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INFLUENCE OF RESPONSE SPECTRA DEFINITIONS ON THE BIDIRECTIONAL SEISMIC BEHAVIOR OF RC BRIDGE COLUMNS

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Abstract

In recent years, some researchers have debated over the appropriate definition for the representation of earthquake demand to be used in the design of structures. Design spectra are based on the two horizontal components of the earthquake motion recorded by sensors and are currently generated using the RotDnn spectra definition, where "nn" refers to the percentile of the response. This definition is independent of the in-situ sensor orientation and does not make use of geometric means in its calculation. In this manner, the commonly used definitions are RotD50, 50th percentile or median, and RotD100, 100th percentile or maximum. The NGA-West2 research project ground motion prediction equations (GMPEs) were based on RotD50 and are the basis for the development of the USGS design maps. However, building codes have recently moved to using the maximum spectra definition (RotD100) in design and concerns have been raised regarding this decision. Furthermore, the bridge engineering community is updating hazard maps and decisions on spectral definition are being delayed due to a lack of understanding regarding the implications. RotD100 response may occur in different orientations at any given period, making it very unlikely that a single orientation of ground motion will have a response as large as the maximum spectra at all periods, which may lead to overly conservative estimates of structural demand. Unlike previous research that has focused on the relationship between the two response spectra definitions, this study aims to evaluate the RotD50 and the RotD100 definitions by using the Direct Displacement-Based Design (DDBD) approach to design SDOF RC circular columns that are then subsequently analyzed via nonlinear time history analysis. A suite of unscaled real acceleration records were used in the design and verification of the SDOF bridge systems. Ground motion data was obtained from two sources: the Pacific Earthquake Engineering Research Center (PEER) NGA-West2 database and the Center for Engineering Strong Motion Data (CESMD). Findings are presented as the ratio of the non-linear time history analysis displacement to that expected from DDBD as a function of period for the two definitions of spectra. The results confirm that the RotD100 definition is more appropriate in the design of SDOF systems while also providing the first known verification of DDBD for bidirectional loading. On average, SDOF RC circular columns designed to the maximum hazard definition, RotD100, show 6% less deformation in the non-linear time history analysis than is expected from DDBD; while those designed to the median hazard definition, RotD50, show deformations 24% greater than expected from DDBD. It is expected that these findings will help deepen the understanding of how directionality impacts structural design.

Keywords: response spectra; SDOF bridge systems; bidirectional response; earthquake loading; displacement-based design

1. Introduction

As the bridge engineering community transitions to performance-based earthquake engineering, it is worth recognizing the critical role of ground motion directionality and how this is represented in design practice. At a particular station, triaxial accelerometers record ground motion accelerations in three orthogonal directions, two in the horizontal plane and one in the vertical. The azimuths of the horizontal sensors are arbitrary. The intensity of ground shaking is not uniform across different orientations. As such, the ground motion models used in the development of the U.S. seismic hazard maps are based on a chosen rotation dependent measure for quantifying the response spectra. Design spectra considers the two horizontal components of the earthquake motion and are currently generated using RotDnn measure [1], where "nn" refers to the percentile of the maximum response across all possible angles or directions of the ground motion. The currently used definitions of this measure are RotD50, 50th percentile or median response, and RotD100, 100th percentile or maximum response.

In recent years, some researchers have debated over the appropriate definition, RotD50 or RotD100, for the representation of earthquake demand to be used in the design of structures. Using factors to convert the median spectra definition to the maximum spectra definition [2], the building community has moved to incorporate RotD100 spectra in their codes, which has raised concerns [3]. For instance, the principal axes of

typical buildings would not both align with the maximum direction during an earthquake. The RotD100 response may occur in different orientations at any given period, making it very unlikely that a single orientation of ground motion will have a response as large as the maximum spectra at all periods, which may lead to overly conservative estimates of structural demand. Only single-degree-of-freedom (SDOF) structural systems would not have preferred directions of response while having the same dynamic properties in all possible horizontal directions, while multiple-degree-of-freedom (MDOF) systems can have varying dynamic properties depending on their principal axes. Furthermore, the bridge engineering community is updating hazard maps and decisions on spectral definition are being delayed due to a lack of understanding regarding the implications in analysis and design of bridge structures. Due to this, further investigation is necessary to be able to reach a consensus.

A systematic computational analysis of the two response spectra definitions is presented as the first step towards understanding their impact in earthquake structural design. For this study, the Direct Displacement-Based Design (DDBD) method [4] is used for the seismic design of the SDOF bridge columns. Historically, seismic design has been done with a focus on forces and the corresponding strength of the structure. However, shortcomings inherent to the force-based method have been recognized, such as not accounting for the interdependency of strength and stiffness, and using the equal-displacement approximation in the definition of ductility capacity [4]. The objective of the DDBD approach is to determine the required strength a structure needs to achieve a chosen displacement level under a prescribed seismic hazard that is represented by a displacement response spectrum. The approach uses a calculated value for secant stiffness, while force-based methods use initial stiffness, and it characterizes the energy dissipation capacity and ductility of a structure by equivalent viscous damping relationships.

The objectives of this research are to evaluate the impact of the RotD50 and RotD100 spectra definitions in the design on RC bridge systems, as well as provide verification of the DDBD approach for bidirectional loading.

2. Design of SDOF Bridge Columns using the DDBD Method

2.1 Generation of RotDnn Response Spectra

A suite of 60 pairs of unscaled real acceleration records were selected from the NGA-West2 database [5] and the Center for Engineering Strong Motion Data (CESMD) to be used in the design of the SDOF bridge systems. This suite is composed of shallow crustal regime records with moment magnitudes ranging from 6 to 8. For each pair of acceleration records, the bidirectional response spectra is generated based on the RotDnn measure, where "nn" refers to the percentile of the response [1]. This measure is independent of the in-situ sensor orientation and does not make use of geometric means in its calculation. The median response, or 50th percentile, and the maximum response, or 100th percentile, are the definitions currently adopted by U.S. codes. Nonetheless, it is worth noting that the RotDnn measure has the characteristic of being able to define any percentile of the response beyond just the median and maximum. In this paper, these two percentiles will be referred to as the two response spectra definitions: RotD50 and RotD100. In addition, given the nature of the design approach, which uses the DDBD methodology [4], the response spectra shown from this moment forward will be displacement spectra.

