AN INTRODUCTION TO UNIFIED PERFORMANCE-BASED DESIGN OF BRIDGE PIERS

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Abstract

This paper introduces a new seismic design philosophy titled Unified Performance-Based Design (UPBD) for designing reinforced concrete (RC) bridge piers. It is an up-gradation of the existing Direct Displacement Based Design (DDBD) philosophy. DDBD is a comparatively new design philosophy for seismic design where the designer can satisfy some pre-defined target design criterion under a given hazard level. The existing DDBD methods consider only drift as the sole design parameter and are silent about the structural Performance Level (PL) of the structure. In UPBD method, both drift and Performance Level (PL) are considered in the design formulation. Choudhury (2008) introduced UPBD method for dual system. Choudhury and Singh (2013) developed UPBD method for RC frame buildings. But bridges have not been designed using the UPBD method. The present paper tries to extend the UPBD philosophy to the design of circular RC bridge piers. As per the philosophy of UPBD method, an expression is developed for the bridge pier size (diameter) which satisfies the design drift and target Performance Level (PL) simultaneously. In the present study, a series of bridge piers have been designed using the proposed UPBD method for different combinations of drift and PL. The designed bridge piers have been subjected to nonlinear time history analysis under spectrum compatible ground motions, and the achieved drift and PL have been noted. It has been found that the proposed philosophy gives satisfactory results. The proposed design philosophy is innovative. The proposed design methodology does not require any iteration for member size calculation.

Keywords: Bridge, Pier, Circular, RC, UPBD.

1. Introduction

1.1. General

Codal seismic design of structures is essentially force-based. Here force is taken as the core design parameter. In force-based method design, it is difficult to design the structures for any pre-established design criterion without using large number of iterations. Alternative design methods available are displacement-based design (DBD) and performance-based design (PBD). Structural performance criteria can be described in terms of deflections, crack width, drift, plastic rotation, etc. In PBD, the designer intends to design the structure for some given performance criteria under some specified hazard level. A family of DBD is direct displacement-based design (DDBD) applicable for various structures. But the DDBD method considers only one design criterion, namely, drift. The performance level (PL) (in terms of plastic rotation of members) is not considered here. Choudhury (2008) [1] developed a method christened as Unified performance-based design (UPBD) which could address both drift and PL simultaneously. Also, the member sizes were obtained in the beginning of design so that iterations are not required. However, the UPBD method was applied to dual system (Choudhury, 2008) [1] and frame buildings (Choudhury and Singh, 2013) [2] only. In the present study, the UPBD method has been applied for circular RC bridge pier designing. A formula for pier diameter has been established which satisfies both design drift and PL of pier.

1.2.DDBD method of design

Priestley (2000) [3] introduced the DDBD method. The method was applied in RC frame buildings (Pettinga and Priestley, 2005) [4] and in dual system (Sullivan *et. al.*, 2006) [5]. In this method, a multi-degree-of-freedom (MDOF) system is converted to an equivalent single degree of freedom (ESDOF) system, and the ESDOF properties are calculated. Now, for a given drift criterion, the target displacement is established from displacement spectra corresponding to design spectra. Base shear force is calculated using the effective time period and is distributed at different levels of the structure. The design is carried out considering the expected strengths of the materials. In this method of design, only drift was taken as the target design criterion.

1.3. Unified performance-based design (UPBD) method

Choudhury (2008) [1] introduced UPBD method, primarily for dual system buildings, which takes into account two design target parameters, namely, drift and PL. This theory unifies two performance criteria - drift and PL (in terms of member plastic rotation) together and is an up-gradation of the DDBD method. The various PLs considered were Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). In IO PL, the structure can be used immediately after the hazard is removed. In LS PL, the structure might need to be reinvented after the hazard is removed, but lives are safe. In CP PL, the structure needs to go through large repair if hit by strong ground motions, and lives may be threatened, but structure does not collapse. Choudhury and Singh (2013) [2] developed UPBD method for reinforced concrete frame buildings, where the depth of beam satisfying the target design criteria was given by Eq. (1).

$$h_b = \frac{0.5\varepsilon_y l_b}{\theta_d - \theta_{pb}} \tag{1}$$

In Eq. (1), h_b = depth of the beam, ε_y = yield strain of rebar, l_b = length of beam, θ_d = design interstorey drift, and θ_{pb} = allowable plastic rotation in beam corresponding to the PL. The width of beam was taken half to two-thirds of the beam depth. Rest of the steps in design were similar to the DDBD method as given by Pettinga and Priestley (2005) [4] for designing RC frame structures.

