Cover page

Title: **Implementation of Displacement Based Design for Highway Bridges**

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Implementation of Displacement Based Design for Highway Bridges

Vinicio Suarez and Mervyn Kowalsky

ABSTRACT

Six bridges classified as ordinary bridges in the Seismic Design Criteria (SDC) by Caltrans are designed according to that criteria and are also designed using the Direct Displacement Based Design (DDBD) method. The bridges include two types of substructures, symmetric and asymmetric configurations and plan curvature. The performance of each of the resulting structures is evaluated by performing nonlinear time history analysis. This work aims to (1) compare the effectiveness of DDBD and SDC in the design of a sample of six ordinary bridges and (2) investigate the items needed for improvement of current DBD practice emphasizing in the determination of displacement demand, displacement capacity and soil-structure interaction effects. Special attention is put on the determination of the displacement demand and an alternative procedure is proposed based on the Substitute Structure Method (SSM). Also, the existing target ductility limits are reviewed considering P-Delta effects for column bents on rigid foundations and drilled shafts bents.

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INTRODUCTION

After the Loma Prieta earthquake in 1989, extensive research has been conducted to develop improved seismic design criteria for concrete bridges, emphasizing the use of displacements rather than forces as a measure of earthquake damage and the application of capacity design principles to assure ductility failure mechanisms and concentration of damage in specified regions. Several Displacement Based Design (DBD) methods have been devolved including:

- The Direct Displacement Based Design Method (Priestley, 1993) that can be used for the seismic design of bridge columns (Kowalsky et al, 1995), pile and drilled shaft bent substructures (Suarez and Kowalsky, 2006) , continuous bridges (Dwairi, 2005; Kowalsky, 2002) and concrete buildings (SEAOC, 2004; Priestley and Kowalsky, 2000)
- The Seismic Design Criteria by Caltrans (2004) that shifted towards displacement based design in 1999 consolidating ATC-32 (American Technology Council, 1996) recommendations and state-of-the-art knowledge and it is currently used for the design of ordinary bridges in California.

Direct Displacement Based Design (DDBD)

In DDBD, an inelastic system at its peak response is replaced by an equivalent linear system with secant stiffness and equivalent viscous damping. The procedure requires the definition of a target displacement profile and yields the stiffness and strength required such that the target displacements do not be exceed under seismic attack. The main steps involved in the application of DDBD are:

1) Initial sizing of bridge substructure
2) Determination of target displacements based on target strain, curvature or ductility limits and modal shapes (Dwairi and Kowalsky, 2006).
3) Determination of Equivalent Viscous Damping EVD based on ductility demands at the target displacements (Dwari et al, 2005; Suarez and Kowalsky, 2006).
4) Determination of required stiffness and strengths using displacement design spectra
5) Design of shear reinforcement and design of protected elements according to capacity design principles (Priestley and Calvi, 1996).

Seismic Design Criteria (SDC)

In the SDC by Caltrans, the displacement demands are estimated from a linear elastic response spectra analysis of the bridge with effective (secant to yield point) component stiffness. The procedure checks that the displacement demand of all individual components is less than their displacement capacity. Application of this procedure requires:

1) Initial sizing of bridge substructure including estimation of reinforcement
2) Determination of displacement demand by performing elastic response spectra analysis. The elastic displacement demand it is assumed equal to the inelastic displacement demand according to the Equal Displacement Approximation EDA (Veletsos and Newmark, 1960) for single-degree-of-freedom (SDOF) systems.
3) Determination of the displacement capacity for each individual component by performing nonlinear static “pushover” analysis.
4) Checking that displacement capacity exceeds displacement demand for all resisting members.
5) Design of shear reinforcement and design of protected elements according to capacity design principles.

SDC and DDBC are displacement-based in nature since they use displacements to quantify demand and capacity of the earthquake resisting elements. However, besides differences in their implementation that will be noted later in this paper, there is a fundamental difference on how demand is determined. In the SDC the bridge is modeled with at-yield member stiffness and the displacement demand is estimated using the EDA. The EDA also used in all Force-Based-Design procedures is applied without consideration of the substructure type or soil interaction effects. In DDBD the bridge is modeled with secant-member stiffness compatible with the target displacement profile and energy dissipation is accounted for using EVD.