For one oscillator with a corresponding period of vibration, the response time series $a_{ROT}(t;\theta)$ can be computed for a range of azimuths at a rotation angle (θ) increment following Eq. (1) [1]:

$$a_{ROT}(t;\theta) = a_1(t)cos(\theta) + a_2(t)sin(\theta) \qquad (1)$$

Where $a_1(t)$ and $a_2(t)$ are the original pair of horizontal acceleration time series. This procedure can be repeated for all possible oscillators and all non-redundant angles (0° to 180°) at a chosen angle increment, as shown in Fig. 1 . (1For a single period, the response varies depending on the orientation, and the maximum response does not occur at the same orientation for all oscillators' periods. Following this procedure, (1Table 1 summarizes the displacement responses for three SDOF systems obtained for a pair of records from the 2011 Christchurch earthquake with Record Sequence Number (RSN) 8099 from the PEER Database. Sorting the

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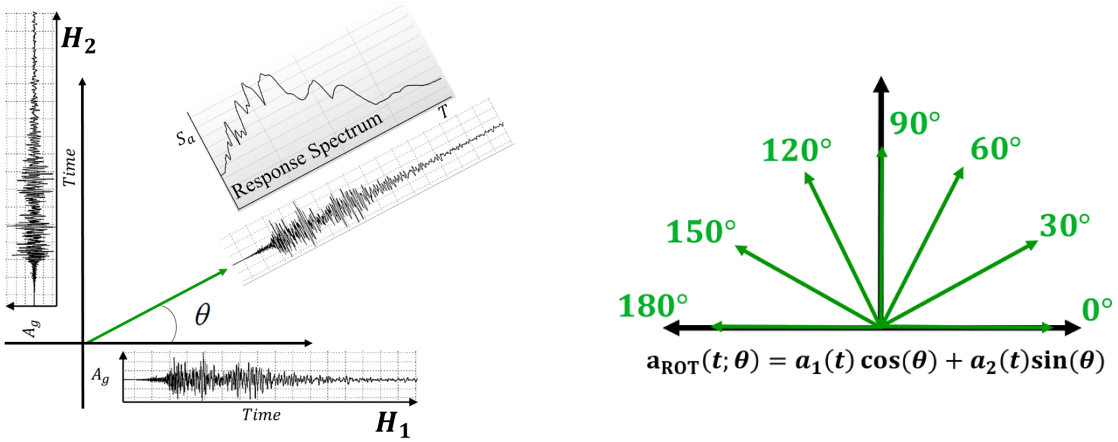
displacement response from lowest to highest at each period (right side of Table 1), allows the identification of the percentile (nnth) that defines the measure of ground motion for that oscillator's period.



(a) Combination of a pair of orthogonal as-recorded acceleration time series

(b) Range of azimuths with an angle increment of $\Delta\theta = 30°$

Fig. 1 – Computation of bidirectional response at rotation angle increments.

The minimum response, or RotD00, corresponds to the lowest values of response (pink), the median response, or RotD50, to the values at the 50th percentile, and the maximum response (blue), RotD100, to the maximum values (red). Fig. 2 shows the possible range of displacement response for these three fundamental periods under a pair of ground motion records (RSN8099).

Table 1 – Displacement response for three oscillators with periods 1, 2, and 3 seconds for the seven chosen azimuths at 30° increments.

Displacement Response [mm]					Sorted Response [mm]		
θ [°]	T = 1s	T = 2s	T = 3s		T = 1s	T = 2s	T = 3s
0	41.55	125.62	105.83		35.23	69.27	75.83
30	43.69	141.77	120.79		36.18	97.07	76.5
60	43.61	151.66	104.90		41.55	123.61	81.67
90	45.02	123.61	76.50		**41.55**	**125.62**	**104.9**
120	36.18	69.27	75.83		43.61	125.62	105.83
150	35.23	97.07	81.67		43.69	141.77	105.83
180	41.55	125.62	105.83		**45.02**	**151.66**	**120.79**

The displacement spectra of records from the 2011 Christchurch earthquake (RSN8099), and the 1992 Landers earthquake (RSN879), given by the two individual as-recorded horizontal components, SD1 and SD2, and the two definitions, RotD50 and RotD100 is shown in Fig. 3 considering a wider range of periods (1 to 5 seconds at $\Delta T = 0.02s$) and smaller rotation angle increment ($\Delta\theta = 10°$). For both records, it can be observed that the combined displacement response given by the maximum definition, RotD100, is greater than the rest, while the RotD50 response lies in between the responses given by the two individual components, as expected. For the Landers record, the SD1 (individual component) signal is more dominant in the RotD100 response across the period range shown (See Fig. 3 In contrast, for the Christchurch record each of the individual signals are dominant in the RotD100 response at different period ranges.

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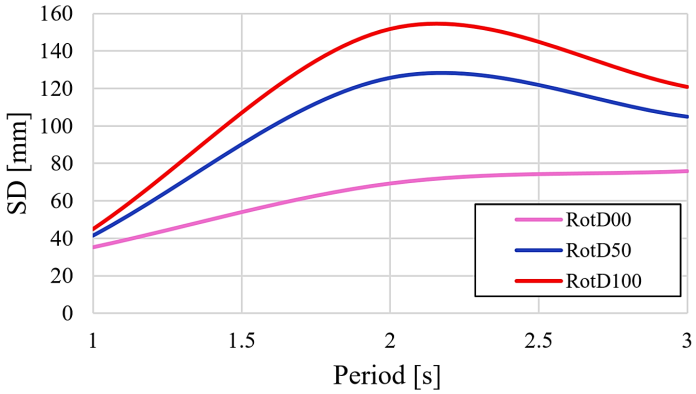
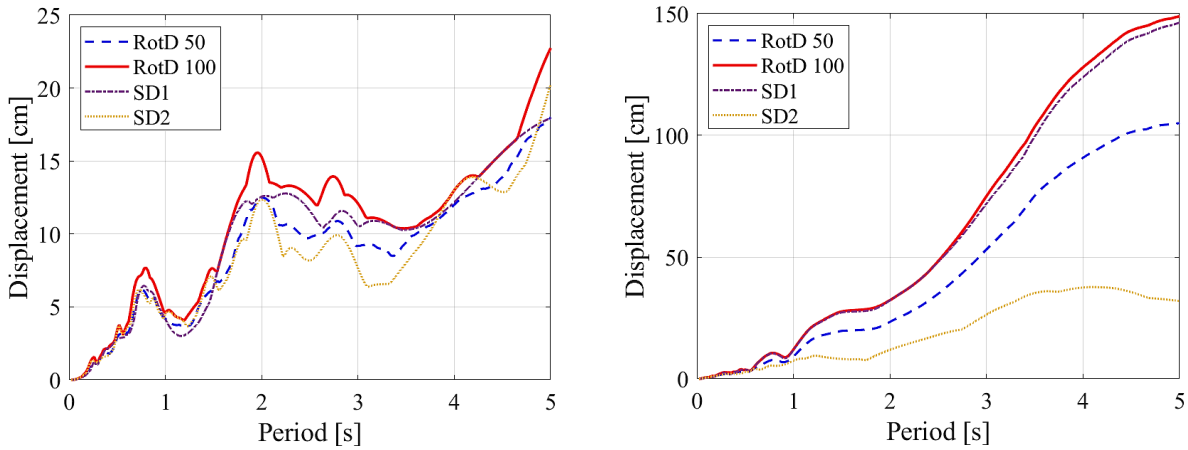


Fig. 2 – RotDnn displacement response spectra at 00th, 50th, and 100th percentiles for three oscillators.



