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Quasi-static loading protocols for bridge piers considering different types of earthquakes

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ABSTRACT: Identifying the inelastic capacity of structures undergoing seismic loads is one of the main concerns in seismic structural design. One way to assess such capacity is through quasi-static cyclic testing programs, which are commonly used in civil engineering laboratories. In this study, an incremental dynamic analysis-based approach is introduced to develop quasi-static cyclic loading protocols for bridge piers considering crustal, intraplate and subduction earthquakes. Fiber modeling approach was implemented to represent the typical hysteretic characteristics of a bridge pier and to capture the demands peculiar of three different types different types of earthquakes. For the analysis, displacement ductility demand levels of two, four, and eight were taken as target demands. A direct relationship between inelastic cycles and structural damage was established, whereby the number of inelastic cycles and the cumulative ductility damage were considered as reference parameters to construct the loading protocols. It was found that crustal and intraplate earthquakes represent similar inelastic demands into the bridge pier, whereas those from subduction earthquakes are considerably different. The numerical procedure presented is a relatively simple approach that leads to develop accurate cyclic loading protocols for bridge piers that can also be implemented to develop loading protocols for different structural systems.

1 INTRODUCTION

In earthquake engineering, understanding the behavior of structural components has always been one of the major challenges. Regularly, structures are design for less than the actual seismic demands so they can deform inelastically and dissipate energy without loss of strength (i.e. damage but not collapse). Hence, enough protection is necessary and requires knowledge of the post-yield characteristics of the structural elements. It is a common practice in research and experimental studies to utilize quasi-static cyclic loading tests to evaluate the inelastic performance of structures. Here, the load is applied in a very slow, controlled and predetermined manner which allows relating specific structural measurements (e.g. displacement) to visual damage. Results from these kinds of tests have been utilized to establish current earthquake design procedures for structural components. Knowing about inelastic seismic performance during reverse cyclic loading (post-cracking and post-yielding stages), including strength and stiffness degradation, becomes crucial. Additionally, design codes, including modern bridge design codes (e.g. AASHTO 2017, CHBDC 2019), have been gradually moving towards the "Performance-based design" (PBD) approach, which implies that extensive experimental and analytical studies are needed to define accurate limited states and acceptance criteria. There are currently a few guidance documents available for seismic performance assessment. The very first efforts for developing guidance documents were concentrated on concrete and steel structures these kind of structures (ATC 1992; ACI 1999; Krawinkler et al., 2001). Further efforts have led to establish general testing programs for different materials and structural systems (e. g. FEMA 2007 and ACI 2013). However, all these procedures may not always be adequate for reinforced concrete (RC) bridge piers because of the differences in their structural characteristics, such as strength and deformation capacities. Consensus-based quasi-static cyclic test programs for the seismic assessment of RC bridge piers are highly required to produce consistent results. Representative and properly developed loading protocols will strongly influence the future update of limit states and acceptance criteria for the PBD of different bridge codes.

For the reasons just quoted, this study presents a numerical procedure leading to the development of quasi-static cyclic loading protocols for RC bridge piers considering crustal, intraplate and subduction earthquakes.

An Incremental Dynamic Analysis (IDA) and fiber modeling approach were implemented to determine the displacement time history response of an archetype bridge pier for target ductility demands of two, four and eight. A direct relationship between inelastic cycles and the structural damage was established, whereby the number of inelastic cycles and the cumulative ductility displacement (CDD) damage index were considered as the main reference parameters. The rain flow counting algorithm specified by ASTM-E1049-85 (ASTM 2017) and a statistical analysis were utilized to extract and transform the time-history ductility displacement responses into loading protocols. The cyclic loading protocol development procedures by Krawinkler et al. (2001), Mergos and Beyer (2014), and Bazaez and Dusicka (2016), were considered. It is worth noting that previous studies on loading protocol development have used results from time-history analysis (THA) of Single-Degree-of-Freedom Systems (SDOF) and a constant ductility design to reach targeted ductility demands through an iterative process (i.e. varying the structure's stiffness to reach predetermine responses) (Bazaez and Dusicka 2016). The correct assessment of different structural components plays a fundamental role, therefore suitable cyclic loading histories that allow one to obtain consistent, reliable, and comparable results are in great demand.