Objectives of the study

This work aims to (1) compare the effectiveness of DDBD and SDC for the design of a sample of six ordinary bridges as defined by Caltrans and (2) investigate the items needed for improvement of current DBD practice emphasizing the determination of displacement demand, displacement capacity and soil-structure interaction effects. These objectives have been achieved by performing the following tasks:

1) Displacement ductility limits are investigated for column bents on rigid foundation and drilled shafts bents, based on a damage control curvature capacity of the section and P-D effects.
2) Six ordinary bridges are designed using SDC and DDBD. Alternately to the use of the EDA, the Substitute Structure Method SSM (Shibata and Sozen,1976) is also used to obtain the displacement demand.
3) Then, a set of earthquakes records that are compatible with the design spectrum are applied to each of the designed structures to verify its performance. Results are compared.

DISPLACEMENT DUCTILITY CAPACITY

SDC and DDBD require the designer to check that the displacement capacity of the substructure elements is higher than the displacement demand. Caltrans (1999) requires that ordinary bridges be designed to meet “Safety-evaluation” performance criteria: under the Maximum Considered Earthquake MCE, damage in the bridge would require closure to repair. Displacement capacity is restricted by damage that can be measured directly from strains in concrete or reinforced steel, or indirectly from section curvature, curvature ductility and member displacement ductility or drift. In addition to this, the displacement capacity might also be limited to avoid excessive moment magnification caused by P-Delta effects. In the SDC it is recommended that P-Delta moments at maximum displacement demand should be less that 20% of the flexural capacity of the column or drilled shaft section.

In DDBD, the amplitude of the target displacement profile is controlled by the damage in one or more substructure elements. The damage can be specified as strain or curvature but is converted to displacement ductility and top displacement using the plastic hinge method (Paulay and Priestley, 1993). For drilled shaft bents, the application of the plastic hinge method requires the definition of an equivalent model that accounts for soil-structure interaction effects (Suarez, 2006). A “damage control” curvature ϕ_c can be calculated for a RC circular section as a function of the axial load A_g, compressive strength f'_c, section area A_g and diameter D (Eq.1) (Kowalsky, 2000). This level of damage is compatible with the damage expected in the safety evaluation.

$$\phi_D = \left(0.068 - 0.068\left(\frac{P}{f_c^{'} A_g}\right)\right)\frac{1}{D} \qquad (1)$$

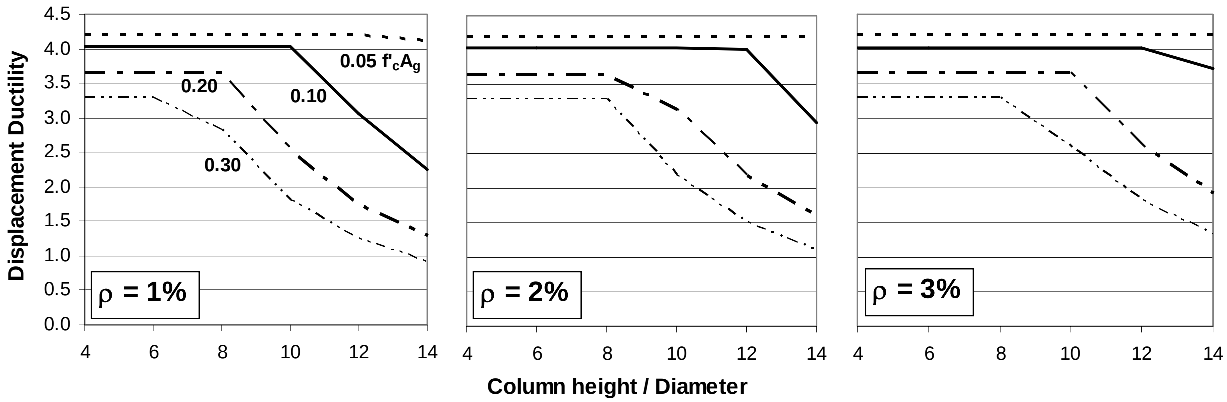


Figure 1. Displacement ductility capacity for column bents in rigid foundations assuming fixed head condition