(a) Response spectra for 2011 Christchurch earthquake at Kaipoi North School (RSN8099)

(b) Response spectra for 1992 Landers earthquake at Lucerne Station (RSN879)

Fig. 3 – Displacement response spectra ($\xi = 5\%$) for each individual as-recorded component, SD1 and SD2, and for the median and maximum definition, RotD50 and RotD100.

2.2 Design Approach

The DDBD approach [4] aims to determine the required strength a structure must possess to achieve a chosen displacement level under a prescribed seismic hazard that is represented by a displacement response spectrum. This design approach has been shown to compare well with nonlinear time history analyses (NLTHA) for seismic loading in one direction as numerous validation studies have been conducted under those conditions [4]. The research described in this paper is the first known bidirectional study on DDBD. The two response spectra definitions, RotD50 and RotD100, were evaluated by designing SDOF RC circular columns based on each spectra definition, and comparing their expected design performance (Δ_t) to the corresponding performance given by the bidirectional NLTHA.

The SDOF structures are reinforced concrete (RC) circular columns. For each of the 60 pairs of as-recorded motions, the displacement spectra was generated by solving the equation of motion with the Duhamel integral for periods up to 5s for seven damping ratios (ξ) at corresponding ductility (μ) levels ranging from $\mu = 1$ to $\mu = 8$, as characterized by the damping ductility relationship for bridge structures shown in Eq.(2)[4].

$$\xi = 0.05 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right) \qquad (2)$$

The damping ductility relationship for bridge structures [4] used in design is compatible with the modified Takeda degrading stiffness model [6]. This hysteretic model is represented in Ruaumoko3D [7] with constants (α & β) that allow the modification of the hysteretic shape. In this case, the Takeda Thin (TT)

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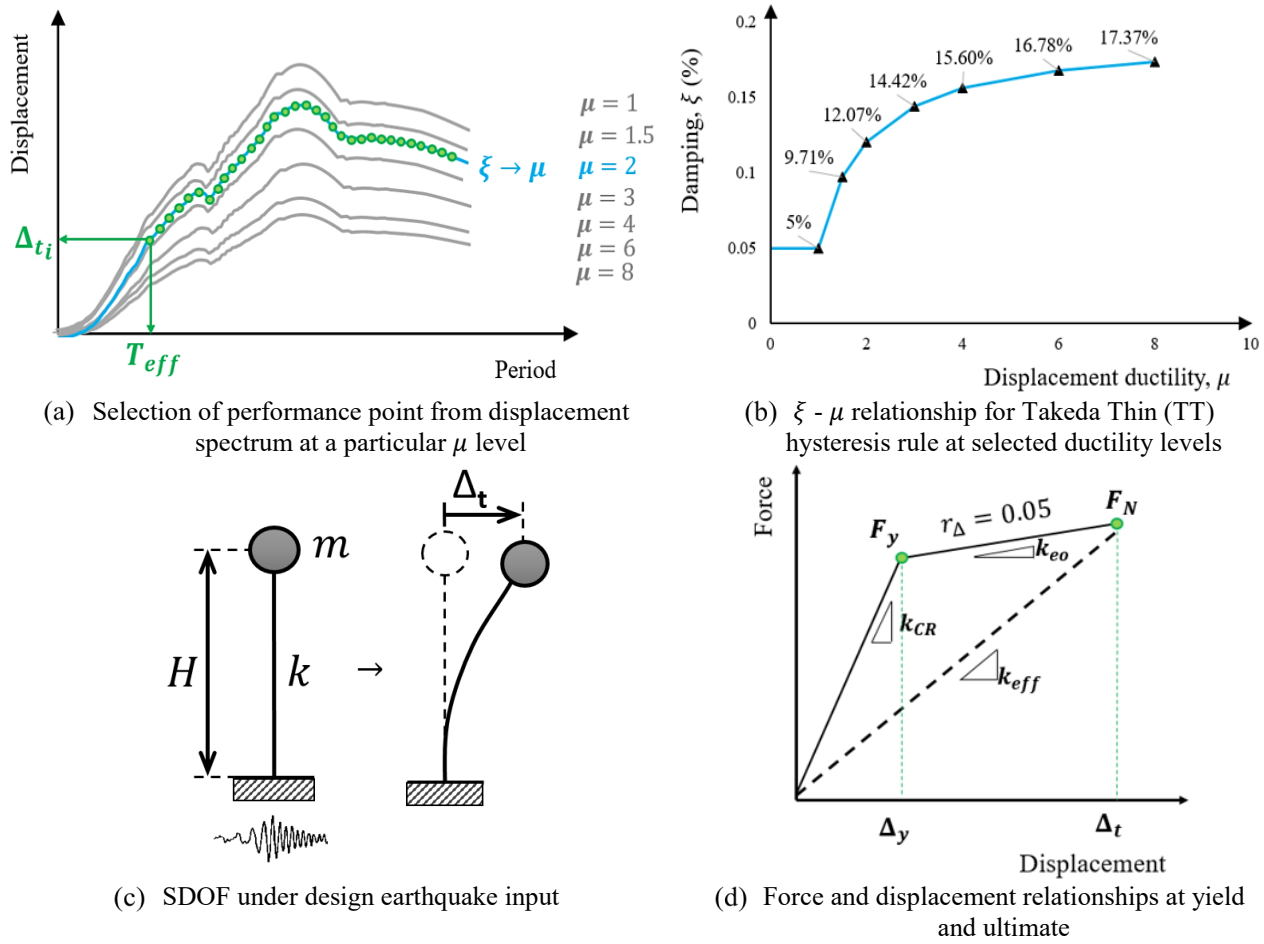
hysteretic model ($\alpha = 0, \beta = 0.5$) results in the thinnest possible shape and was chosen as typical energy dissipation for RC bridge columns.

