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TO STUDY THE BEHAVIOUR OF STRUCTURAL ELEMENTS OF OVERHEAD BANGALORE METRO LINE

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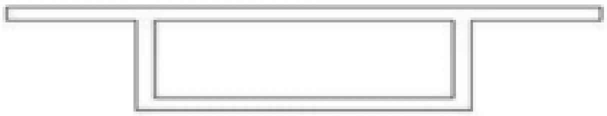
ABSTRACT: A metro system is a railway transport system in an urban area with a high capacity, frequency and the grade separation from other traffic. Metro System is used in cities, agglomerations, and metropolitan areas to transport large numbers of people. An elevated metro system is more preferred 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 in the first part of the study. In the second part, a parametric study on behaviour of box girder bridges is carried out by using finite element method. The finite element model is validated with model of Gupta et al. (2010). The parameters considered to present the behaviour of Single Cell Box Girder, Double Cell Box Girder and Triple Cell Box Girder bridges are radius of curvature, span length and span length to the radius of curvature ratio. These parameters are used to evaluate the responses of box girder bridges namely, longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency of three types of box girder bridges.
The performance assessment of selected designed pier showed that, the Force Based Design Method may not always guarantee the performance parameter required and in the present case the pier achieved the target requirement. In case of Direct Displacement Based Design Method, selected pier achieved the behaviour factors more than targeted Values. These conclusions can be considered only for the selected pier. The parametric study on behaviour of box girder bridges showed that, as curvature decreases, responses such as longitudinal stresses at the top and bottom, shear, torsion, moment and deflection decreases for three types of box girder bridges and it shows not much variation for fundamental frequency of three types of box girder bridges due to the constant span length. It is observed that as the span length increases, longitudinal stresses at the top and bottom, shear, torsion, moment and deflection increases for three types of box girder bridges. As the span length increases, fundamental frequency decreases for three types of box girder bridges. Also, it is noted that as the span length to the radius of curvature ratio increases responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges. As the span length to the radius of curvature ratio increases fundamental frequency decreases for three types of box girder bridges.

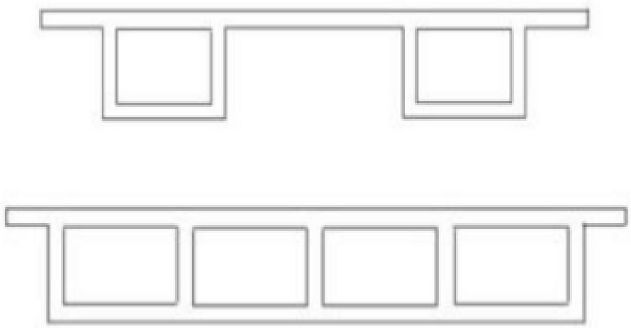
I. INTRODUCTION

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. A typical elevated metro bridge model is shown in Figure 1.1 (a). 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. A typical pier considered for the present study is shown in Figure 1.1 (b). 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 as shown in Figure 1.2.

a) Typical Elevated Metro Bridge (b) Typical Pier
Figure 1.1: Typical Elevated Metro Bridge and its Elements



(a) Single Cell Box Girder



(b) Multiple Spine Box Girder (c) Multi cell Box Girder
Figure 1.2: Types of Box Girder

II. SIGNIFICANCE OF THE STUDY

A force based seismic design approach is conventionally used to design the metro bridge pier. During a seismic loading, the behaviour of elevated bridges relies mostly on the ductility and the displacement capacity of the pier. It is important to check the ductility of such single piers. Force based methods do not explicitly check the displacement capacity at the design stage. 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. The behaviour of a box girder curved in plan is significantly different from a straight bridge and it is dependent on many parameters. A limited number of studies have been conducted on this aspect.

III. OBJECTIVE

- To study the performance of a pier designed by Force Based Design Method (FBD) and Direct Displacement Based Design (DDBD) Method.
- To study the parametric behaviour of a Curved Box Girder Bridges.

SCOPE

- The present study is limited to those practical cases that come across in an elevated metro project.
- With regard to the geometry of the pier considered, the present study is limited to
  - Rectangular pier cross section
  - Single pier structural system Reinforced concrete pier

Parametric Study on Box Girder is limited to,

- Linear static and dynamic analysis and Nonlinear analysis is not considered
- Rectangular box section with flanges.
- Reinforced concrete box girder section and not applicable to pre-stressed bridges.
- Single Cell and Multi Cell Box Girder and not applicable to Multi Spine box girder.
- Zero percentage gradient of the superstructure and super elevation is not considered in the modelling

IV. ORGANIZATION OF THE THESIS

This thesis consists of five chapters. Chapter 1 gives the introduction about the present study which covers the significance, objective and scope of the study. Chapter 2 gives literature review which includes a method of design of the pier and parametric studies on box girder. Chapter 3 presents the performance study of a pier designed by Force Based Design Method and Direct Displacement Based Design Method. Chapter 4 describes the parametric study on the behaviour of curved box girder bridges. Chapter 5 presents summary and conclusion of the present study.

