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Comparative Study of Rocking Bridge Piers with Ductile and Isolated Bridge Piers

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ABSTRACT

The dissipation of seismic energy is integral to the design of earthquake-resistant structures. Seismic energy can be dissipated in several ways such as introduction of the ductile elements, base isolations, or rocking mechanisms in the system.

Ductile design is a popular technique widely used in piers and columns of current seismic-resistant bridges. Ductility is the ability of a structural member to deform without significant loss of load-carrying capacity after yielding; however, without damage ductility cannot be achieved, and in many cases, the structures cannot be self-centered. Isolation bearings have been used as one of the most widely accepted seismic protection systems for buildings and bridges. Two major categories of isolation bearings are commercially available and recommended by the codes: lead rubber bearing (LRB) and friction pendulum bearing (FPB). In recent years, low-damage seismic design technology has been developed to minimize and potentially eliminate the damage to bridge substructures during earthquakes. The low-damage design uses dissipative controlled rocking (DCR) connections between the pier-cap, column, and footing/pile-cap in a bridge substructure.

This paper compares the seismic performance of bridges designed with ductile elements, base isolations, or rocking mechanisms. It is intended to be a reference for bridge designers, owners, and the construction industry to promote customized cost-effective solutions that can be adopted to address resilient and cost-effective Accelerated Bridge Construction (ABC) techniques.

Keywords: Rocking Column, Ductile Design, Energy Dissipation, Seismic Performance, Seismic Isolation.

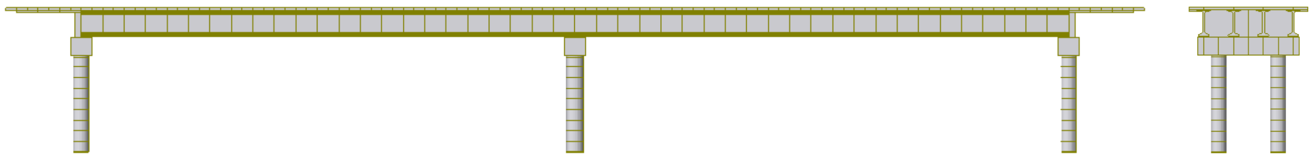
INTRODUCTION

Engineers have been looking for low or no damage and self-centering earthquake resistant systems for many years. Low-damage seismic design aims to minimize damage in a bridge during an earthquake [1]. In recent decades, the need for reduction of direct and indirect seismic losses has dictated the shift toward development of high-performance low-damage earthquake resistant systems [2]. Dissipative control rocking (DCR) column supported bridges are considered among the high-performance and low-damage earthquake resistant systems. Many studies have been performed on the DCR systems; however, very few bridges have been designed and built using this system. Bridge designers and owners do not have enough comparative information between conventional earthquake resistant (CER) and DCR systems to make decision in favor of the DCR system. This study will provide a comparison between the CER and DCR systems. Several inelastic static pushover analyses (ISPA) have been carried out on four types of prototype bridges, which are compared, and summarized in this paper. Soil-structure interaction (SSI) is not considered in this study in order to compare performance of the substructures only.

The novelties of this study are – 1) modelling of double rocking columns in isolated abutment bridge, 2) supporting of superstructure fully on rocking columns without utilizing of bearing, and 3) developing of backbone curves (general links) for modelling of rocking connections using moment-rotation and axial force-displacement relationships. A detailed methodology and procedure will be presented in future papers; however, brief analysis results are presented herein.

PROTOTYPE STRUCTURE

To accomplish the objectives of the study, a two-span isolated abutment [3-4] type bridge is chosen as a prototype structure. Center-to-center span of the bridge is 46 m. The width of the bridge is 11 m including two traffic lanes, barriers, and shoulders. In both abutments, a 6 m long "jump span" (approach slab) is used. The jump span is supported on a sleeper slab at its end. The sleeper slab is designed to kick off the jump span during large seismic events without violating serviceability and seismic performance criteria of the bridge. The clear height of the columns and bridge are 9 m and 10.755 m respectively. Elevation and typical cross-section of the bridge are shown in Figure 1.