The target displacement (Δ_t) can be identified as any point along the curve with its corresponding effective period (T_{eff}) for a particular response spectrum at a specific damping ratio (Fig. 4a). Given that the target displacement and ductility level is known, the yield displacement (Δ_y) for that performance point can be obtained as the ratio of Δ_t to the corresponding value of μ (Fig. 4b).



(a) Selection of performance point from displacement spectrum at a particular μ level

(b) ξ - μ relationship for Takeda Thin (TT) hysteresis rule at selected ductility levels

(c) SDOF under design earthquake input

(d) Force and displacement relationships at yield and ultimate

Fig. 4 – Summary of complete application of DDBD method for the design of RC bridge columns.

Assuming single bending, if the height of the column is known, the equivalent yield curvature can be calculated in terms of the column height (H), ductility level (μ), and target displacement (Δ_t), as shown in Eq. (3). The weight ($W = m.g$) of the column can be obtained from Eq. (4) as a function of steel yield strain, concrete strength, and equivalent yield curvature based on analytical results of yield curvature for RC columns and assuming an axial load ratio of 10%.

$$\phi_y = \frac{3}{H^2}\left(\frac{\Delta_t}{\mu}\right) \quad \because \quad \Delta_y = \frac{\Delta_t}{\mu} = \frac{\phi_y H^2}{3} \tag{3}$$

$$W = 0.1\, f'_c \left[\frac{\pi}{4}\left(\frac{2.25\varepsilon_y}{\phi_y}\right)^2\right] \tag{4}$$

The DDBD approach can be followed to calculate the effective stiffness (k_{eff}) and the corresponding cracked section stiffness (k_{cr}) with Eq. (5) and Eq.(6), as shown in Fig. 4d. A bilinear factor (r_Δ) of 5% was assumed for the second slope of the force-displacement response for all columns.

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$$k_{eff} = \frac{4\pi^2 \cdot W}{g.T_{eff}^2} \quad (5)$$

$$k_{CR} = \frac{k_{eff} \cdot \mu}{(r_\Delta \mu - r_\Delta + 1)} \quad (6)$$

Likewise, the base shear and moment capacity are given by Eq. (7) and Eq. (8).

$$F_N = V_b = k_{eff} \cdot \Delta_t \quad (7)$$

$$M_b = V_b \cdot H \quad (8)$$

The previous series of steps can be followed for any performance point along a specific response spectrum (Fig. 4a), represented by either the RotD50 or RotD100 definition. For each ground motion pair, the design was conducted for 50 points (Δ_t) along each of the resultant 840 response spectrum curves, half of which were each spectra definition. This equals 21,000 RC columns designs for each RotD50 and RotD100.

3. Verification of the DDBD Method for Bidirectional Loading

3.1 Nonlinear Time History Analyses

NLTHA were performed using the program Ruaumoko3D [8] as a tool to subject each RC column design to the corresponding pair of as-recorded accelerations simultaneously to obtain its 3D response through the duration of the loading. Fig. 5 illustrates this with an idealized column as a one component Giberson Beam frame element with lumped mass at the top node (Y= H_{col}), which is free while the bottom node (Y=0) is fixed. The structure is then subjected to the pair of as-recorded motions and the top node is free to displace in any direction. The maximum displacement (Δ_{max}) of the RC column is identified as the maximum distance between the top node and the point of origin (X = 0, Z = 0).

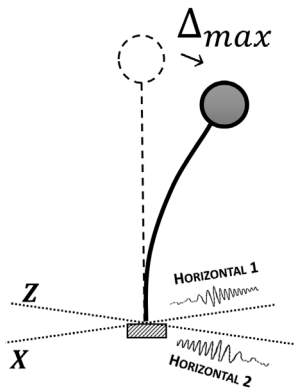

Fig. 5 – Schematic of idealized RC column design under corresponding pair of as-recorded motions.

Other system properties necessary for input in the NLTHA, such as the moment-curvature bilinear factor and plastic hinge length were taken into consideration as well [9]. The damping was modelled using tangent stiffness proportional Rayleigh damping, where the damping matrix is established using secant stiffness and the mass proportional term is removed. For all columns, the analyses were done using the modified Takeda degrading stiffness hysteresis rule [7], which is compatible with design assumptions mentioned in section 2.2.

In this manner, the NLTHA were performed for each RC circular column designed previously (as described in section 2) by subjecting it to the actual ground motion pair used in the generation of the response spectrum (RotD50 or RotD100). This allowed the comparison of the expected maximum displacement (Δ_t) and the maximum displacement given by the NLTHA (Δ_{max}) as a displacement ratio of the maximum to the target displacement (Δ_{max}/Δ_t). If this ratio is equal to one, it indicates that the intended performance was achieved as verified with the NLTHA. If the displacement ratio is above one, the structure sustained deformations larger that intended. On the contrary, if the displacement ratio is below one, the structure did not achieve the target design displacement, and it can be considered a conservative design.

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3.2 NLTHA response of four RC Bridge Columns

As described in section 2, for each spectra definition, the DDBD approach was followed using response spectra generated for 7 damping ratios corresponding to 7 ductility levels at a specific effective period. Fig. 6 depicts the 14 column designs designed to both definitions under response spectra from a 1992 Landers earthquake record (RSN879), for a specific $T_{eff} = 3s$ and their corresponding target displacement. To illustrate the different responses evaluated in terms of displacement ratios that can be obtained, the NLTHA results of four of these 14 RC columns are presented, specifically for two ductility levels ($\mu = 1, and\ \mu = 2$) with two columns designed using RotD50 spectra and two columns designed using RotD100 spectra.

The NLTHA results presented here for four completely different structures (see Fig. 7 and Fig. 8), except for the variables kept constant (i.e., column height). The comparison is focused on the ratio of the maximum displacement response (Δ_{max}) and the target displacement (Δ_T), and the observed behavior for each design separately. The progression of time of the response is depicted by the change in color from royal blue ($t = 0$) to yellow ($t = t_{final}$). The elastic behavior is constrained by the shaded grey areas in the plot of the top XZ trace, meaning that the column has yielded if its response is outside of this area. The displacement histories are presented as the coupled response (Square Root of the Sum of the Squares) of the displacements in the X and Z directions (Δ_x and Δ_z).