2 SELECTION OF GROUND MOTIONS

The selection of ground motion is one of the most important steps for the development of suitable loading protocols. Ground motions should represent typical conditions of the place where the seismic assessment is to be tested (Krawinkler et al. 2001). For this study, the geography of northwestern California, United States, and the southwestern coast of British Columbia (BC), Canada (shaped by the Cascadia subduction zone), is selected. Three different type of earthquakes from Cascadia: deep (crustal), shallow (intraplate), and subduction earthquakes are selected for the analysis (CREW 2009). Thus, ground motion sets of 11 records of each type of earthquake are selected. The ground motion records, for crustal and intraplate earthquakes, were obtained from the Pacific Earthquake Engineering Research Center (PEER) ground motion database (PEER 2011), and for subduction earthquakes, the records were obtained from the Kyoshin Network (K-Net) database. Information about the selected ground motions is shown in Table 1.

Table 1. Ground motion sets information.

Ground motion set	Number of records	Moment magnitude range	R^a (km)	PGA range (g)
Crustal	11	6.61 – 7.40	13 - 51	0.109 – 0.568
Intraplate	11	6.80 – 7.60	59 - 93	0.187 – 0.489
Subduction	10	9	152 - 166	0.800 – 1.246

R^a = Epicenter distance range.

3 SELECTION OF A REPRESENTATIVE BRIDGE PIER

3.1 *Geometry and Design*

Information on the response behavior of representative structural systems subjected to various types of ground motions is required for the development of loading protocol (Krawinkler et al. 2001). In 2017, Siddiquee and Alam developed a highway bridge inventory for BC under the responsibility of the BC Ministry of Transportation and Infrastructure (BC MoT). In brief, an extensive survey was conducted with the objective of classifying the major highway bridge types of the province, where eleven bridges were identified as bridges with single column. For this study, these types of bridge piers were selected as the main archetype to control the development of the loading protocols. The objective is also to consider a bridge pier that represents the common construction and design practice of these bridge components.

In relation to the above discussion, the bridge pier was assumed to be in the Vancouver city area and was seismically designed as a Major Route bridge following the Canadian Highway Bridge Design Code (CHBDC) [CSA S6-19 (National Research Council of Canada 2019)]. The height of the pier (L) is 9.14 m and the diameter of the column (D) was 1.83 m, corresponding to an aspect ratio (D/L) of 5, ensuring a flexure dominated behavior. The pier was reinforced with 40 longitudinal reinforcing bars of 32mm diameter (reinforcement ratio of 1.22%) and 20-mm-diameter steel spirals at 80 mm pitch (transverse reinforcement ratio of 0.91%). The spiral design was controlled by the confinement requirements, which intended to provide adequate curvature ductility. The cross section and elevation of the designed bridge pier is shown in Figure 1.

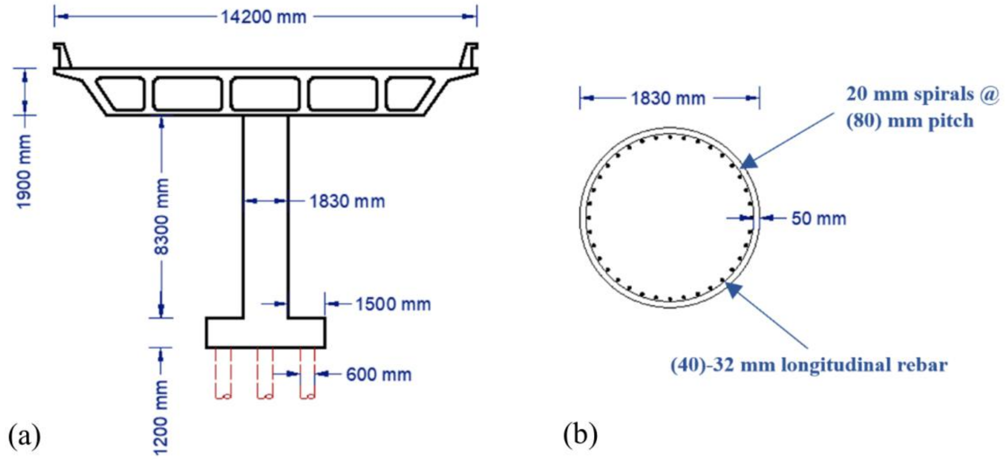

Figure 1. Bridge pier: (a) elevation and (b) cross section.