(a) *(b)*

Figure 1. Two-span isolated abutment type bridge: (a) elevation, (b) typical cross-section

The following structural systems, shown in Table 1, are used in this study. The bridges are assumed to be located in Vancouver, British Columbia, Canada on a major route.

Table 1: Different structural systems

Type	Girder	Definition	Span (m)	Total length (m)
DRC	4-NU2400	Superstructure supported on ductile reinforced concrete columns	2×46	92
DCR	4-NU2400	Superstructure supported on dissipative control rocking columns	2×46	92
LRB	4-NU2400	Superstructure supported on lead rubber bearings	2×46	92
FPB	4-NU2400	Superstructure supported on friction pendulum bearings	2×46	92

In DRC bridges, the superstructure, substructure, and foundation are monolithically connected. In seismic events, plastic hinges are expected to form in columns at column-cap/foundation interfaces. Plastic hinges are properly designed in order to meet strain requirements at different performance levels recommended by the bridge design code. Minimal to extensive damages are expected in order to achieve desired ductility.

In DCR bridges, the superstructure, substructure, and foundation (footing/pile-cap) are not monolithically connected and are rather pre-compressed against each other by gravity loads, unbonded post-tensioning tendons (PT) and supplementary energy dissipaters (ED). Unbonded PTs are installed at center of the hollow-core column and EDs are bolted along perimeter of the column. Generally, concrete filled steel tube (CFST) is recommended for the rocking column. The rocking interface undergo gap opening and closing during later loading; therefore, the interfaces are made with steel plates to allow minimal damage along edge of the column. A shear key is embedded inside of the column-cap/foundation interface to restrain horizontal shears.

In LRB bridges, the superstructure is supported on lead rubber bearings (LRB). The LRBs can be installed on either cantilever column, hammer-head column, or multi-column bent. LRBs are low-damping laminated rubber bearings with a lead plug inserted in the core of the device. The purpose of inserting the lead plug is to increase both the stiffness at relatively low horizontal force levels and the energy dissipation capacity. The resulting force-displacement curve is a combination of the linear response of the rubber bearing and the elasto-plastic response of a confined lead plug. Rubber is very sensitive due to temperature change. It becomes softer in the summer and stiffer in the winter. Therefore, winter stiffness governs the forces to determine the number of piles; however, summer stiffness governs the maximum displacement for the extreme seismic event. Eight 1000 mm diameter and 257 mm tall bearings are used for the bridge, two are used for each abutment and four for pier. Diameter of the lead core is 250 mm.

In FPB bridges, the superstructure is supported on friction pendulum bearing (FPB). Similar to LRBs, the FPBs can also be installed on either cantilever column, hammer-head column, or multi-column bent. FPBs are based on the concept of a pendulum motion. The principle is simple, the structure to be isolated is supported on an articulated teflon-coated load element sliding on the inside of a spherical surface. Any horizontal movement therefore implies a vertical uplift of the supported weight. If friction is neglected, the equation of motion of the system is similar to that of a pendulum with equal mass and length to the radius of curvature of the spherical surface. Usually, FPBs are categorized as Single Pendulum Bearing (SPB) and Triple Pendulum Bearing (TPB). TPBs are more efficient allowing large displacement and they are 60% more compact than SPBs. SPBs are used for this study. The bearing layout is kept the same as LRB. Diameter and radius of curvature of the bearing are 1570 mm and 1500 mm respectively.

MATERIAL AND SECTION PROPERTIES

For inelastic static pushover analysis (ISPA) of ductile reinforced concrete (DRC) column and dissipative control rocking (DCR) column, the following material properties are used.

- 28-days compressive strength of concrete column is 30 MPa,
- Specified minimum yield and ultimate strength of rebar and energy dissipater are 400 and 600 MPa,
- Specified minimum yield and ultimate strength of structural steel are 350 and 480 MPa,
- Specified minimum yield and ultimate strength of low-relaxation strand are 1670 and 1860 MPa.

