) reported the results of a field study of a curved twin-spine composite box-girder bridge in Springfield, Mass.

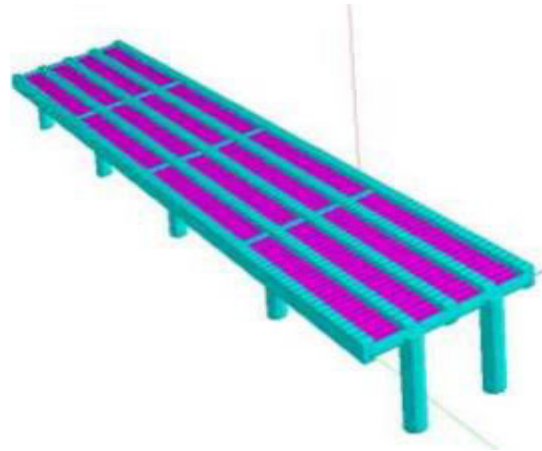
III.PERFORMANCE STUDY OF A PIER DESIGNED BY FBD AND DDBD

3.1 OVERVIEW

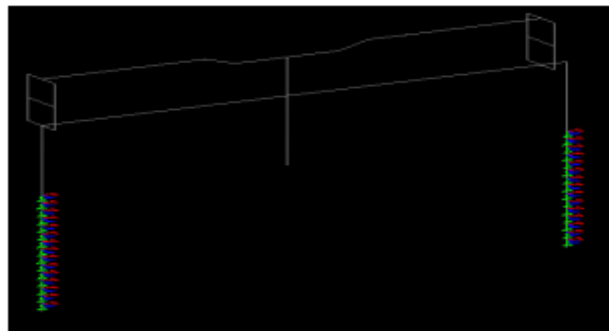
Performance study of the typical pier designed by a Force Based Design (FBD) Method and Direct Displacement Based Design (DDBD) Method is described in this chapter. The pier is designed based on FBD and DDBD Method. Performance assessment is carried out for the designed pier and the results are discussed briefly.

3.2 DESIGN OF PIER USING FORCE BASED DESIGN

The geometry of pier considered for the present study is based on the design basis report of the Bangalore Metro Rail Corporation (BMRC) Limited. The piers considered for the analysis are located in the elevated metro station structure. The effective height of the considered piers is 13.8 m. The piers are located in Seismic Zone II, as per IS 1893 (Part 1): 2002. The modelling and seismic analysis is carried out using the finite element software STAAD Pro. The typical pier models considered for the present study are shown in figure 3.1.



(3D Rendering View)



(Figure 3.1: Typical Pier Model)

3.2.1 Material Property

The material property considered for the present pier analysis for concrete and reinforcement steel are given in Table 3.1.

Table 3.1: Material Property for Pier

Properties of Concrete	
Compressive Strength of Concrete	60 N/mm ²
Density of Reinforced Concrete	24 kN/m ³
Elastic Modulus of Concrete	36000 N/mm ²
Poisson's Ratio	0.15
Thermal Expansion Coefficient	1.17 x 10 ⁻⁵ /°C
Properties of Reinforcing Steel	
Yield Strength of Steel	500 N/mm ²
Young's Modulus of Steel	205,000 N/mm ²
Density of Steel	78.5 kN/m ³
Poisson's Ratio	0.30
Thermal Expansion Coefficient	1.2 x 10 ⁻⁵ /°C

3.2.2 Design Load

The elementary design load considered for the analysis are Dead Loads (DL), Super Imposed Loads (SIDL), Imposed Loads (LL), Earthquake Loads (EQ), Wind Loads (WL), Derailment Load (DRL), Construction & Erection Loads (EL), Temperature Loads (OT) and Surcharge Loads (Traffic, building etc.) (SR). The approximate loads considered for the analysis are shown in Table 3.2. The total seismic weight of the pier is 17862 kN.