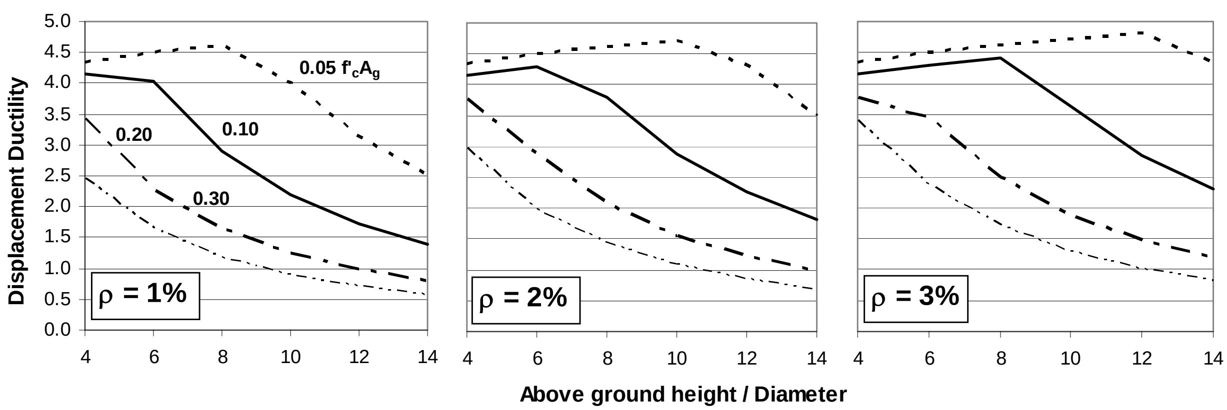


Figure 2. Displacement ductility capacity for drilled shaft bents assuming fixed head condition

Figures 1 and 2 have been prepared to show the maximum displacement ductility levels that can be sustained by column bents and drilled shaft bents without exceeding the damage curvature limit in the plastic hinges and without causing P-Delta moments higher than 20% of the flexural capacity of the column sections. The graphs consider three different reinforcement ratios, ρ, and four levels of axial load corresponding to 5%, 10%, 20% and 30% of $A_g f'_c$. Fig. 1 shows displacement ductility capacity as a function of the ratio between the column height and diameter for column bents on rigid foundations assuming that the top of the column displaces without rotation (fixed head contition). Fig. 2 shows displacement ductility capacity as a function of the ratio between the above ground height and diameter for drilled shaft bents with fixed heads, embedded in sand. Figures 1 and 2 were developed using plastic hinge method (Paulay and Priestley, 1993 ; Suarez 2006) where the response of the concrete sections was found from moment curvature analysis. The material properties are: f'_c= 28 MPA, Elastic modulus of concrete E_c= 24800 MPA, steel yield stress f_y = 450 MPA, effective friction angle of sand $\phi'=37^o$.

Figures 1 to 2 show the how the displacement capacity is affected by P-Delta effects. As the bents become more flexible, the yield displacement increases, and the ductility capacity can not be developed since P-Delta effects start to govern. This is especially critical for drilled shaft bents where the soil added flexibility increases the yield displacement up to a point where the displacement capacity is largely controlled by P-Delta effects.

BRIDGE DESIGN EXAMPLES

Six ordinary bridges were designed in the transverse direction following SDC and DDBD methods. The SSM was also investigated for determination of displacement demand as an alternative to the use of the equal displacement approximation in SDC. The bridges were designed to meet the safety-evaluation performance criteria (Caltrans, 1999) with a maximum credible earthquake of magnitude 7.25, peak base acceleration 0.7g and soil type C. The computer program SAP 2000 (CSI, 2003) was used in the design process to perform static and response spectrum analyses.

The superstructure for all bridges is a continuous reinforced concrete box girder. The moment of inertia in the strong axis is 100 m^4, the torsional constant is 7 m^3. The dead load including self weight of the superstructure is 200kN/m. Two types of substructure were considered: column bents on rigid foundation and drilled shaft bents. The columns bents supported by a rigid foundation were modeled as fixed at the ground level. The drilled shaft bents are embedded in sand with an effective friction angle $\phi' = 37^o$. The soil-structure interaction was accounted for by using an equivalent model (Suarez, 2006) in which the soil-column system is replaced by a column with an equivalent length that is fixed at its base. The equivalent column has the same section as the real column; however an inertia reduction factor is used in the stiffness calculations since it accounts for the rotation that exists in the soil-column system at the assumed point of fixity. The elastic modulus of concrete is 24800 MPA, the compressive strength is 28 MPA. The yield strength of the reinforced steel is 450 MPA. Details specific to each bridge are:

BR-7-14-21: (Fig. 4): This Bridge has four spans of 50m and has three column bents on a rigid foundation. The bents have 3 circular RC columns and the cap beam is built integral to the superstructure. Going from left to right, the first bent is 7m tall, the second if 14m tall and the third is 21m tall.

BR-7-14-21-DS: (Fig. 4): Similar to bridge BR-7-14-21 but it is supported on drilled shaft bents.

BR-7-14-7: (Fig 4): Similar to bridge BR-7-14-21 but, going from left to right; the first bent is 7m tall, the second if 14m tall and the third is 7m tall.