Mander model for confined concrete, Park Strain Hardening model for mild steel and Ramberg-Osgood model for post-tensioning strands are used. The stress-strain diagrams of unconfined and confined concrete, rebar and energy dissipater, structural steel, and low-relaxation strand are presented in Figure 2.

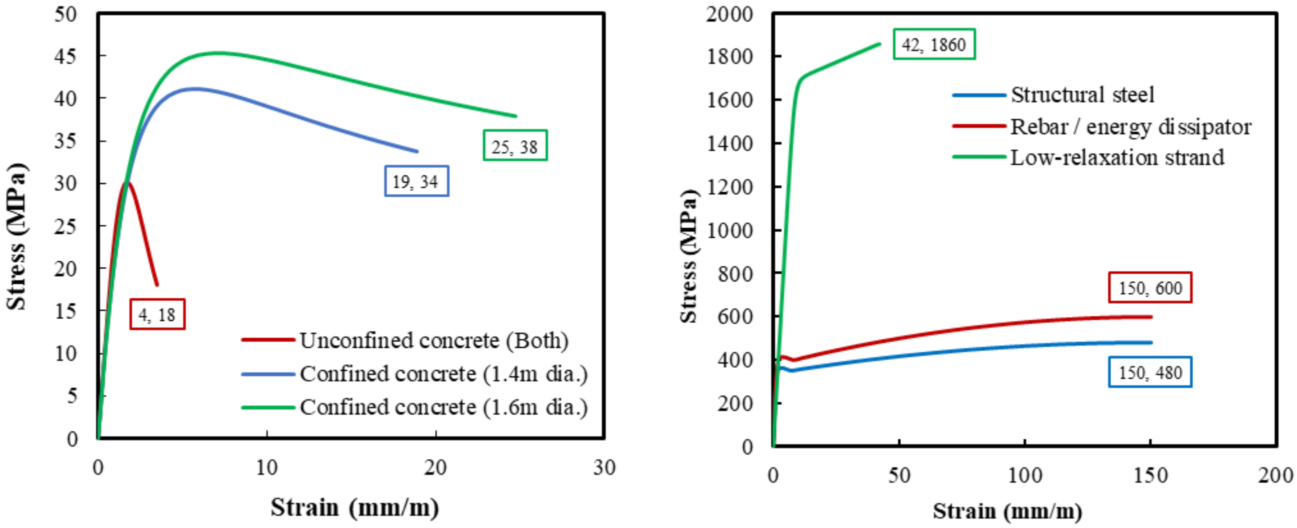


Figure 2. Stress-strain curves: (a) confined and unconfined concrete, (b) post-tensioning and mild steel.

Two-column bent is used for both isolated abutments and pier. Reinforced concrete columns are used for bridge type DRC, LRB and FPB. Concrete filled steel tubes (CFST) with hollow core inside are used for DCR bridge columns. The diameter of the abutment and pier columns are 1400 mm and 1600 mm respectively. The volumetric ratio of longitudinal and transverse reinforcement of 1400 mm diameter columns is 3.25% and 0.92%, and for 1600 mm diameter column is 3.58% and 1.33% respectively. Both ends thread excluded 25.2 mm diameter mild steel round bars are used for energy dissipater (ED). Total 24 EDs are considered at each end of the DCR columns. Three unbonded post-tensioning tendons are used at center of each DCR column. Each tendon contains 27-15.24 mm diameter low-relaxation strands. Typical sections of DRC and DCR columns are shown in Figure 3.