3.2 *Numerical Model*

For this study, fiber element–based nonlinear analysis program SeismoStruct 2020 software was employed to obtain the time-history displacement response of the column required to develop the loading protocols. The bridge pier was modeled using a three-dimensional inelastic force-based element with circular section. Nonlinearity was captured through the concrete and reinforcement steel constitutive laws which were defined as per the Mander et al. (1988) and Menegotto and Pinto (1973) models, respectively. It is important to mention that the steel model considers the Bauschinger effect, which represents the columns' stiffness degradation under cyclic loading. A model scheme of the bridge pier is shown in Figure 2.

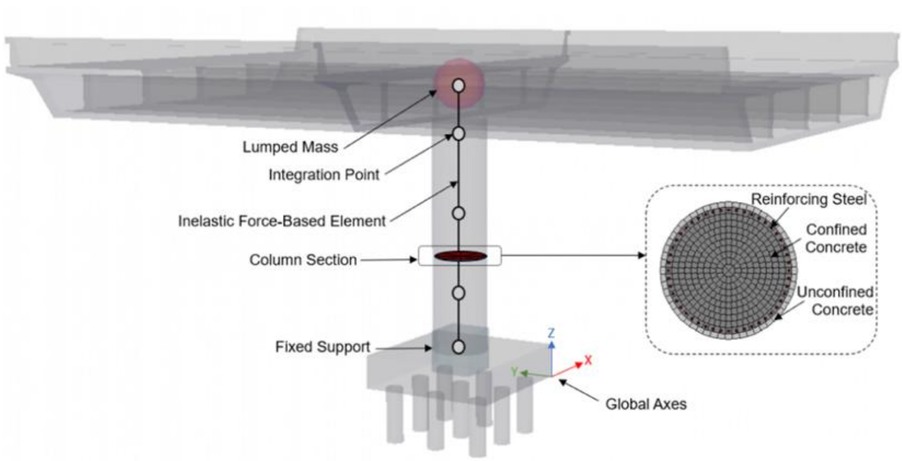

Figure 2. Analytical model scheme of the bridge pier.

4 CUMULATIVE DAMAGE

During seismic load cycles, ductile structural components experience damage that can be directly related to the strength and deformation capacity of the system. (Krawinkler et al., 1983). The gradual loss of element resistance due to inelastic deformation makes cumulative damage concepts the basis for the development of a loading history representative of the seismic response behavior. For this study, the cumulative displacement ductility (CDD) index (Park 1989) was considered to represent the seismic behavior of the column. This index is calculated by accumulating the ratio of post yield (δpi) to yield (δy) displacement under an excursion, as shown in Equation 1.

$$CDD = \sum_{i=1}^{N} \frac{\delta_{pi}}{\delta_y} = \sum_{i=1}^{N} \mu_i \quad (1)$$

Two important principals come from this model and should be considered in the loading protocol development. First, the structure's capacity is expected to decrease as the number of inelastic cycles increases, and second, large cycles cause much more damage than small cycles (Krawinkler et al. 2001). Thus, the primary parameters to be considered are the number of inelastic cycles (N), the range of each cycle and the sum of each range. For that reason, the number of inelastic cycles (N) and the cumulative displacement ductility (CDD) was taken as the target for the loading protocol development assuming a direct relationship between them.

5 TARGET RESPONSE– INCREMENTAL DYNAMIC ANALYSIS

For bridge piers, the best mediator between response and seismic input is the tip displacement. This measurement can be directly related to the component ductility capacity and, in turn, can be assessed from dynamic models (e.g. force-based fiber models). Moreover, most modern seismic design codes for bridges (AASHTO 2017, CHBDC 2019) rely on the structure's maximum ductility, which is defined as the ratio of the maximum imposed displacement to the yield displacement capacity ($\mu = \delta/\delta_y$) of the structure. For those reasons, the ductility demand imposed on the bridge pier was defined as the target demand parameter to represent the development of the loading protocols. Specific values of two, four, and eight (i.e. $\mu = 2, 4, and\ 8$) are selected to account for low, moderate, and high ductility demands, respectively. A damping ratio of 5% was considered.