V. DESIGN OF PIER

Conventionally the pier of a metro bridge is designed using a force based approach. Recent studies (Priestley et al., 2007) show that the force based design may not necessarily guarantee the required target performances. The codes are now moving towards a performance-based design approach, which consider the design as per the target performances at the design stage. As the present study focus on the application of displacement based approaches to pier design, a brief introduction of the two methods, force-based and displacement based design is summarised in the following sections.

1) FORCE BASED DESIGN METHOD

Force Based Design Method (FBD) is the conventional method to design the metro bridge pier. In Force based design method, the fundamental time period of the structure is estimated from member elastic stiffnesses, which is estimated based on the assumed geometry of the section. The appropriate force reduction factor (R) corresponding to the assessed ductility capacity of the structural system and material is selected in the force based design and applied to the base shear of the structure.

The design of a pier by force based seismic design method is carried out as per IS 1893: 2002 Code. The design procedure to find the base shear of the pier by FBD method is summarized below.

Step 1: The structural geometry of the pier is assumed.

Step 2: Member elastic stiffness are estimated based on member size.
Step 3: The fundamental period is calculated by:
$T = 0.075\ h^{0.75}$
Where h = Height of Building, in m
Step 4: Seismic Weight of the building (W) is estimated.
The total design lateral force or design seismic base shear force (V_B) along any principal direction is given by
$V_B = A_h\ W$
Where A_h = Design Horizontal Seismic Coefficient and
W= Seismic Weight of the Building
2) DIRECT DISPLACEMENT BASED DESIGN METHOD
The direct displacement based seismic design (DDBD) is proposed by Priestley et al. (2007) is used in the present study to design a metro bridge pier. The design philosophy of DDBD is based on the determination of the optimum structural strength to achieve a given performance limit state, related to a defined level of damage, under a specified level of seismic intensity., Priestley et al. (2007). The pier designed by DDBD method gives the uniform risk factor for the whole structure.
The design procedure to find the base shear of the pier by DDBD method is summarized below.

Step 1: Yield Curvature is calculated by
$\Phi y = (2.10 * \varepsilon y)/hc$
Where, εy is the yield strain and
hc is the section depth of rectangular column

Step 2: Yield Displacement is calculated by
$y = \Phi y\ (H + Lsp)2 / 3$
Where, H is the Column Height and
Lsp is the Effective additional height representing strain penetration effects

Step 3: Design Displacement is lesser of
$_d = \theta_d *H$ or $\mu*\ _y$
The ductility at design displacement is, $\mu =\ _d /\ _y$
Where, θ_d = Drift limit

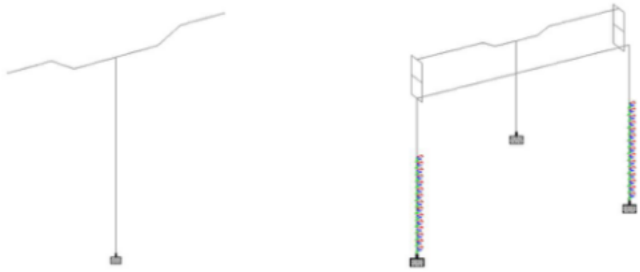
Step 4: Equivalent viscous damping
$\xi_{eq} = 0.05 + 0.444(\mu -1/ \mu\ \pi)$

Step 5: Maximum spectral displacement is calculated from Design Displacement Spectra given in Priestley et al. (2007).

3) BOX GIRDER BRIDGES
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 box-girder bridges.

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

DESIGN OF PIER USING FORCE BASED DESIGN
The geometry of pier considered for the present study is ased 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.



(Type A) (Type B)
Figure 3.1: Typical Pier Model

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} /^{0}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} /^{0}C

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 %

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 ductili,ty, 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