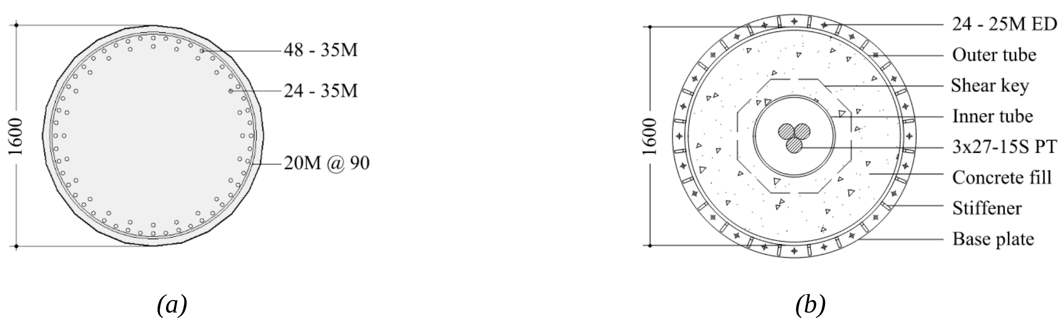
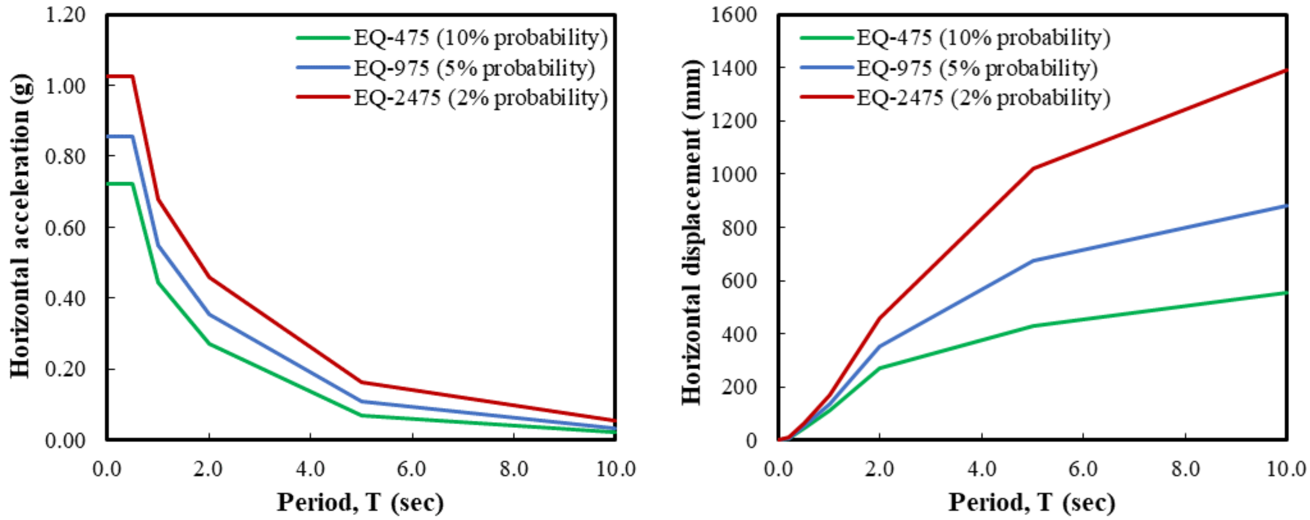


Figure 3. Typical section of pier column: (a) DRC column, (b) DCR column

DESIGN SPECTRAL ACCELERATION AND DISPLACEMENT

Seismic design of the prototype bridges has been carried out using the performance-based design (PBD) approach specified in the Canadian Highway and Bridge Design Code (CHBDC) [5] based on meeting specific structural, functional, and service performance criteria under specified seismic hazards. The seismic hazard represented by the design spectral acceleration for various probability of exceedance are obtained from the interactive websites of the Geological Survey of Canada. The horizontal design spectral acceleration and displacements for Site Class E (soft soil) are presented in Figure 4.