BR-7-14-7-DS: (Fig. 4): Similar to bridge BR-7-14-7 but it is supported on drilled shaft bents

BR-14-14-7-7: (Fig. 5): This bridge frame has three spans of 50m and it is supported on four column bents on a rigid foundation. The bents have 2 circular RC columns and the cap beam is built integral to the superstructure. Going from left to right, the first and second bents are 14m tall, and the third and fourth are 7m tall. The super structure has a slope of 4%. Interaction with other frames or abutments is not considered.

BR-14-14-7-7-C: (Fig. 5): This bridge frame is similar to BR-14-14-7-7 but the superstructure is curved with a subtended angle of 90^o.

Bridges BR-7-14-21, BR-7-14-21-DS, BR-7-14-7 and BR-7-14-7-DS have seat type abutments. It is assumed that the shear keys do not have enough capacity to transfer the lateral forces generated during the MCE event. For design purposes, a lateral stiffness equal to half of the lateral stiffness of the adjacent bent was assigned to the abutments following the recommendations in SDC section seven (Caltrans, 2004).

Application of DBD methods

The SDC was applied to each of the bridges as shown in a flowchart in the appendix. An initial estimate of the cracked section stiffness was taken from SDC (2004). For comparison, the displacement demand was also determined using the SSM (Shibata and Sozen, 1976) (see flowchart in appendix). This approach is iterative and requires de evaluation of the secant stiffness and equivalent viscous damping for the columns or drilled shafts. The effective stiffness is a function of an initial/cracked stiffness and displacement ductility demand. However, the initial stiffness is related to the amount of reinforcement and axial load on the section, therefore the SSM, as well as the SDC, requires an initial assumption of the reinforcement in the columns of shafts. The equivalent viscous damping as a function of the ductility demand is presented in Fig. 3 for columns on rigid foundations and for drilled shafts bents (Dwairi, 2005; Suarez, 2006). The equivalent damping was combined in proportion to the work done by each column

(Kowalsky, 2002) and a demand reduction factor for the structure at its effective period was found using (Eq. 2) (Eurocode 1988).

$$\beta = \sqrt{\frac{7}{2+\xi_{eq}}} \tag{2}$$

DDBD was applied following the recommendations of Dwari (2005) (See flowchart in appendix). The effective mode shape method (Kowalsky, 2002) was used to determine target displacement profiles. The design objective for DDBD and SDC was to design the structures to reach a target displacement ductility of four under the MCE design earthquake. Additionally, the maximum displacements should be controlled such that the generated P-Delta moments do not exceed 20% of the flexural capacity of the columns. The displacement ductility limit is recommended by ATC-32 and is in good agreement with values in Figures 1 and 2.

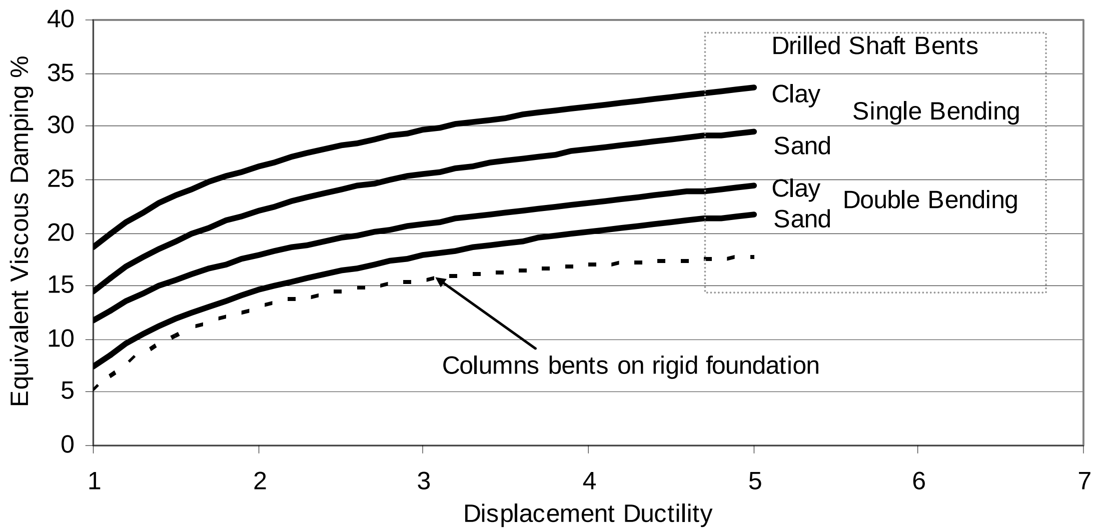


Figure 3. Equivalent viscous damping for RC columns and drilled shafts bents

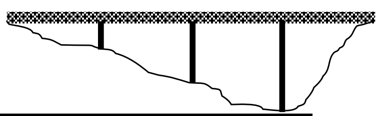
The design procedure for the curved bridge was different. The response spectrum analysis was conducted with two components of excitation acting perpendicular. The modal combination was done using the CQC rule, as in the other bridges, and the directional combination was done using the SRSS rule. The displacement demand was measured in the plane of each bent; therefore the displacement demand for all bents is not in the same direction.