Previous studies on loading protocol development have used results from time-history analysis (THA) of Single-Degree-of-Freedom Systems (SDOF) and a constant ductility design to reach targeted ductility demands through an iterative process (i.e. varying the structure's stiffness to reach predetermine responses) (Bazaez and Dusicka 2016). However, for this study, an Incremental Dynamic Analysis (IDA)-based approach was utilized to reach the desired ductility demands. This approach allows one to have a continuous picture of the dynamic structural response of the structure (i.e. elasticity to yielding and/or to collapse) as the load is gradually incremented. In this way, the general methodology followed to develop the loading protocols consists of five main steps: (1) selection and matching of ground motion records; (2) analytical modeling of a representative bridge pier; (3) iterative determination of desired seismic demands (IDA); (4) statistical post-processing of results; and (5) construction of loading protocols. The procedure is illustrated in Figure 3.

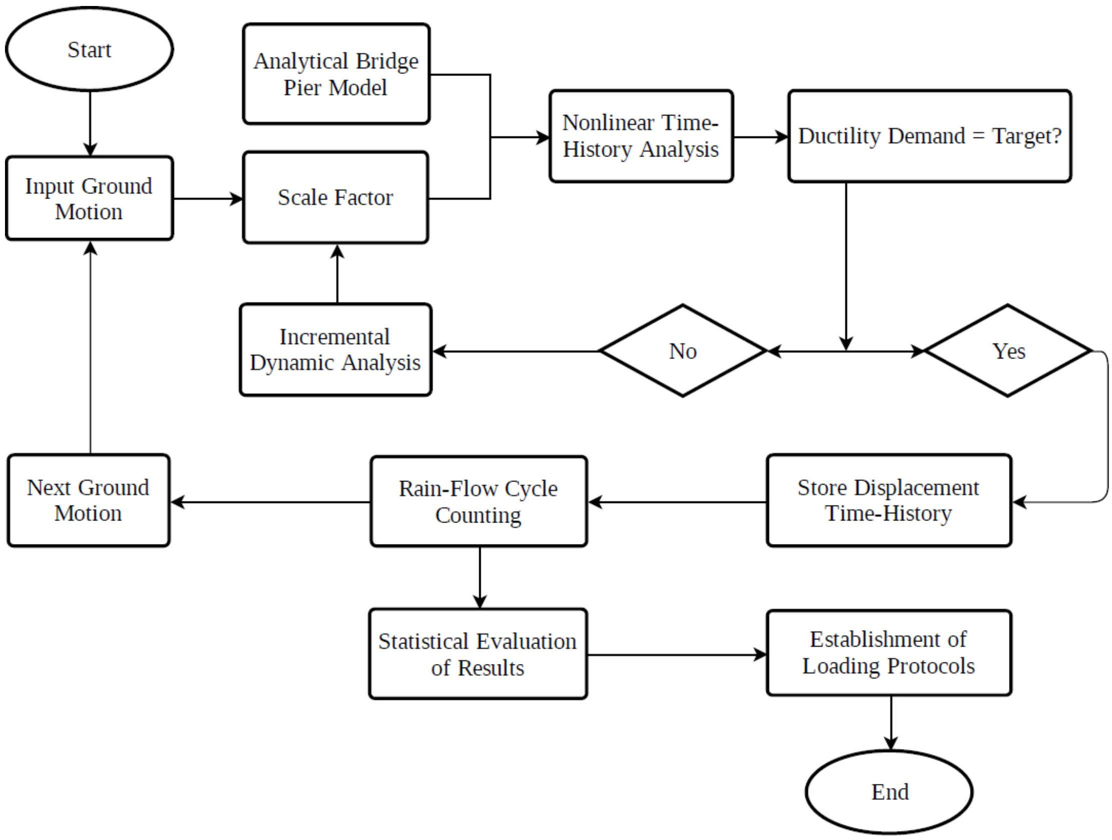

Figure 3. Flow chart of methodology for the development of loading protocols.

6 CONSTRUCTION OF THE LOADING PROTOCOLS

6.1 *Cycle Counting*

When a structure undergoes seismic demands, its response is rarely constant and does not follow a consistent sequence of cycles. To develop a loading protocol, this response needs to be converted into series of cycles before they can be used. Therefore, a cycle counting method must be employed to reduce the complex displacement time-history response into a series of constant amplitude events. For this study, individual excursions were extracted and ordered by means of the rain-flow cycle counting algorithm suggested by ASTM E1049-85 (ASTM 2017). The complex cyclic time histories are decomposed into various excursions that correspond to fully closed hysteresis loops in the stress/strain history.