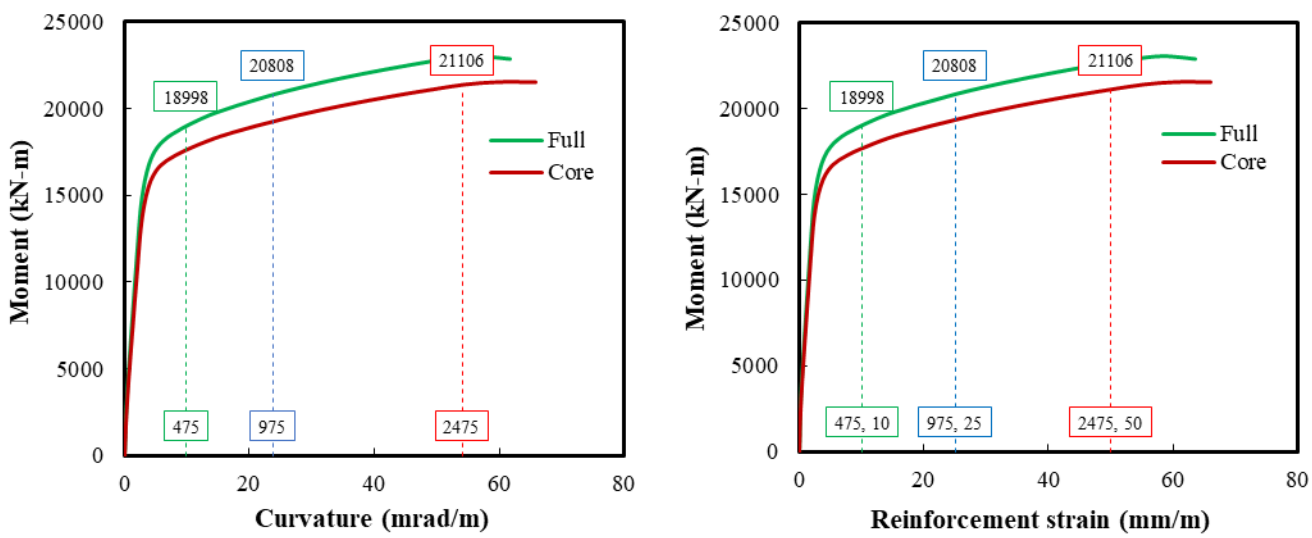


(a) *(b)*

Figure 4. Horizontal design spectral curves: (a) acceleration, (b) displacement.

SECTIONAL ANALYSIS

The reinforced concrete sectional analyses of the DRC columns for both full and core of the section have been performed using Response-2000 (version 1.9.6) software. Moment-curvature and moment-strain diagrams of the pier columns are presented in Figure 5. The limiting strains per CHBDC at 475, 975 and 2475 earthquake events, and corresponding moment capacities and curvatures are also plotted and presented in the figures.



(a) *(b)*

Figure 5. Sectional analysis curves of ductile pier column: (a) Moment-curvature, (b) moment-strain.

Moment-rotation analyses of double rocking columns have been performed using an in-house tool. The analysis tool was developed in Excel and Visual Basic platform by this author. Moment-rotation and force-displacement relationships of the free-standing rocking (FSR) column, post-tensioning control rocking (PCR) column and dissipative control rocking (DCR) column are presented in Figure 6.

Inelastic static pushover analyses were performed by Hossain et al. for 5000 different configurations of bridge piers using 3D continuum FE analysis [6]. A simplified method of analysis has been developed by this author to represent rocking behaviors of the columns. The behavior of FSR columns has been validated with the FE analysis results.