Verification Analyses

Nonlinear Time History (NTH) analyses were performed to verify the performance of the designs that resulted of the application of SCD and DDBD. The computer program OpenSees (MacKenna et al, 2004) was used for this purpose. The superstructure was modeled using elastic frame elements. The columns were modeled with nonlinear beam-column elements to which the Hysteretic Bilinear section response model was assigned with pinching coefficients of 0.7 for curvature and 0.2 for moment. The yield curvature and yield moment was obtained from a separate moment curvature analysis of the RC sections as designed. In the bridge models with drilled shafts, the soil was idealized as a uniform layer of sand and the OpeenSees module PysimpleGen (Brandenberg,2004) was used to generate P-y elements along the embedded length of the column. The PySimple1 material model (Boulanger, 2003) was utilized to model the sand with properties to match the API P-y model for Sand (API, 1987).

A set of five earthquake records was applied to each bridge model. The records were made compatible with the design spectrum within periods ranging from the fundamental period to a period slightly longer that the effective period found using DDBD. The compatibility was achieved by using wavelet decomposition (Montejo, 2004). The maximum displacement assigned to each column or drilled shaft is the average of the maximum displacements recorded from each earthquake record. For the straight bridges the records were applied in the transverse direction. In the analysis of the curved bridge, the compatible records were applied in nine different directions with the purpose of capturing the maximum response .

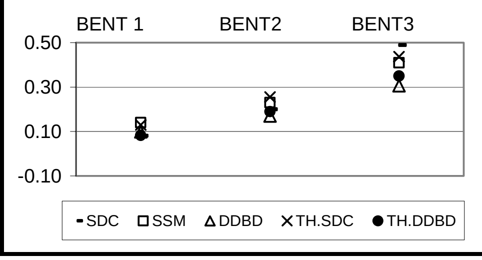
BR 7-14-21



ITEM	BENT 1	BENT 2	BENT 3
COLUMNS	3	3	3
HEIGHT	7	14	21
DIAMETER	1.5	1.5	1.5

FOUNDATION: RIGID

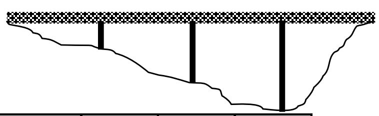
DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

SDC	BENT1	BENT2	BENT3
μ_Δ	0.82	0.51	0.56
P-delta	0.17	0.42	**1.02**
Steel	1.4%	1.4%	1.4%
DDBD	**BENT1**	**BENT2**	**BENT3**
μ_Δ	**1.00**	0.43	0.35
P-delta	0.18	0.30	0.55
Steel	1.8%	1.8%	1.8%

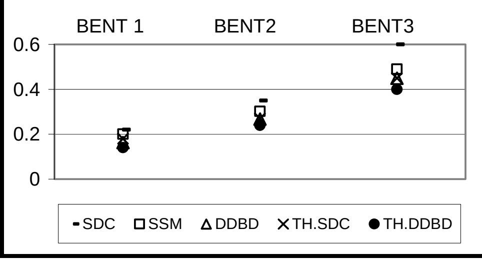
BR 7-14-21-DS



ITEM	BENT 1	BENT 2	BENT 3
COLUMNS	3	3	3
HEIGHT	7	14	21
DIAMETER	1.5	1.5	1.5

FOUNDATION: DRILLED SHAFT IN SAND

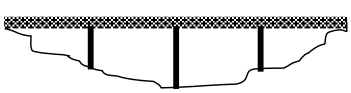
DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

SDC	BENT1	BENT2	BENT3
μ_Δ	0.77	0.56	0.56
P-delta	0.37	0.58	**1.00**
Steel	1.9%	1.9%	1.9%
DDBD	**BENT1**	**BENT2**	**BENT3**
μ_Δ	0.43	0.32	0.31
P-delta	0.36	0.60	**1.01**
Steel	1.3%	1.3%	1.3%