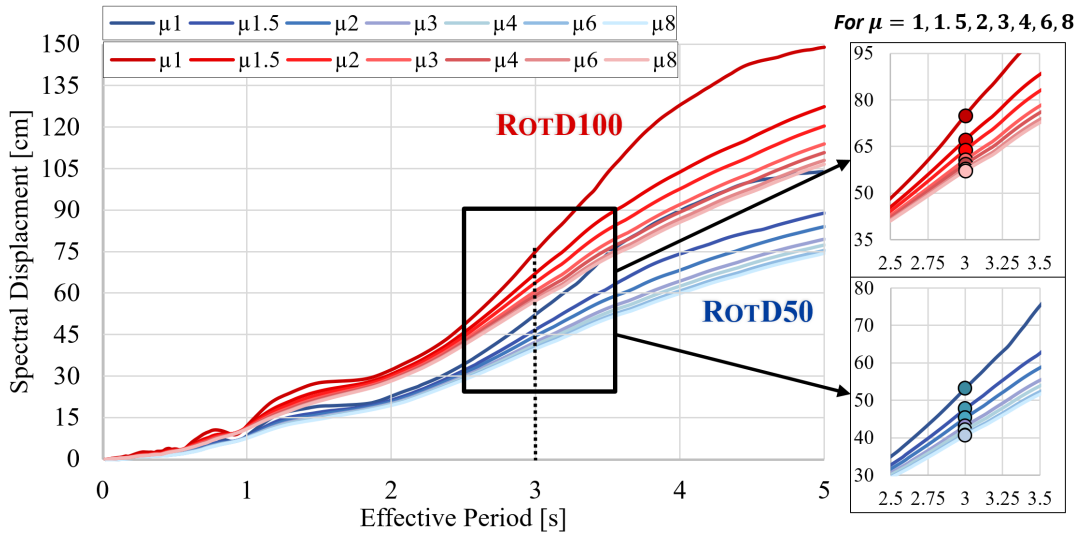

Fig. 6 – Target displacements at effective period equal to 3 seconds for RotD50 and RotD100 spectra across seven ductility levels. Spectra generated for the 1992 Landers earthquake record at the Lucerne station.

For a level of ductility equal to one ($\xi = 5\%$), the structure is considered to be elastic, meaning the top node of the column should go back to its initial position at the end of the dynamic loading without permanent deformation. As seen in Fig. 7abc, the previous statement holds true for an RC column designed using the maximum spectra definition, RotD100. Fig. 7a shows that the column, designed to the RotD100 response spectrum at ductility level 1 ($\xi = 5\%$), aligned with the critical direction of the motion and its maximum displacement (Δ_{max}) occurred in this direction (dashed line). The displacement ratio ($\Delta_{max}/\Delta_t = 752/751$) for this column was equal to 1.0. In contrast, Fig. 7def presents the NLTHA results for a column designed to ductility 1 but using a RotD50 response spectrum. This column does not have a completely elastic behavior, as indicated by the XZ trace of the top node (Fig. 7d), which does not return to the original position and goes outside the shaded area. In addition, the critical direction of its response is not as obvious as the one observed for the column designed using RotD100 spectrum. The displacement ratio ($\Delta_{max}/\Delta_t = 785/532$) for this column was equal to 1.48, which indicates the column sustained deformations 48% larger than the target. The force-displacement response (Fig. 7f) corroborates that this structure sustained permanent deformations, however small, most of which is focused in the X direction.

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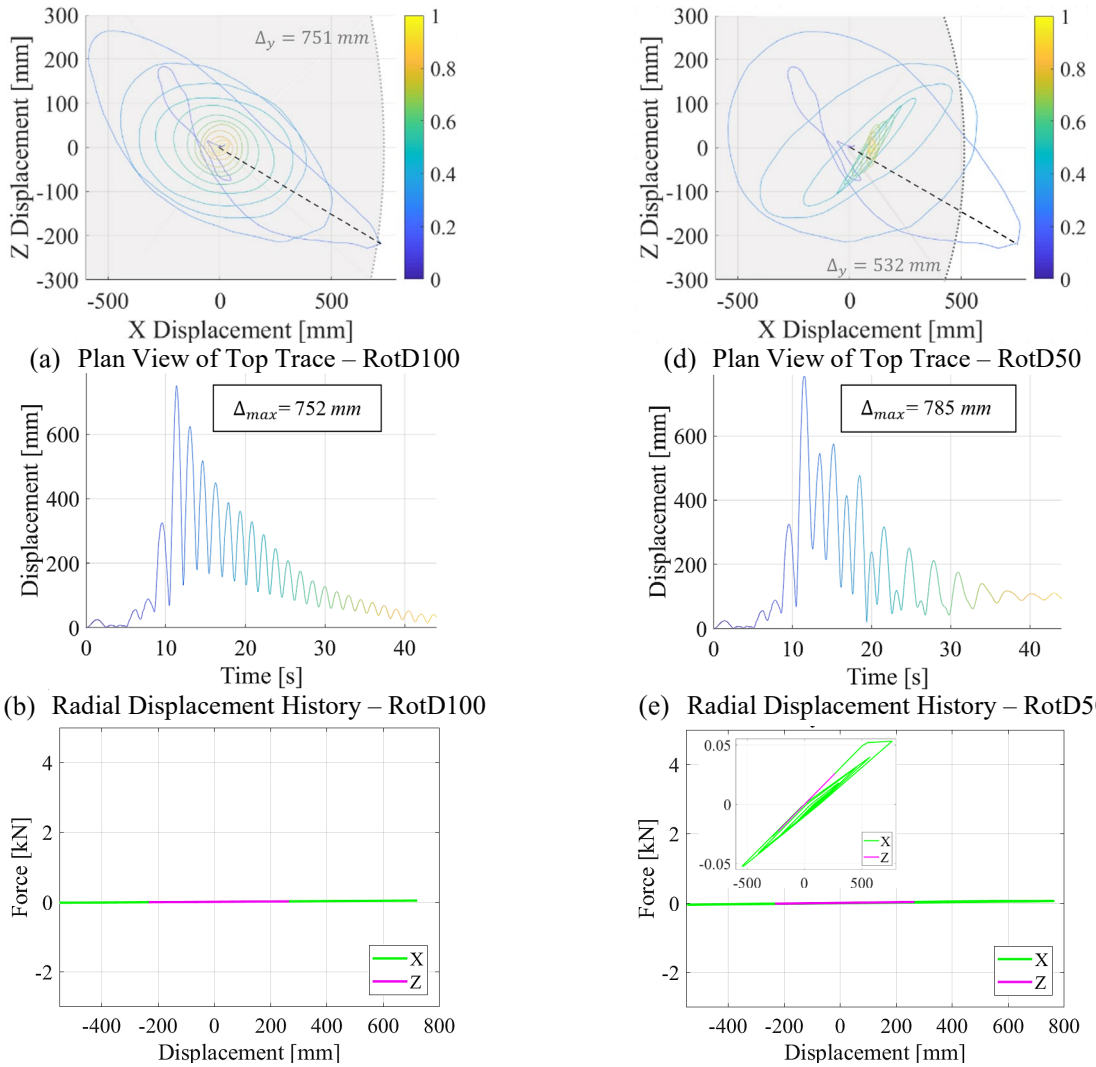