Since the CDD is affected by the number and amplitude of cycles, some considerations were established. Only pre-peak excursions are considered (i.e. only excursions that occurs before either the maximum or minimum are considered), and the mean effect is ignored (i.e. the amplitude of inelastic cycles are half of their relative range) in order to have a gradually increased progression of excursions centered to the origin (i.e. cycles with the same positive and negative amplitudes) and to avoid the overestimation of cumulative damage, respectively (Krawinkler et al. 2001). The rain-flow counting algorithm was applied in each displacement ductility time-history response for all ground motion records to obtain the number of inelastic cycles (i.e. cycles of $\mu > 1$), and the CDD was computed using Equation (1).

6.2 *Statistical Analysis*

The rain-flow algorithm provided a series of excursions with well-defined range. When arranged in increased order, and since only inelastic excursions were considered, it resulted in a string of numbers (excursion amplitudes) from 1 (i.e. first inelastic amplitude) on upwards. Then, a ductility amplitude step of 0.5 is utilized to compute the number of inelastic cycles and the CDD. The procedure is repeated for each stored time history response to further statistically reduce the data collected. For reasonable comparisons and conservative estimations of the target parameters the mean values plus one standard deviation (84th percentile) are obtained within each ground motion record for each ductility amplitude step (i.e. from 1 to 1.5, from 1.5 to 2, and so on until the specific targeted ductility).Results from this analysis showed that the number of inelastic cycles, as well as the CDD from subduction earthquakes are considerably higher (more than 60%) than those from the other two types of earthquakes for all ductility demands. However, the value from crustal and intraplate earthquakes are similar. The difference between all ductility values (μ) is, on average, 17% and 11%, for inelastic cycles and CDD, respectively. Additionally, to confirm this relative similarity, two statistical tests were carried out to compare the two parameters between the two types of earthquakes for all ductility demands. A significance of 5% was selected. Results showed that there is insufficient statistical evidence to conclude that both parameters differ between the two types of earthquakes. Consequently, in a conservative manner, the statistical values for intraplate earthquakes (slightly higher values than crustal earthquakes) were considered for all ductility demands.

7 PROPOSED TESTING PROTOCOLS

After the extensive analysis, two different loading protocols are proposed for the target ductility responses (i.e. μ= 2, 4 and 8). The protocols consist of several ductility symmetric cycles alternated in positive and negative directions (arbitrarily started at positive amplitude) and incrementally increased to the correspondent target ductility value. Since only inelastic cycles were considered in the analysis and following previous studies recommendations (Krawinkler et al. 2001; FEMA 2007; Dusika and Bazaes 2016), the proposed protocols were divided into two main stages. The first stage is aimed to visualize low damage states and consists of ten elastic cycles applied to all the protocols with the following distribution: 3 cycles at 0.25(μ), 0.5(μ) and 0.75(μ) amplitudes and one cycle at 1.0(μ) amplitude. Likewise, the second stage is meant to replicate the inelastic demands imposed on concrete bridge columns and consist of the inelastic cycles obtained from the statistical analysis. The number and amplitude of each inelastic cycles of this stage are illustrated in Table 2.

As previously discussed, a pre-peak excursions approach was considered to avoid an overestimation of the cumulative damage and the post-peak cycles were considered separately. All the post-peak cycles are referred here as "trailing" cycles and are given secondary consideration (Krawinkler et al. 2001). Trailing cycles where utilized to match the CDD from the loading protocol test to the CDD from the statistical analysis considering all excursions and ensure the correct achievement of the damage into the column. Thus, for this purpose the proposed protocols were followed by a corresponding number of trailing cycles. The amplitude of the trailing cycles was arbitrary considered as 75% of the maximum target ductility for each correspondent protocol. This consideration was made to avoid excessive or insignificant number of trailing cycles (Krawinkler et al. 2001). Trailing cycles for all ductility demands are shown in parenthesis in Table 2. The entire proposed protocols are illustrated in Figure 4.

Table 2. Proposed loading protocols.