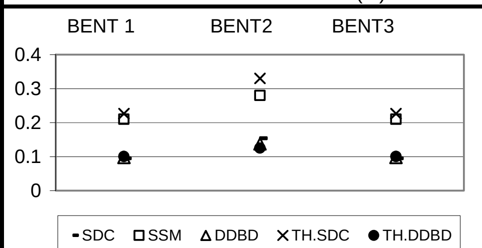
BR 7-14-7



ITEM	BENT 1	BENT 2	BENT 3
COLUMNS	3	3	3
HEIGHT	7	14	21
DIAMETER	1.5	1.5	1.5

FOUNDATION: RIGID

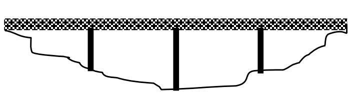
DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

SDC	BENT1	BENT2	BENT3
μ_Δ	**0.97**	0.39	0.97
P-delta	0.34	0.55	0.34
Steel	1.1%	1.1%	1.1%
DDBD	**BENT1**	**BENT2**	**BENT3**
μ_Δ	**1.00**	0.35	1.00
P-delta	0.15	0.22	0.15
Steel	3.1%	3.1%	3.1%

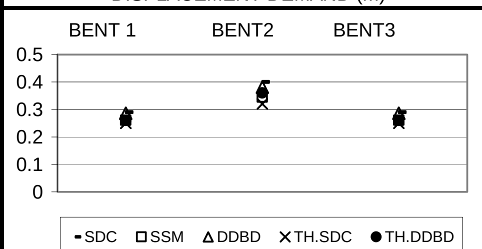
BR 7-14-7-DS



ITEM	BENT 1	BENT 2	BENT 3
COLUMNS	3	3	3
HEIGHT	7	14	21
DIAMETER	1.5	1.5	1.5

FOUNDATION: DRILLED SHAFT IN SAND

DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

CALTRANS	BENT1	BENT2	BENT3
μ_Δ	**1.01**	0.64	**1.01**
P-delta	0.54	0.74	0.54
Steel	9000	9000	9000
DDBD	**BENT1**	**BENT2**	**BENT3**
μ_Δ	**0.99**	0.61	**0.99**
P-delta	1.02	1.36	1.02
Steel	9600	9600	9600

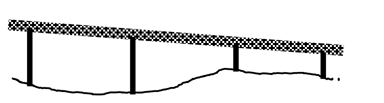
Figure 4. Summary of results for BR-7-14-21, BR-7-14-21-DS, BR-7-14-7 and BR-7-14-7-DS

Analysis of Results

Design results as well as verification results are summarized in Figures 4 and 5 for each of the 6 bridges considered the study. There are three columns in these figures, the first one shows the configuration of the bridges, the second shows the displacements predicted by the DBD methods and by the NTH analyses performed on the designed structures and the third column shows demand-capacity ratios and designed longitudinal steel ratios in the columns or drilled shafts. The charts showing displacements have five data series: **SDC**, contains the displacement demand predicted using the seismic design criteria. **SSM**, shows the displacement demand determined with the substitute structure method. **DDBD**, shows the target displacement profile used with direct displacement based design. **TH-SDC,** shows the displacements that resulted of the NTH analysis on the bridge design using SDC and **TH-DDBD,** shows the displacements that resulted of the NTH analysis on the bridge design using DDBD.

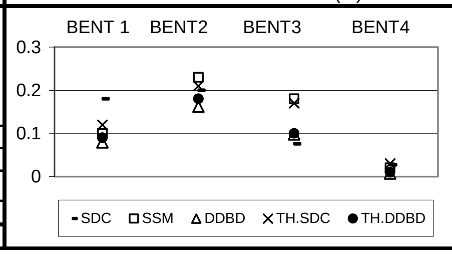
BR-7-14-21: The design using SDC was controlled by P-Delta effects on Bent 3. SDC over predicted the displacement demand at Bent 3 (SDC > TH-SDC). However, the displacement demand was under predicted at Bent 1 (SDC < TH-SDC) such that the displacement ductility demand limit of four is exceeded. The displacement demand found using the SSM is in good agreement with TH-SDC and shows that the displacement capacity of Bent 1 is exceeded if 1.4% steel is provided. The target displacement profile found in DDBD recognized Bent 1 as the critical element. To meet the displacement capacity of Bent 1 DDBD requires a stiffer and stronger bridge. DDBD displacement profile is in good agreement with TH-DDBD.