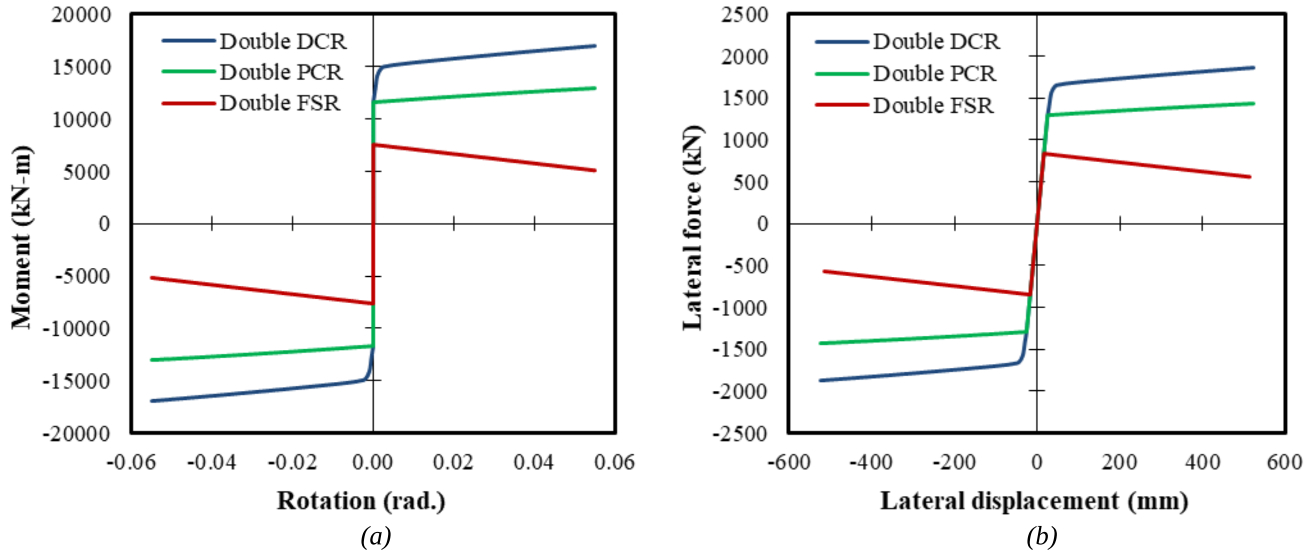


Figure 6. Sectional analysis curves of double rocking pier column: (a) Moment-rotation, (b) lateral force-displacement.

LOADS AND LOAD COMBINATIONS

Only dead and seismic loads are considered in this parametric study. Self-weight of bridge elements is automatically converted to masses by the program. Other dead loads are assigned as "loads to masses" in the program. The approximate deadload per unit length of the superstructure and jump span are 182 kN/m and 106 kN/m. The deadload of diaphragm and bent cap are 660 kN and 768 kN. The tributary weight on each abutment and pier columns are 4900 kN and 3000 kN respectively. In accordance with CHBDC Clause 4.4.9.2, the horizontal seismic loads are combined as maximum of 1.0X+0.3Y or 0.3X+1.0Y where X and Y represent longitudinal and transverse axis of the bridge.

GLOBAL ANALYSIS

Midas Civil 2023 (version 1.1) was used for analyzing prototype bridge models. The moment-rotation curves are developed and modeled to represent plastic hinge properties of the DRC columns. Similarly, the lateral force-displacement curves are used to represent shear deformation of the LRB and FPB bridge. These backbone curves are presented in Figure 7.