With this method, the designer is given the freedom to choose a combination of drift and PL to be achieved under any given hazard level. Though the designer may choose any combination of drift and PL for designing a structure, unrealistic combinations have to be avoided.

1.4. Extending the UPBD method to RC bridge piers

In the present study, the UPBD design philosophy has been applied in designing circular RC bridge piers. Bridges are special structures and play an important role in our lives. The pier, an important and critical part of a bridge structure, is considered for designing using the UPBD method. An expression is derived to calculate the diameter of the bridge pier using the UPBD method theory, which satisfies the drift and PL simultaneously. As the bridge pier diameter is obtained from formula established, no iteration is necessary to arrive at the diameter.

2. Proposed theory for designing circular RC bridge piers

2.1. Scope

In this study, only one column at a bridge bent location is considered. Regular RC bridges with circular piers fixed at the base and free at the top are taken.

2.2. Proposed expression to calculate diameter of pier

The basic concept behind the formulation of the expression of the UPBD theory lies in the understanding that, design drift (θ_d) is the summation of the yield rotation (θ_y) and plastic rotation (θ_p) (refer Fig. 1).

$$\theta_d = \theta_y + \theta_p \qquad (2a)$$

Therefore, one can represent the yield rotation in terms of plastic rotation deduced from the design drift.

$$\theta_y = \theta_d - \theta_p \qquad (2b)$$

Of these three terms, a designer is given the design drift, for which the structure is to be designed, the yield rotation can be found out from the standard expressions available, and the plastic rotation value is to be referred from different design documents.

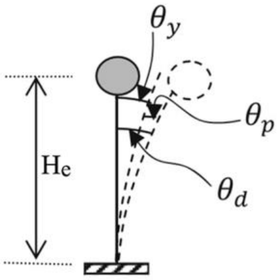

Fig. 1– ESDOF System

(Source: Choudhury and Singh, 2013)

Yield curvature of a circular column can be given by Eq. (3) (Priestley *et. al.*, 2007) [6].

$$\phi_y = \frac{2.25\varepsilon_y}{D} \qquad (3)$$

In Eq. (3), D is the diameter of the circular column, and ε_y is the yield strain of material.

Now, yield deflection can be measured with the help of yield curvature using Eq. (4) (Priestley *et. al.*, 2007) [6].

$$\Delta_y = C_1 \phi_y \left(H_e + L_{sp}\right)^2 \tag{4}$$

In Eq. (4), Δ_y = yield deflection at the top of the pier, ϕ_y = yield curvature, H_e = effective height of the column, L_{sp} = strain penetration length, C_1 = constant, depending on end condition of column.

The formula depends on the end fixity conditions of the column. If the superstructure is bearing supported, and the footing is considered rigid against rotation and translation, the effective height H_e is measured from the base of the column to the centre of the bearing; the strain penetration length (L_{sp}) into the footing is $0.022 f_{y_e} d_{bl}$ units, and the coefficient C_1=$1/3$ (Priestley *et. al.*, 2007) [6].

The yield deflection divided by the effective height of the column gives the yield rotation at the base of the column.

$$\theta_y = \frac{\Delta_y}{H_e} \tag{5}$$

Rearranging the Eq. (3), Eq. (4), and Eq. (5) gives the following expression in Eq. (6).

$$D = \frac{0.75 \times f_y \times \left(H_e + 0.022 f_{y_e} d_{bl}\right)^2}{E_s \times H_e \times \left(\theta_d - \theta_p\right)} \tag{6}$$

Eq. (6) gives the diameter of a bridge pier designed for a given drift and PL. The plastic rotation of piers (θ_p) corresponding to any PL are obtainable from ASCE-41-13.