BR 14-14-7-7



ITEM	BENT 1	BENT 2	BENT 3	BENT 4
COLUMNS	1	1	1	1
HEIGHT	14	14	7	7
DIAMETER	1.5	1.5	1.5	1.5
FOUNDATION: RIGID				

DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

CALTRANS	BENT1	BENT2	BENT3	BENT 4
μ_Δ	0.48	0.57	**0.94**	0.33
P-delta	0.53	0.62	0.26	0.09
Steel	1%	1%	1%	1%

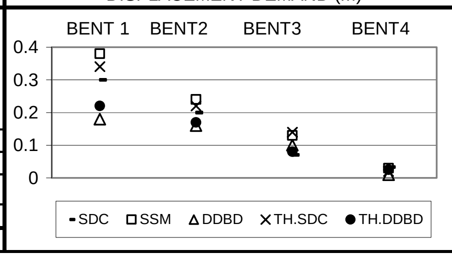
DDBD	BENT1	BENT2	BENT3	BENT 4
μ_Δ	0.20	0.41	**1.00**	0.10
P-delta	0.10	0.17	0.10	0.03
Steel	1%	3.20%	3.20%	1.00%

BR 14-14-7-7-C

CURVED BRIDGE $\theta = 90^o$

ITEM	BENT 1	BENT 2	BENT 3	BENT 4
COLUMNS	1	1	1	1
HEIGHT	14	14	7	7
DIAMETER	1.5	1.5	1.5	1.5
FOUNDATION: RIGID				

DISPLACEMENT DEMAND (m)



DEMAND/CAPACTITY RATIOS

CALTRANS	BENT1	BENT2	BENT3	BENT4
μ_Δ	**0.77**	0.51	0.71	0.34
P-delta	0.67	0.44	0.16	0.07
Steel	1%	1%	1%	1%

DDBD	BENT1	BENT2	BENT3	BENT4
μ_Δ	1.80	1.60	**4.00**	0.40
P-delta	0.87	0.85	0.16	0.08
Steel	3.1%	3.1%	3.1%	3.1%

Figure 5. Summary of results for BR-14-14-7-7 and BR-14-14-7-7-C

BR-7-14-21-DS: In SDC and DDBD the design is controlled by P-Delta effects in Bent 3. SDC seems to over predict the displacement demand (SDC > TH-SDC). SSM results are in good agreement with NTH analysis (SSM similar to TH-SDC). DDBD requires less reinforcement and the target displacements reasonably agree with TH-DDBD.

BR-7-14-7: The bridge is symmetric and the design is controlled by ductility capacity on Bents 1 and 3. SDC under predicts the displacement demand (SDC << TH-SDC). The fundamental period of this bridge is 0.7s and it is in the limit of equal displacement region of the spectrum. SSM shows to be effective to predict displacement demand and DDBD requires higher reinforcement levels to keep the displacement demand within the capacity limits.

BR-7-14-7-DS: This bridge is symmetrical and more flexible than the previous due to soil-structure interaction. The design was controlled by ductility capacity on Bents 1 and 3. Both procedures yield similar results and show good agreement with NTH analyses.

BR-14-14-7-7: In SDC and DDBD the design is controlled by Bent 3. However, SDC under predicts the demand and indicates that 1% reinforcement is enough in all columns. The SSM and TH-SDC show higher displacement with that column strength. DDBD was more accurate in predicting the displaced shape and required strength in the columns since the target displacement profile agrees with TH-DDBD

BR-14-14-7-7-C: The same observations as in BR-14-14-7-7

CONCLUSIONS

In all design examples, DDBD identified the element that controls the displacement capacity of the structure. The target displacement profile found with the effective mode shape method is in good agreement with the shape and amplitude of the displacement profile found with NTH analyses.

The SSM seems to render a displacement demand profile that agrees in shape and amplitude with results of NTH analyses. SSM could be used as an alternative method to determine displacement demand in SDC.

The displacement demand found using the equal displacement approximation, was not in good agreement with the NTH analyses in most cases but BR-7-14-7-DS which is symmetrical and more regular than the other bridges. It seems that this rule applied to bridges does not take into account that the stiffness distribution at yield is different to the stiffness distribution at maximum response. This is due to the different levels of ductility demand in the columns and affects the shape and amplitude of the displacement profile.

The SDC method was the most easy to apply, the SSM followed and the DDBD method was more time consuming due mainly to the number of iterations required to determine the target displacement profile. It is worth noting that for design in the longitudinal direction, DDBD is straight forward since the target displacement profile is found without modal analysis. If P-Delta effects are found to control, all methods become more time consuming since more iterations are required to satisfy the imposed displacement limits.