Table 3.2: Approximate design Load

Load from Platform Level	Load	Load from Track Level	Load
Self Weight	120 kN	Self Weight	160 kN
Slab Weight	85 kN	Slab Weight	100 kN
Roof Weight	125 kN	Total DL	260 kN
Total DL	330 kN	SIDL	110 kN
SIDL	155 kN	Train Load	190 kN
Crowd Load	80 kN	Braking + Tractive Load	29 kN
LL on Roof	160 kN	Long Welded Rail Forces	58 kN
Total LL	240 kN	Bearing Load	20 kN
Roof Wind Load	85 kN	Temperature Load	
Lateral	245 kN	For Track Girder	20 kN
Bearing Load	14 kN	For Platform Girder	14 kN
		Derailment Load	80 kN/m

The force based design is carried out for Pier as per IS 1893:2002 and IRS CBC 1997 Code and the results are shown in Table 3.3. From the FBD, it is found out that the minimum required cross section of the pier is only 1.5 m x 0.7 m for 2 % reinforcement. The base shear of the pier is 891 kN.

Table 3.3: Reinforcement Details as per Force Based Design

Pier Type	Cross Section (m)	Diameter of Bar (mm)	Number of Bars	% of Reinforcement	
				Required	Provided by BMRC
Pier Type A	2.4 x 1.6	32	#32	0.8 %	1.48 %
Pier Type B	2.4 x 1.6	32	#38	0.8 %	1.48 %

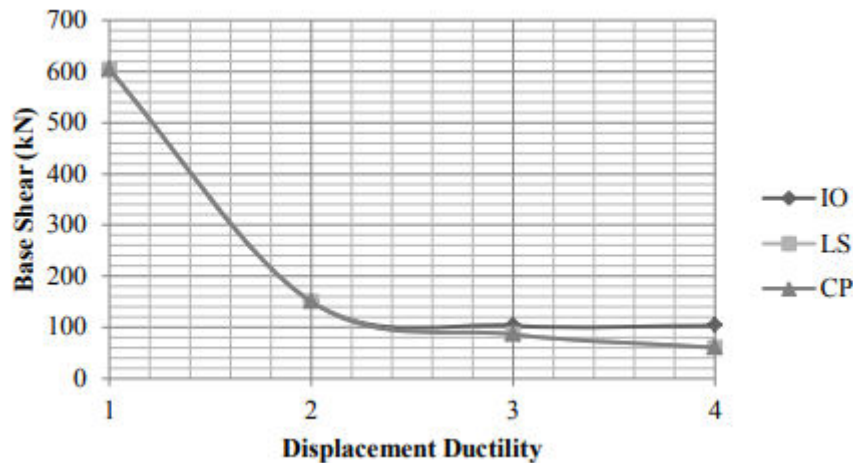
3.3 DESIGN OF PIER USING DIRECT DISPLACEMENT BASED DESIGN

The direct displacement based seismic design method proposed by Priestley et al. (2007) and IRS CBC 1997 Code is used to design of Pier Type B and the results are shown in Table 3.4. The performance level considered for the study is a Life Safety (LS) level.

Table 3.4 Reinforcement Details as per Direct Displacement Based Seismic Design

Displacement Ductility	Drift Limit (m)	Cross Section (m)	Base Shear V_b (kN)	Diameter of Bar (mm)	Number of Bars	% of Reinforcement Required
1	0.276	1.5 x 0.7	604	32	#16	1.2 %
2	0.276	1.5 x 0.7	150	32	#12	0.8 %
3	0.276	1.5 x 0.7	86	32	#12	0.8 %
4	0.276	1.5 x 0.7	60	32	#12	0.8 %

The parametric study is carried to know the effect of displacement ductility on base shear for different Performance levels and the results are shown in Figure 3.2. The figure shows that as the displacement ductility level increases the base shear of the pier decreases and also the difference between different performance levels is about 40 %.



(Figure 3.2: Effect of displacement ductility on base shear for different Performance levels)

3.4 PERFORMANCE ASSESSMENT

The performance assessment is done to study the performance of designed pier by Force Based Design Method and Direct Displacement Based Design Method. For this purpose, Non-linear static analysis is conducted for the designed pier using SeismoStruct Software and the results are shown in Table 3.5. The section considered is 1.5 m x 0.7 m. Performance parameters behaviour factor (R'), structure ductility (μ') and maximum structural drift (Δ'_{max}) are found for both the cases. The behaviour factor (R') is the ratio of the strength required to maintain the structure elastic to the inelastic design strength of the structure. The behaviour factor, R' , therefore accounts for the inherent ductility, over the strength of a structure and difference in the level of stresses considered in its design. FEMA 273 (1997), IBC (2003) suggests the R factor in force-based seismic design procedures. It is generally expressed in the following form taking into account the above three components,