Eq. (6) can be used to design a bridge pier for any given combination of drift and PL, but the combination of drift and PL has to be realistic. Very high drift should not be combined with very high PL.

2.3. Modification of the proposed expression for pier diameter

A series of bridge piers have been designed using the proposed theory. The drift and PL (in terms of plastic rotation) have been obtained for the designed piers through nonlinear analyses. From the results obtained, it was found that the achieved drift values do not match the target drift values for which the bridge piers are designed. The drift values achieved were found to be less than the target values. This phenomenon is explained with the fact that, unlike buildings, the bridge structures gain extra lateral restraint from the abutments. This makes the drift achieved less than the design drift. Therefore, the target design drift values are to be magnified before the start of the design to take this effect into consideration. A coefficient K_1(> 1) is introduced here, to be multiplied with desired target drift values, to take into account the effect of abutment. So, magnified drift to be considered in design is given by Eq. (7).

$$\theta_d{}' = K_1 \times \theta_d \tag{7}$$

The value of K_1 depends on the length of spans and number of spans of the bridge. The less the length of a bridge, the higher is the value of the coefficient K_1. Therefore, the modified expression to calculate the size of the pier is given by Eq. (8).

$$D = \frac{0.75 \times f_y \times \left(H_e + 0.022 f_{y_e} d_{bl}\right)^2}{E_s \times H_e \times \left(\theta_d{}' - \theta_p\right)} \tag{8}$$

By trial studies, the following values of $K_1$are suggested: For IO PL, K_1= 2; for LS PL, K_1=3.

2.4. Design Steps

After the diameter of the pier is determined, the rest of the design process follows the recommendations of Pettinga and Priestley (2005) [4] for designing RC frame structures with the exception that the bridge pier is already idealized as an SDOF system, and therefore, it does not need the conversion of the MDOF system to an ESDOF system. Also, the distribution of the base shear force is not required. For clarity, the design steps are furnished below.

1) The equivalent mass (M_e) of the structure acting on the top of each pier is calculated. Equivalent mass is obtained by summing the mass of half of the span length of the superstructure on both sides of a pier and one-third of the pier mass (Priestley, 2007) [6]. This equivalent mass acts at the top of the equivalent height of the pier.
2) Corresponding to the magnified drift ($\theta_d{}'$) and effective height of the pier (H_e), design deflection of the pier at the top is calculated (Eq. 9). The yield deflection at the top of the pier is calculated from the values of yield rotation and effective height (Eq. 10). Yield rotation (θ_y) can be referred from Eq. 2b.

$$\Delta_d = \theta_d{}' \times H_e \tag{9}$$
$$\Delta_y = \theta_y \times H_e \tag{10}$$

3) The ductility index (μ) is obtained by applying Eq. 11. From ductility, the equivalent damping is obtained by applying Eq. 12 (Priestley *et. al.* 2007) [6].

$$\mu = \frac{\Delta_d}{\Delta_y} \tag{11}$$

$$\xi = 0.05 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right) \tag{12}$$

4) Displacement spectra corresponding to the design spectrum is generated for various damping (ξ) (Fig. 2).
5) Corresponding to the design displacement (Δ_d, Eq. 9), and equivalent damping obtained, the effective time period (T_e) is obtained from displacement spectra.

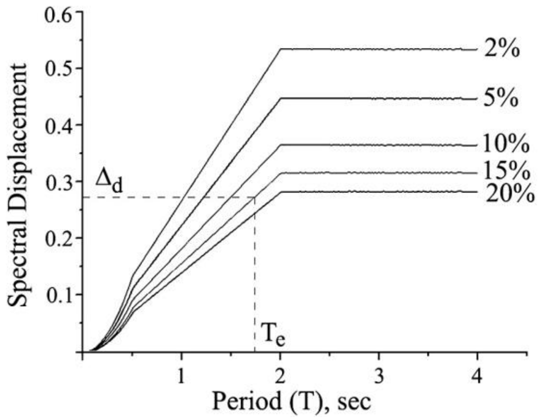

Fig. 2–Displacement spectra corresponding to EC-8 design spectra at 0.6g level for various damping.