(a) Plan View of Top Trace – RotD100 (d) Plan View of Top Trace – RotD50

(b) Radial Displacement History – RotD100 (e) Radial Displacement History – RotD50

(c) Force-Displacement Response – RotD100 (f) Force-Displacement Response – RotD50

Fig. 7 – NLTHA results for two RC columns designed for RotD50 spectrum and RotD100 spectrum at $\mu = 1$

For a level of ductility of 2 ($\xi = 12.07\%$) the RC column designed to the RotD100 spectrum had a displacement ratio ($\Delta_{max}/\Delta_t = 377/638$) equal to 0.59, meaning that the structure sustained less displacement that it was expected in the design (Fig. 8abc). A hypothesis is that this "low ratio" is due to the structure's response not reaching the effective period (T_{eff}) and staying somewhere in between the elastic response, consistent with its fundamental period (T_n), and the target displacement. In addition, this column has some permanent deformation. On the other hand, the RC column designed to the RotD50 spectrum has a displacement ratio ($\Delta_{max}/\Delta_t = 442/453$) equal to 0.98, meaning it reached its target performance (Fig. 8def). This is unexpected since structures designed to RotD50 spectra, in general, tend to achieve displacements greater than their intended target.

Overall, for this sample of 14 RC columns [9], the displacement ratios for those designed to RotD100 spectra are observed to be at or below the target performance, making them conservative designs, while the majority of RC columns designed to RotD50 spectra exceed their target performance and are deemed to be non-conservative. Given that trends cannot be generalized by considering only one pair of recorded motions, this procedure was followed for the selected suite of 60 pairs of as-recorded motions with their corresponding response spectra at the seven ductility levels for the two spectra definitions, RotD50 and RotD100. Through the implementation of the NLTHA using the two components or pair of ground motion records, the DDBD method was validated for bidirectional loading.

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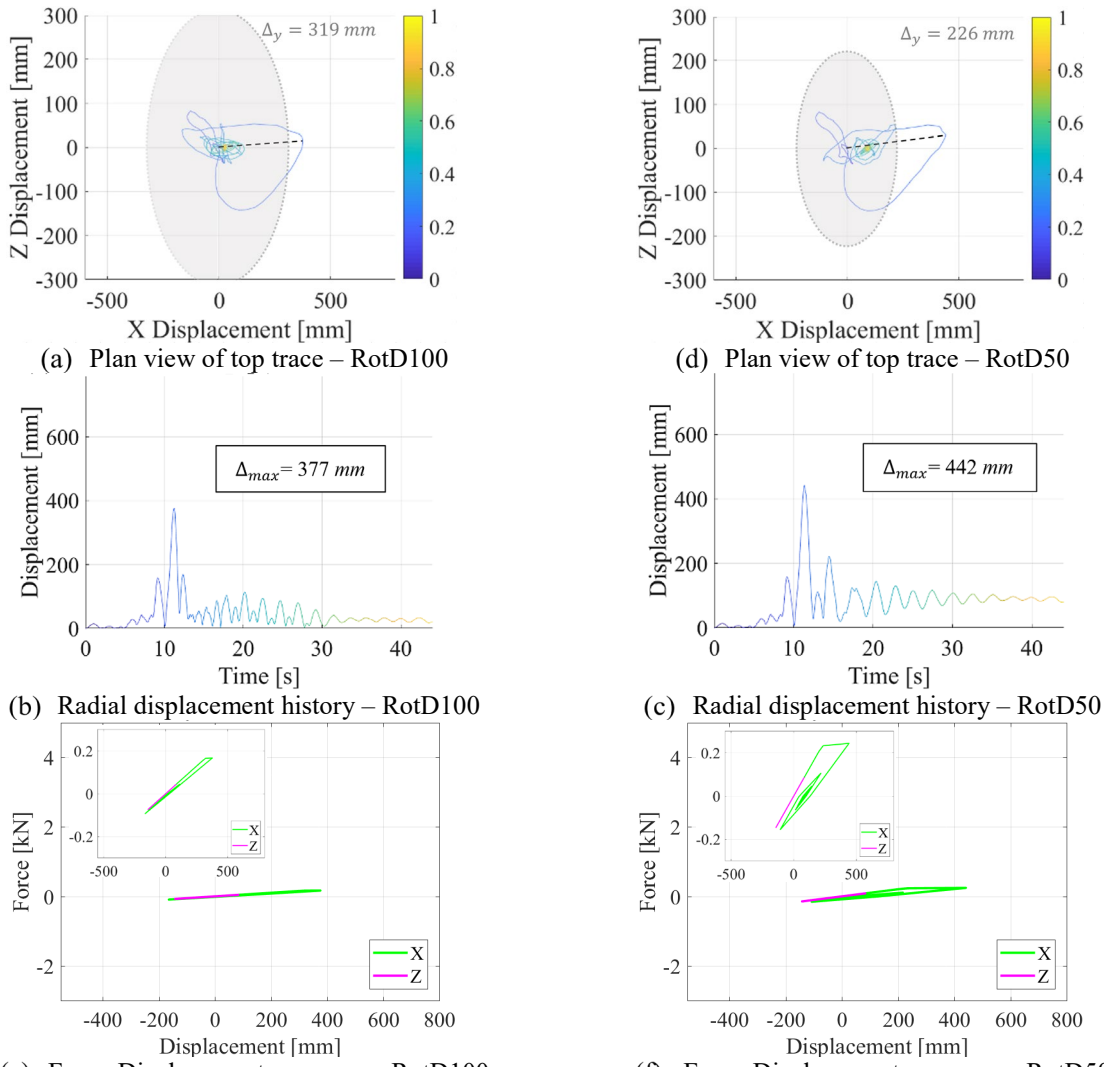

(a) Plan view of top trace – RotD100 (d) Plan view of top trace – RotD50

(b) Radial displacement history – RotD100 (c) Radial displacement history – RotD50

(c) Force-Displacement response – RotD100 (f) Force-Displacement response – RotD50