$$R' = R_{\mu} \bullet R_S \bullet Y$$

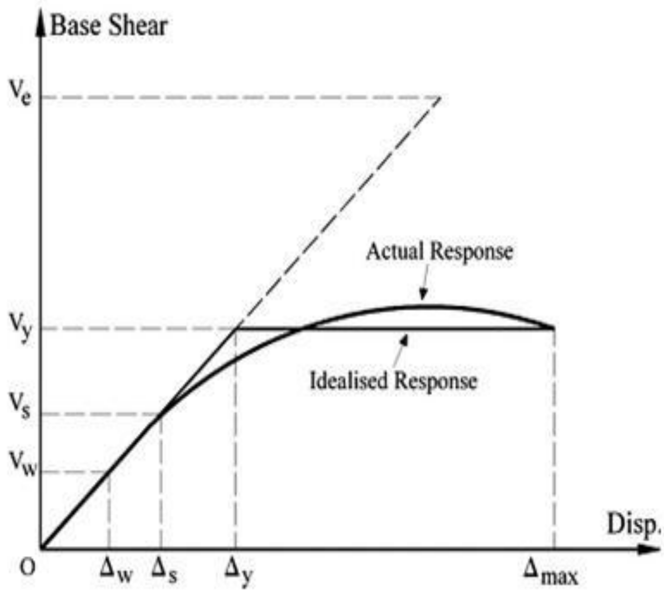


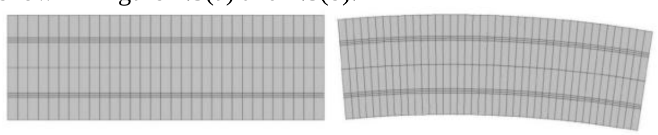
Figure 3.3: Typical Pushover response curve for evaluation of performance parameters

Performance Assessment of designed Pier

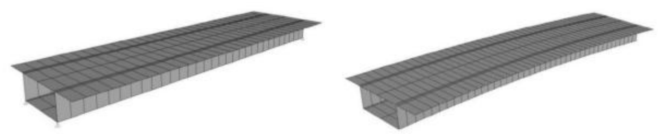
Designed			Type of design	V_b (kN)	% of Steel	Φ (mm)	No. of Bars	Performance Parameters Achieved		
μ		R						μ		R
		2.5	FBD	891	2 %	32	#28			2.74
1	0.276		DBD	604	1.2 %	32	#16	3.5	0.35	3.25
2	0.276		DBD	150	0.8 %	32	#12	3.4	0.34	11.63

FINITE ELEMENT MODELLING

The finite element modelling methodology adopted for validation study is used for the present study. The modelling of Box Girder Bridge is carried out using Bridge Module in SAP 2000. The Shell element is used in this finite element model to discretize the bridge cross section. At each node it has six degrees of freedom: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. The typical finite element discretized model of straight and curved simply supported box Girder Bridge in SAP 2000 is shown in figure 4.3(a) and 4.3(b).



Plan



3D Model

Figure 4.3(a) (b): Discretized model of simply supported Straight Box Girder Bridge in SAP 2000

PARAMETRIC STUDY

The parametric study is carried out to investigate the behaviour (i.e., the longitudinal stress at the top and bottom, shear, torsion, moment, deflection and fundamental frequency) of box girder bridges for different parameters viz. radius of curvature, span length, span length to radius of curvature ratio and number of boxes.

Radius of Curvature

Two lane 31 m Single Cell Box Girder (SCBG), Double Cell Box Girder (DCBG) and Triple Cell Box Girder (TCBG) Bridge are analysed for different radius of curvatures to illustrate the variation of longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency with radius of curvature of box girder bridges.

To express the behaviour of box girder bridges curved in plan with reference to straight one, a parameter α is introduced. α is defined as the ratio of response of the curved box girder to the straight box girder. The variation of longitudinal stress at top with radius of curvature of box girder bridges is shown in Figure 4.4. As the radius of curvature increases, the longitudinal stress at the top side of the cross section decreases for each type of Box Girder Bridge. Variation of Stress between radius of curvature 100 m and 400 m is only about 2 % and it is same for all the three cases. Stress variation between each type of box girder is only about 1 %. Figure 4.5 represents a non-dimensional form of the stress variation for all the three types of box girder. It shows that stress variation pattern is same for all the three types of box girder.

SUMMARY AND CONCLUSIONS

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. In the first part of this study, 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. In the second part, parametric study on behaviour of box girder bridges is carried out by using finite element method. The numerical analysis of finite element model is validated with model of Gupta et al. (2010). The parameter considered to present the behaviour of Single Cell Box Girder, Double Cell Box Girder and Triple Cell Box Girder bridges are radius of curvature, span length and span length to the radius of curvature ratio. These parameters are used to evaluate the response parameter of box girder bridges namely longitudinal stresses at the top and bottom, shear, torsion, moment, deflection and fundamental frequency of three types of box girder bridges.

VII. CONCLUSIONS

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.
- These conclusions can be considered only for the selected pier. For General conclusions large numbers of case studies are required and it is treated as a scope of future work.

The parametric study on behaviour of box girder bridges showed that,

- As the radius of curvature increases, responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are decreases for three types of box girder bridges and it shows not much variation for fundamental frequency of three types of box girder bridges due to the constant span length.

- As the span length increases, responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and fundamental frequency decreases for three types of box girder bridges.
- As the span length to the radius of curvature ratio increases responses parameter longitudinal stresses at the top and bottom, shear, torsion, moment and deflection are increases for three types of box girder bridges and as span length to the radius of curvature ratio increases fundamental frequency decreases for three types of box girder bridges.

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