6) The equivalent stiffness of the system is calculated for this effective time period, as given by Eq. (13).

$$K_e = 4\pi^2 \frac{M_e}{T_e{}^2} \tag{13}$$

7) The design base shear is given by Eq. (14)

$$V_b = K_e \times \Delta_d \quad (14)$$

As there is only one level of mass, the base shear is not to be distributed and is applied at the top of the equivalent height of the pier.

8) Design is carried out using the expected strengths of the materials following FEMA 356 recommendation (*i.e.* 1.5 times of the 28-days characteristic strength for concrete and, 1.25 times of yield strength for rebar). Load combinations considered are -

$D + L$
$D + L \pm F_x$
$D + L \pm F_y$

Where, D stands for dead load, L stands for live load, F_x is seismic load in long direction of bridge and F_y is seismic load in transverse direction of bridge. For symmetrical pier section, F_x=F_y= V_b.

3. Validation of the proposed theory

3.1. General

To validate the proposed UPBD theory, four bridge piers have been designed using the proposed UPBD method. The bridges are modelled in CSI Bridge v.20 software [7]. Two bridges are designed for the combination of IO PL with 0.5% drift (bridges are named as '**IO1**' and '**IO2**'). Another two bridges have been designed for the combination of LS PL with 1% drift (bridges are named as '**LS1**' and '**LS2**'). The values of plastic rotation corresponding to different PLs are obtained from the ASCE 41-13.

3.2 Details of the bridges considered

Each of the bridges considered has four numbers of spans and three numbers of bents along the total length. The alignments of the bridges are kept straight and no change of elevation of the superstructures throughout the lengths of the bridges is considered.

Details of the dimensions of the bridges are presented in Table 1.

Table 1 –Details of the bridges considered

Property		**Bridge names**			
		IO1	**IO2**	**LS1**	**LS2**
Length of bridge		96 m	100 m	96 m	100 m
Number of spans		4	4	4	4
Deck details (refer Fig. 3)	*L*	7.5 m	7.5 m	7.5 m	7.5 m
	b	1.8 m	1.8 m	1.5 m	1.5 m
	t1	0.3 m	0.3 m	0.3 m	0.3 m
	t2	0.4 m	0.4 m	0.4 m	0.4 m
Pier dimensions	*H*	8 m	10 m	8 m	10 m
	D	2.093 m	2.591 m	1.495 m	1.850 m
Cap beam dimension (m)		2.5×2.5×7.5	2.8× 2.8×7.5	1.8×1.8×7.5	2×2×7.5
Abutment type	Start	Rocker	Rocker	Rocker	Rocker
	End	Roller	Roller	Roller	Roller
Lane width		5.5 m	5.5 m	5.5 m	5.5 m
Target design criteria	Drift	0.5%	0.5%	1%	1%
	PL	IO	IO	LS	LS

The bridges are supported on abutments which are fixed on the ground at the ends. The deck rests on a beam, at each bent location, supported centrally by a circular pier. Height of piers is taken constant for any particular bridge, though the pier height is varied with bridges. The lengths of the bridges are varied in different bridge models along with the dimensions of the superstructures.

Only one pier has been provided at each bent. The bearing connecting the bent cap beam with the deck is free to rotate about the vertical axis and about the axis transverse to the layout line of the bridge whereas it is restrained to rotate or translate in all other remaining directions. Diaphragms of 0.3 metre thickness is considered in the bridge deck.