Cycle Amplitude	Crustal and Intraplate						Subduction					
	$\mu = 2$		$\mu = 4$		$\mu = 8$		$\mu = 2$		$\mu = 4$		$\mu = 8$	
	IC	CDD	IC	CDD	IC	CDD	IC	CDD	IC	CDD	IC	CDD
1.2	1	2.4	1	2.4	1	2.4	3	7.2	3	7.2	3	7.2
1.4	1	2.8	1	2.8	1	2.8	3	8.4	3	8.4	3	8.4
1.5	(2)	0	0	0	0	0	(2)	0	0	0	0	0
1.7	1	3.4	1	3.4	1	3.4	2	6.8	2	6.8	2	6.8
2	1	4	1	4	1	4	1	4	2	8	2	8
2.5	-	-	-	-	-	-	-	-	2	10	2	10
3	-	-	1 (6)	6	1	6	-	-	2 (6)	12	2	12
3.5	-	-	-	-	-	-	-	-	1	7	2	14
4	-	-	1	8	1	8	-	-	1	8	2	16
5	-	-	-	-	-	-	-	-	-	-	2	20
6	-	-	-	-	1 (9)	12	-	-	-	-	2 (9)	24
8	-	-	-	-	1	16	-	-	-	-	1	16
Total	4	12.6	6	26.6	8	54.6	9	26.4	16	67.4	23	142.4

*IC = Inelastic cycles

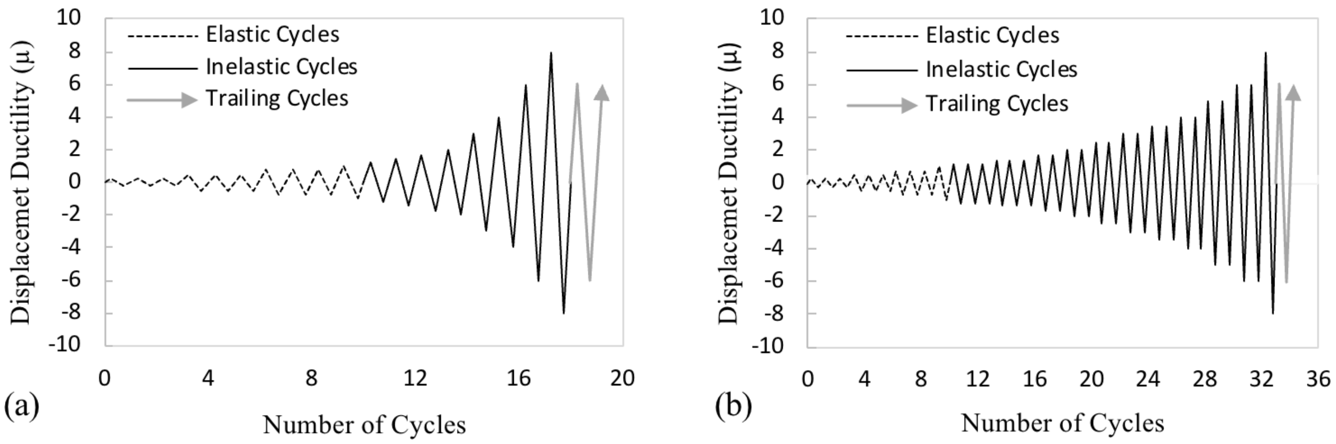

Figure 4. Proposed loading protocols for high, moderate, and low ductility demands a) crustal and intraplate earthquakes and b) subduction earthquakes.

8 CONCLUSIONS

An Incremental Dynamic Analysis (IDA) approach was introduced for the development of suitable quasi static loading protocols for the cyclic seismic testing of bridge piers. To implement the approach, an archetype bridge pier in southwestern British Columbia, Canada was designed and modeled with force-based fiber elements and subjected to three different types of earthquakes: crustal, intraplate and subduction earthquakes. The ASTM E1049-85 simplified rain-flow counting procedure was utilized to extract the number of inelastic cycles in the displacement ductility time-history responses of the bridge pier and compute the correspondent Cumulative Displacement Ductility (CDD) damage index. Both parameters were taken as the main reference and results from a statistical analysis on them were implemented to propose suitable loadings protocol for low, moderate, and high ductility demands.

Observations made on the inelastic demands between the three different types of earthquakes showed that those from subduction earthquakes are considerably higher than those from crustal and intraplate earthquakes. However, a statistical comparison test carried out on the equality of variances and mean values, allowed to determine that inelastic demands from crustal and intraplate earthquakes do not differ between each other. The procedure introduced in this study was aimed to provide a relatively simple development approach of cyclic loading protocols for academic research and practical engineering. The development procedure will permit one to obtain and work with consistent datato test and refine various seismic performance levels of RC bridge piers from bridge codes. It is recommended to consider more types of earthquakes and implement more refined hysteretic models to improve the results presented in this study and refine the procedure for more solid results.

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