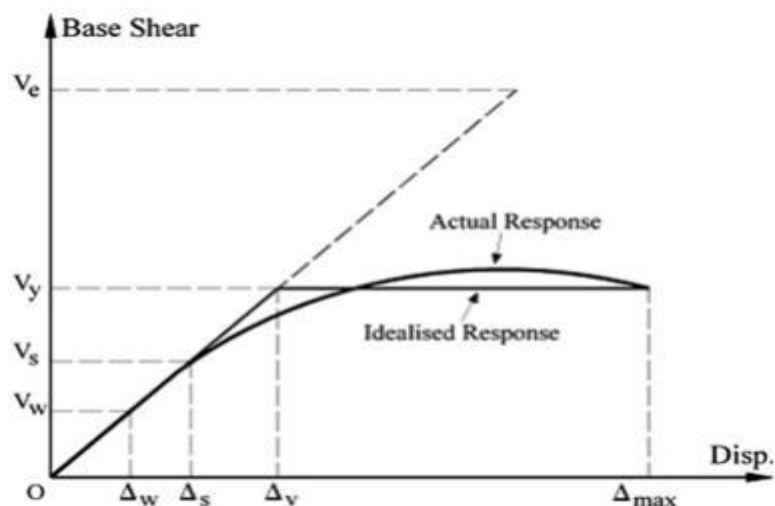
$$R' = R_{\mu} \cdot R_s \cdot Y$$

$$R_{\mu} = V_e/V_y, R_s = V_y/V_s, Y = V_s/V_w$$

where, R_{μ} is the ductility dependent component also known as the ductility reduction factor, R_s is the over-strength factor and Y is termed the allowable stress factor. With reference to Figure 3.3, in which the actual force–displacement response curve is idealised by a bilinear elastic–perfectly plastic response curve, the behaviour factor parameters may be defined as

$$R' (R_w) = (V_e/V_y)(V_y/V_s)(V_s/V_w) = V_e/V_w$$

where, V_e , V_y , V_s and V_w correspond to the structure's elastic response strength, the idealised yield strength, the first significant yield strength and the allowable stress design strength, respectively as shown in the Figure 3.3



(Figure 3.3: Typical Pushover response curve for evaluation of performance parameters)

The structure ductility, μ' , is defined in as maximum structural drift (Δ'_{max}) and the displacement corresponding to the idealised yield strength (Δ_y) as:

$$\Delta'_{max} / \Delta_y = \mu$$

In Force Based Design, a force reduction factor (R) of 2.5 is used, and the design base shear is estimated to be 891kN in the FBD. The performance parameters of the section designed using FBD shows that the behaviour factor R is found to be about 2.74. The same pier is designed using a DDBD method for target displacement ductility and drift, the performance parameters structural ductility and structural drift are found out for these cases. It shows that the achieved performance parameters are higher than assumed in the design stage in both cases of DDBD. Though the FBD may not always guarantee the performance parameter required, in the present case the pier achieves the target requirement. In the case of DDBD, the design considers the target displacement ductility and drift at the design stage, and the present study shows that in both the examples the DDBD method achieves the behaviour factors more than targeted Values. These conclusions can be considered only for the selected pier. For General conclusions large number of case studies is required and it is treated as a scope of future work.

Table 3.5: Performance Assessment of designed Pier

Designed			Type of design	V_b (kN)	% of Steel	Φ (mm)	No. of Bars	Performance Parameters Achieved		
μ	Δ	R						μ	Δ	R
		2.5	FBD	891	2 %	32	#28			2.74
1	0.276		DBD	604	1.2 %	32	#16	3.5	0.35	3.25
2	0.276		DBD	150	0.8 %	32	#12	3.4	0.34	11.63

IV. CONCLUSION

A metro system is an electric passenger railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. An elevated metro system is the most preferred form of metro structure due to ease of construction and less cost compared to other types of metro structures. An elevated metro system has two major components pier and box girder. In this project, study has been carried out on these two major elements.

The performance assessment on designed pier by Force Based Design and Direct Displacement Based Design is carried out. The design of the pier is done by both force based design method and direct displacement based design method.

The performance assessment of selected designed pier showed that,

- Force Based Design Method may not always guarantee the performance parameter required and in the present case the pier just achieved the target required.
- In case of Direct Displacement Based Design Method, selected pier achieved the behaviour factors more than targeted Values.

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