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Performance Study on a Pier Designed Using Force Based and Direct Displacement Methods

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Abstract*— 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. This paper concentrates only on the design of pier and its performance. 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. In this paper, performance of a pier designed by a Direct Displacement Based Design is compared with that of a force-based designed one. The design of a pier is done by both force based seismic design method and direct displacement based seismic design method and performance assessment is done based on both the methods.

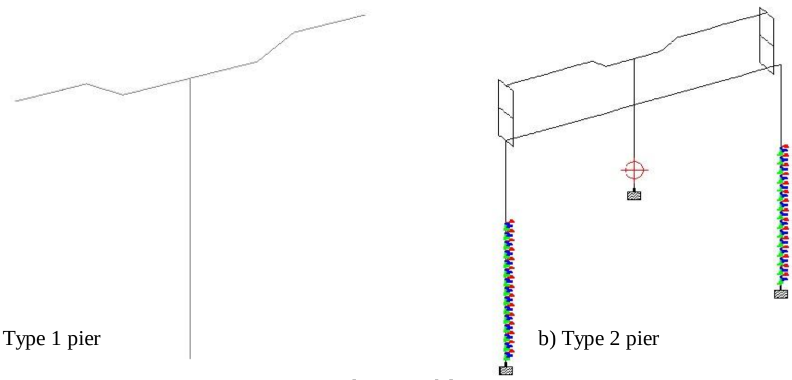
***Keywords*— Elevated Metro System, Bridge Pier, Direct Displacement Based Seismic Design, Performance Based Design, Force Based Design**

I. INTRODUCTION

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.

II. DESIGN OF PIER USING FORCE BASED DESIGN METHOD

The piers considered for the analysis are the normally adopted ones in the elevated metro station structure. The effective height of the considered piers is 13.8 m. The piers are assumed to be located in Seismic Zone II and the designs are as per IS 1893 (Part 1):2002. The modelling and seismic analysis is carried out using the finite element software STAAD Pro. The typical model of the pier is shown below.



a) Type 1 pier b) Type 2 pier

Fig 1. Typical pier model

A. Material Property Adopted

The material property considered for present pier analysis for concrete reinforcement and steel are given in table below.

TABLE I
MATERIAL PROPERTY OF THE PEIR

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^{-2}/ ^{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^{-2}/ ^{0}C

B. Design Loads

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 below. The total seismic weight of the pier is 17862 kN.

TABLE II APPROXIMATE
DESIGN LOADS

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 below. 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 33
REINFORCEMENT DETAILS AS PER FORCE BASED DESIGN

Pier Type	**Cross Section**	**Diameter of Bar (mm)**	**Number of bars**	**Percentage of Reinforcement**	
				Required	**Provided**
Pier A	2.4x1.6	32	#32	0.8	0.8
Pier B	2.4x1.6	32	#38	0.8	0.8

III. DESIGN OF PIER USING DIRECT DISPLACEMENT 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 below. The performance level considered for the study is a Life Safety (LS) level

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 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 %.

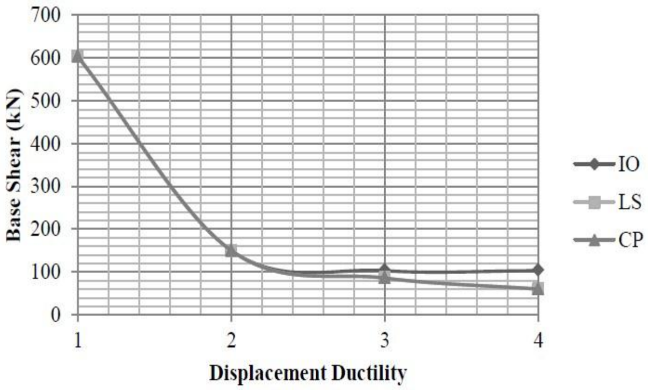


Fig 2. Effect of Displacement ductility on base shear of different Performance Levels

IV. 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 V. 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,

$$R = R_{\mu}.R_{S}.Y$$

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

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, 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

TABLE 44
REINFORCEMENT DETAILS AS PER DIRECT DISPLACEMENT BASED DESIGN

Displacement ductility	**Drift Limit (m)**	**Cross Section (m)**	**Base Shear V_b (kN)**	**Diameter of Bars (mm)**	**No. of Bars**	**Percentage 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	1.2 %
3	0.276	1.5 x 0.7	8	32	#12	0.8 %
4	0.276	1.5 x 0.7	6	32	#12	0.8 %

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

where, Ve, Vy, Vs and Vw 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 below.

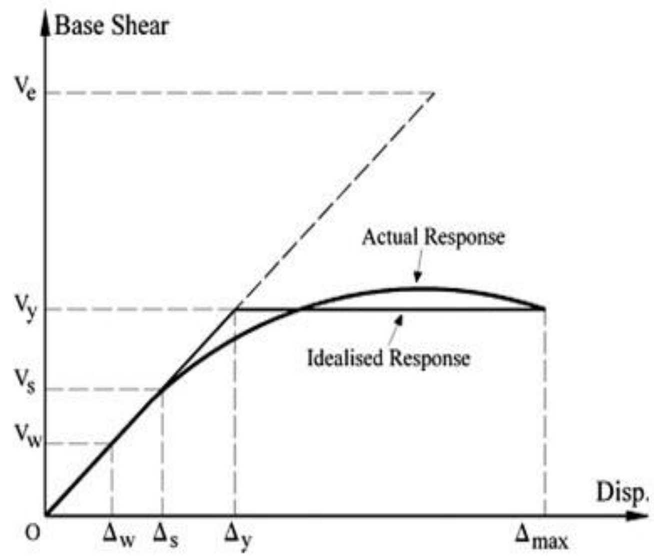


Fig 3. Typical pushover response curve for evaluation of performance parameters

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,

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

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.

V. CONCLUSIONS

The paper concentrates on 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. These conclusions concede to the selected pier only and to get further knowledge about direct displacement approach large number of case studies is to be carried out.

TABLE 5
PERFORMANCE ASSESSMENT OF DESIGNED PIER

Designed			**Type of design**	**V_b (kN)**	**Percentage 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

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