The number of bridges considered was too small as to study the effectiveness of the methods to address soil structure interaction effects. Future research should focus on this matter as well as on other items such as abutments, pinned connections, single column drilled shaft bents, directional effects and skew angles.

Future research should also focus on improving the determination of displacement demand. With the small sample of bridges considered in this study and according to NTH results, it seems that using secant member stiffness and EVD is more effective to find the displacement demand. However, more research is needed to study EVD combination considering the effects of the energy stored in the superstructure.

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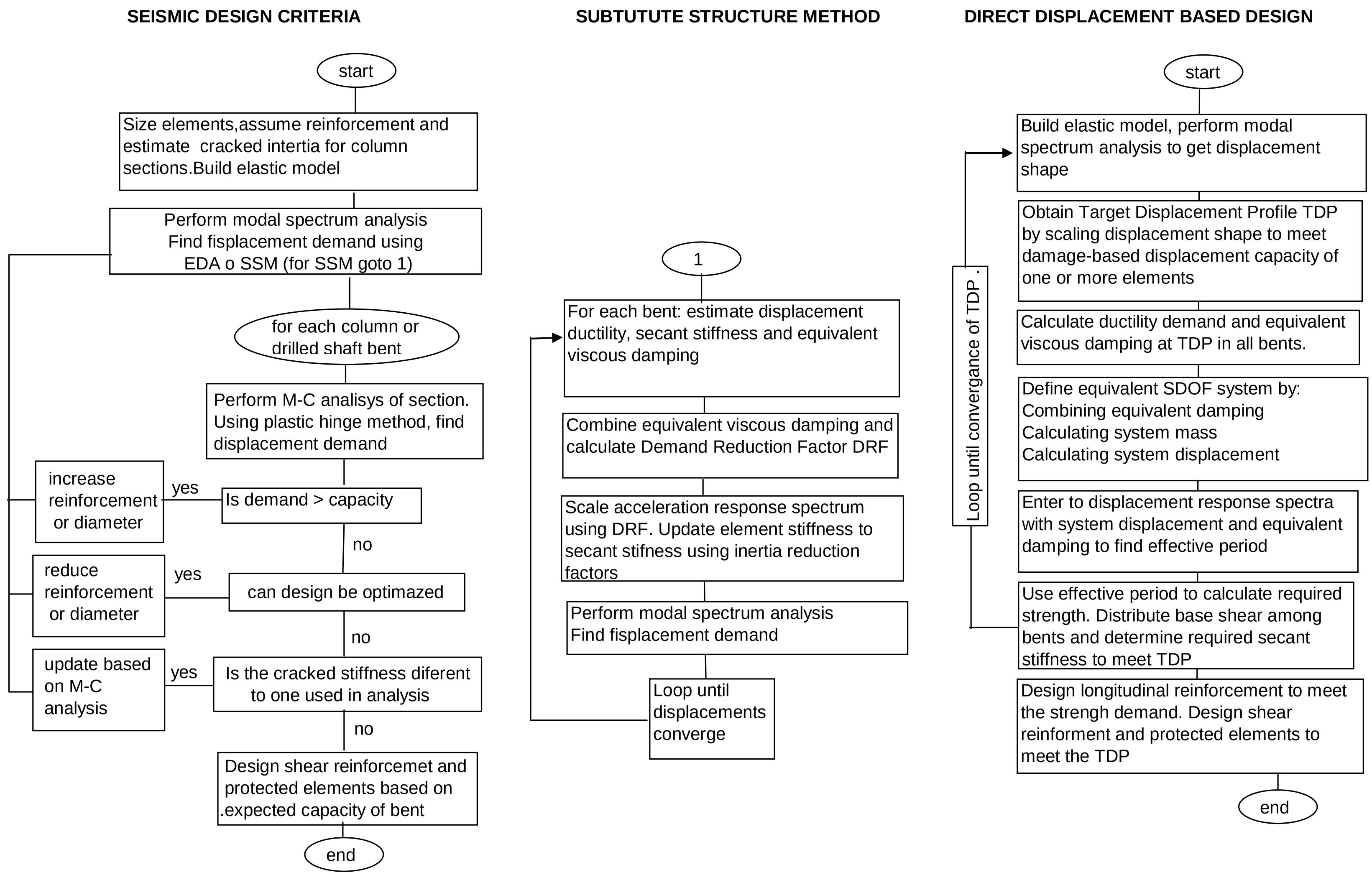

Figure 2. Flow charts for design procedures