Fig. 8 – NLTHA results for two RC columns designed for RotD50 spectrum and RotD100 spectrum at $\mu = 2$

4. Evaluation of RotD50 and RotD100 definitions

Ground motion variability is observed in the displacement ratio results for the suite of the 60 records used in this study. The particular "shape" of the distribution of displacement ratios as a function of period and response spectra definition is unique to each ground motion record. This can be observed by comparing the results for the two records, RSN879 (Fig. 9) and RSN1231 (Fig. 9). Results are shown for seven ductility levels (μ = 1,1.5,2,3,4,6,8) with curves decreasing in color intensity as ductility level increases. For each definition, the mean of the ratios for all ductility levels across the period range (geometric mean of 350 columns) is shown, as well as the corresponding coefficient of variation (COV). For both records, the RotD100 displacement ratios for $\mu = 1$ are equal to one ($\Delta_{max}/\Delta_t = 1$) across the range of periods. This is expected given that the columns designed using the RotD100 spectra for this ductility level remain elastic. On the other hand, RotD50 displacement ratios at the same ductility level ($\mu = 1$) remain above one, indicating that for a ductility level of one the columns designed for RotD50 response spectra exceeded their intended performance ($\Delta_{max} > \Delta_t$). This trend is observed for all of the RC columns designed for a level of ductility 1, regardless of the ground motion record.

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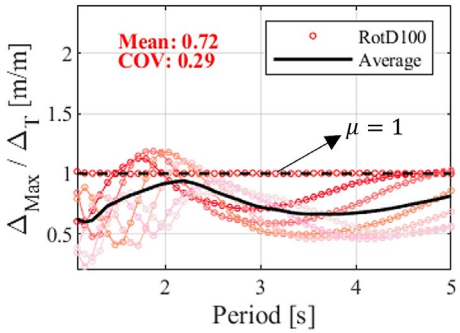
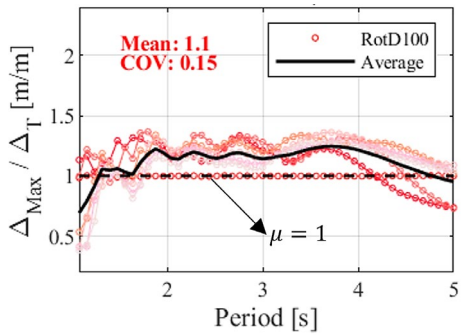
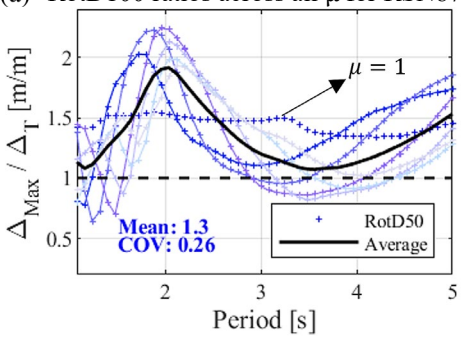


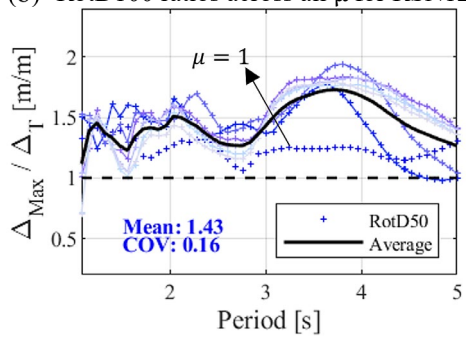
(a) RotD100 ratios across all μ for RSN879



(b) RotD100 ratios across all μ for RSN1231



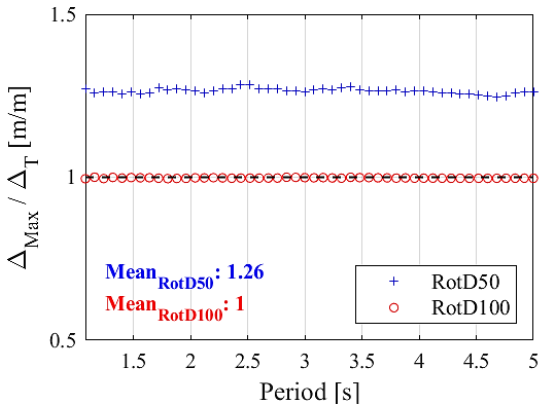
(c) RotD50 ratios across all μ for RSN879



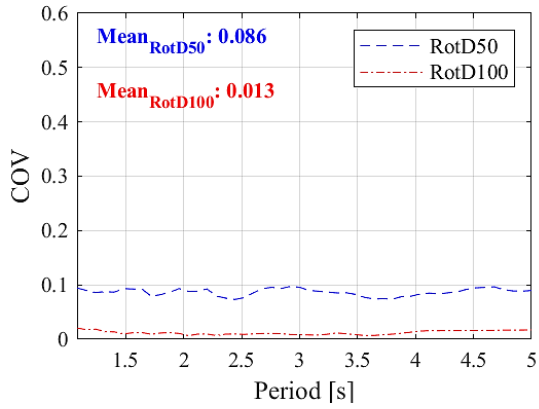
(d) RotD50 ratios across all μ for RSN1231

Fig. 9 – Displacement ratios for median and maximum spectra definition across all seven ductility level observed for the two records: 1992 Landers record (RSN879) and 1999 Chi Chi record (RSN1231).

Results across all analyses performed (60GM = 42,000 columns) confirm that designing structures to a ductility level equal to 1 should be done employing the maximum response spectrum definition (RotD100) because the structure will consistently achieve the intended design performance (Fig. 10). However, if a structure is designed to a $\mu = 1$ using the median response spectrum (RotD50), on average the response will exceed the target by 27%.



(a) Displacement ratios



(b) Coefficient of variation

Fig. 10 – Results for $\mu = 1$ as a function of period for the median (RotD50) and maximum (RotD100) response spectra definitions.

Fig. 11 presents the geometric means and coefficients of variation as a function of ductility level for both response spectra definitions, RotD50 and RotD100. After an initial increase at ductility of 1.5, the displacement ratios for both definitions for higher ductility levels ($2 \leq \mu \leq 8$) start to continuously decrease while their COVs increase. This decrease between ductility levels is more prominent for the RotD100 displacement ratios than for the RotD50 displacement ratios (Fig. 11). The highest variability is focused at ductility levels below 4, after which it appears to stabilize. The results verify that the DDBD method provides accurate estimates of performance for design of SDOF systems under bidirectional loading.