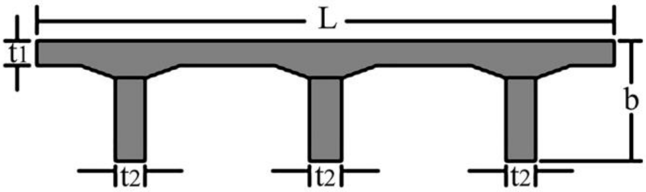

Fig. 3 – Schematic cross section of bridge deck.

3.3. Loading and ground motion considered

IRC Class-A loading has been considered to take into account the effect of moving load on the bridges. The design of the components of the bridge for shear and flexural strength has been carried out following Eurocode-2: 2004.

Table 2 – Details of the time background earthquakes considered

Name	Background earthquake	Station	Magnitude (M_w)	PGA	Duration
SCGM1	San Fernando 1971	Pacoima Dam	6.61	1.164g	41.72 sec
SCGM2	Landers 1992	Yermo Fire Station	7.28	0.721g	44.00 sec
SCGM3	N.E. India 1997	Silchar	6.00	0.933g	26.92 sec
SCGM4	Oroville-04 1975	Oroville Airport	4.37	0.027g	13.00 sec
SCGM5	Point Mugu 1973	Port Hueneme	5.65	0.128g	23.18 sec

For evaluation of the performance of the designed piers, the models are subjected to time history analyses under five spectrum compatible ground motions (SCGM). Design spectrum of EC-8 corresponding to ground type-B and 0.6g level of seismicity has been considered. The SCGMs have been generated using software of Kumar (2004) [8]. Background earthquakes used for generating the SCGMs are given in Table 2.

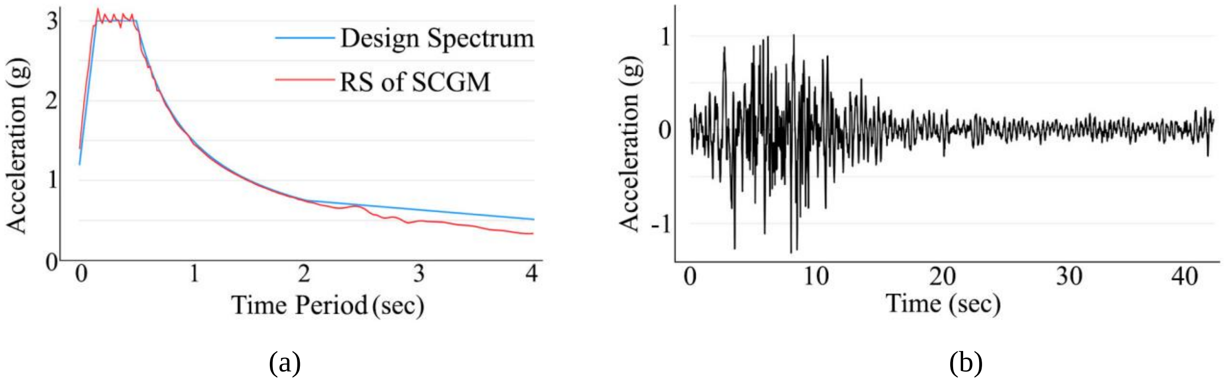

Fig. 4 – Typical ground motion: (a) Matched spectrum of San Fernando earthquake (1971) to response spectrum of Eurocode - 8, (b) Generated SCGM of San Fernando earthquake (1971).

3.4. Results

Nonlinear hinges are formed at the base of the piers when subjected to time history analysis under SCGMs. The colour of the hinges denotes the PL. It is found from the hinge results that each pier achieved the desired PL. Drift of pier is obtained by taking the ratio of defection at pier top to the effective height of the pier.

Table 3 shows the achieved performance of bridge piers.

Table 3 – Achieved vs. target performance criteria

Bridge name	Target values		Achieved values		Deviation in
	Drift	PL	Max. Drift	PL	drift value
IO1	0.5%	IO	0.6%	IO	+20.0%
IO2	0.5%	IO	0.54%	IO	+8.0%
LS1	1%	LS	1.12%	LS	+12.0%
LS2	1%	LS	0.81%	LS	-19.0%

Out of five values of achieved drifts under five SCGMs, the maximum drift has been reported for any bridge. From the results obtained it is found that in all bridge piers the target PL has been obtained. The drifts achieved are also very near the target values (maximum 20% deviation from target drift). This validates the efficacy of the proposed UPBD method for bridge piers.

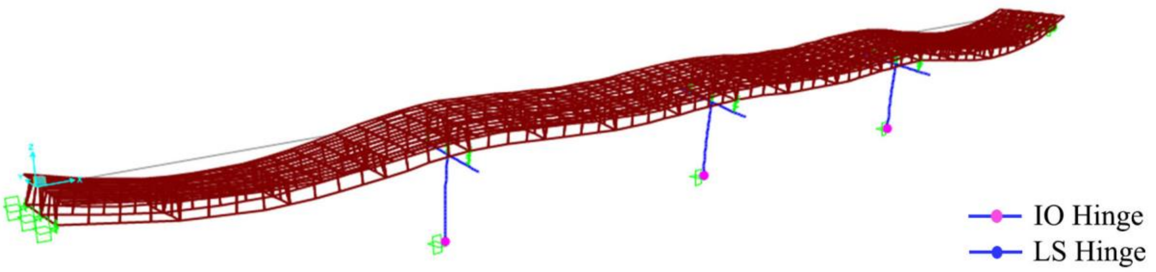

Fig. 5 – Typical model with IO plastic hinge formation.

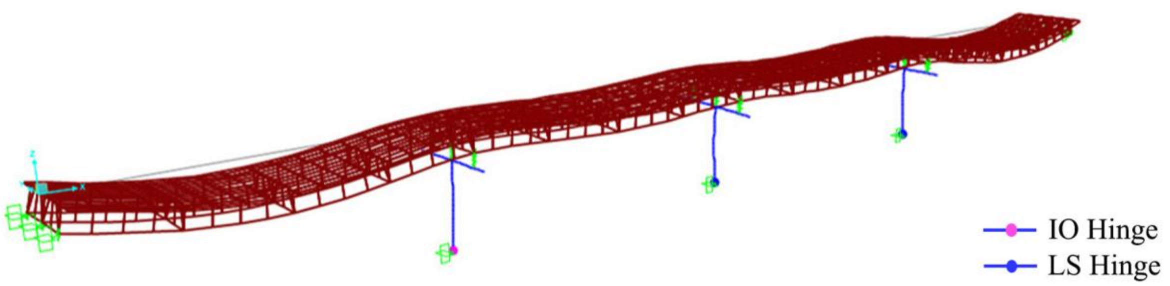

Fig. 6 - Typical model with LS plastic hinge formation.

4. Conclusion

Codal methods for structure designing are force-based. With force-based methods of design, it is laborious to design a bridge for a given performance criterion. DDBD method for bridge (Priestley, 2000) considers only one performance criterion, namely, drift. But it did not consider the PL of the structure. Choudhury (2008) introduced UPBD method for dual system, which takes both drift and PL as the design parameters. Choudhury and Singh (2013) developed UPBD method for RC frame buildings. In the present study the UPBD method is extended to bridge piers. An expression for size of pier has been theoretically developed to accommodate any combination of drift and PL under a given hazard level. A series of bridge piers have been designed using the proposed UPBD method. On comparing the target and achieved results, a modification has been proposed in the expression of pier diameter. Four bridges have been modeled with piers designed using the updated expression of pier diameter. The bridges have been subjected to SCGMs corresponding to Eurocode – 8 design spectrum at 0.6g seismicity level. Two bridges have been designed for a combination of IO PL with 0.5% drift, and two other bridges have been designed for LS PL with 1% drift. It has been found that the achieved PL of the bridge piers match the target PL, and the drift values are within $\pm$20% deviation from the target drift. With the proposed UPBD method, a designer can design a bridge pier for two performance criteria (namely drift and PL) for a given hazard level, without needing any iterations.

5. Copyrights

6. References

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