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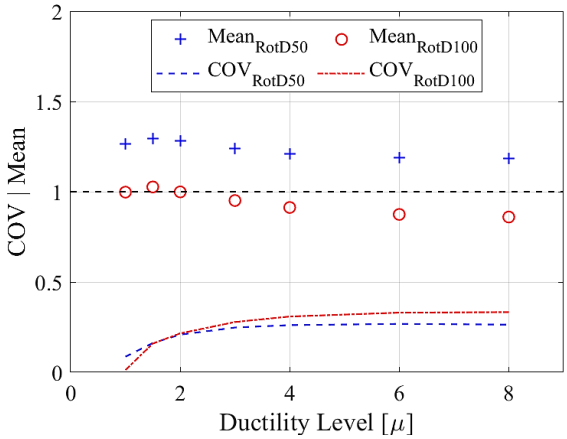
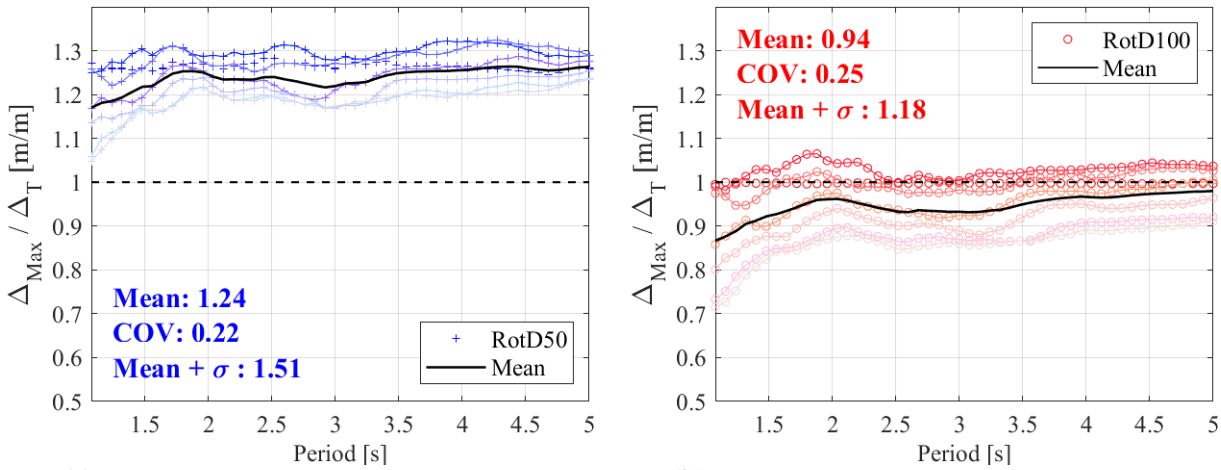


Fig. 11 – Geometric mean and coefficient of variation of the displacement ratios as a function of ductility level for the two response spectra definitions, RotD50 and RotD100.

Shown in Fig. 12 is the summary of all the displacement ratios observed for each ductility level, along with the average across all seven ductility levels (solid black line), for the two definitions of interest. Ductility level increase is identified by lightening of the color hue (blue for RotD50 and red for RotD100). Each point represents the mean displacement ratio of 60 RC columns, leading to 3,000 RC columns considered per ductility level, for a final total of 21,000 RC columns designed to each response spectra definition. From this illustration, the spread between ductility levels for each definition can be appreciated across the period range. For the median definition, the overall mean ratio (geometric mean across the period range) is 1.24 with a COV equal to 22%. Meanwhile, the maximum definition has an overall mean ratio of 0.94 with a COV equal to 25%. The upper bound of the ratios for each definition are shown in Fig. 12, with the displacement ratios having an upper limit equal to 1.51 and 1.18, for RotD50 and RotD100 respectively.



(a) Displacement ratios for median definition (b) Displacement ratios for maximum definition

Fig. 12 – Displacement ratios across all ductility levels for RotD50 and RotD100 definitions. Mean and coefficient of variation across periods for the 21,000 RC columns designed to each spectra definition.

Table 2 – Mean displacement ratios as a function of ductility level and response spectra definition.

	Mean		*Mean + σ*	
Ductility level	**RotD50**	**RotD100**	**RotD50**	**RotD100**
1	1.264	0.998	1.374	1.010
1.5	1.296	1.027	1.506	1.190
2	1.283	0.999	1.550	1.214
3	1.239	0.951	1.546	1.216
4	1.211	0.913	1.527	1.195
6	1.189	0.874	1.508	1.163
8	1.184	0.860	1.497	1.146

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The empirical distribution of the displacement ratios for both definitions fall under a normal distribution, with higher variability between ductility levels for the maximum spectra definition, RotD100. For both definitions, mean values of displacement ratios were obtained as a function of ductility level, and as a function of ductility level and effective period, as shown in Table 2. These ratios are suggested as factors to modify the estimated displacement response depending on which definition of spectra is used during design.

5. Conclusions and Recommendations

For designs of RC circular columns, it was observed that employing the median response spectra (RotD50) will, on average, result in maximum inelastic displacement responses that exceed the target displacement by 24%. In contrast, using the maximum response spectra (RotD100) will result in "conservative" designs, given that on average the maximum inelastic displacements sustained will remain below the target displacement by 6%. The displacement ratios found for RotD50 designs were always higher than for RotD100 designs of the same effective periods. For both definitions, mean displacement ratios were obtained as a function of ductility level, and as a function of ductility level and effective period. For both definitions, displacement ratios show a temporary increase with the first inelastic ductility level ($\mu = 1.5$) followed by decreasing ratios as the level of ductility increases. For design methods that use response spectrum as a tool, depending on the information available, the identified displacement ratios can be employed as factors to modify the expected or estimated displacement response to obtain a more accurate estimation of the displacement demand. Moreover, the DDBD approach is demonstrated to be adequate for design of SDOF systems under bidirectional loading because the maximum inelastic responses for RC circular columns are, on average, close to the RotD100 spectral displacement ordinates (or Δ_t), which in turn validates the use of displacement-based design approach in practice. While an assessment of variability is beyond the scope of this paper, it is recognized as a need and will be studied later. Considering a large number of ground motion records allowed for assessment of average responses, however, deeper exploration of variation for individual spectra is warranted, as opposed to simply attributing it to aleatory uncertainty of earthquake data. In addition, while this study applies to structures that can reasonably be represented as SDOF systems. The need to evaluate structures such as multi-span bridges, which are better described as MDOF systems, is recognized, especially in the transverse direction.

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7. References

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