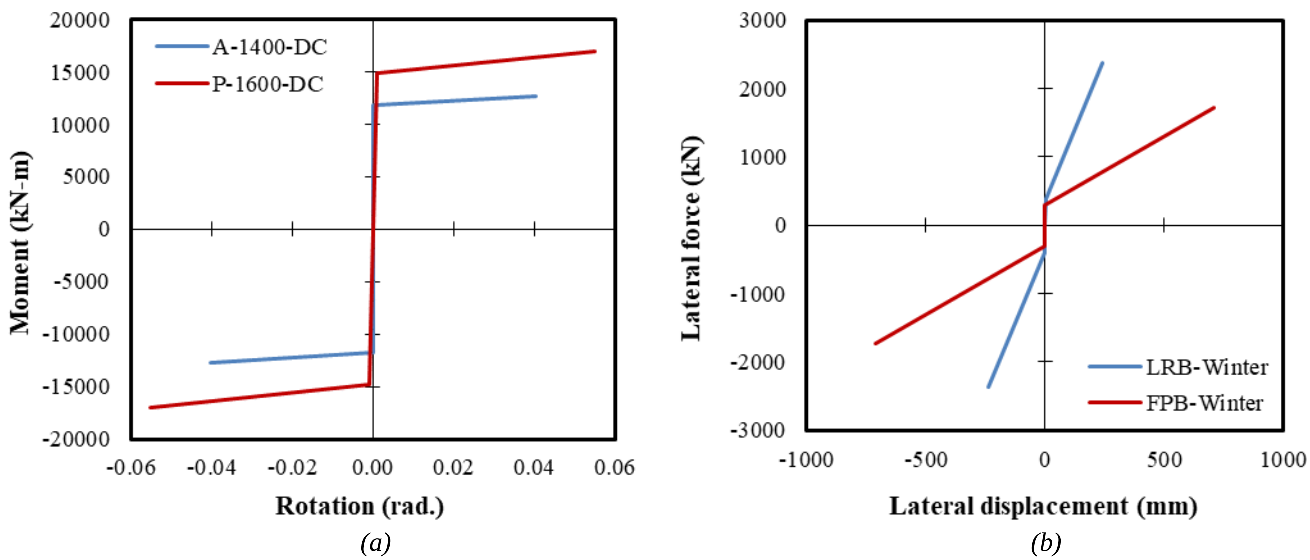
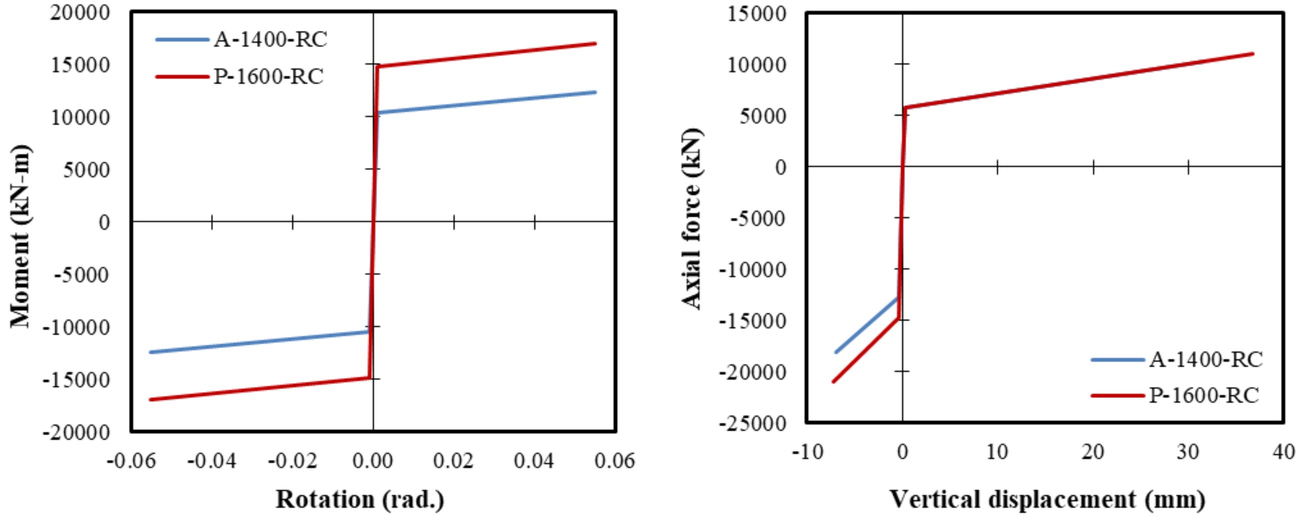


Figure 7. Backbone curves: (a) moment-rotation for DRC column, (b) lateral force-displacement for LRB and FPB.

The moment-rotation and axial force-displacement curves are also developed and modeled to represent rocking behaviors of the DCR columns. These backbone curves are also presented in Figure 8.



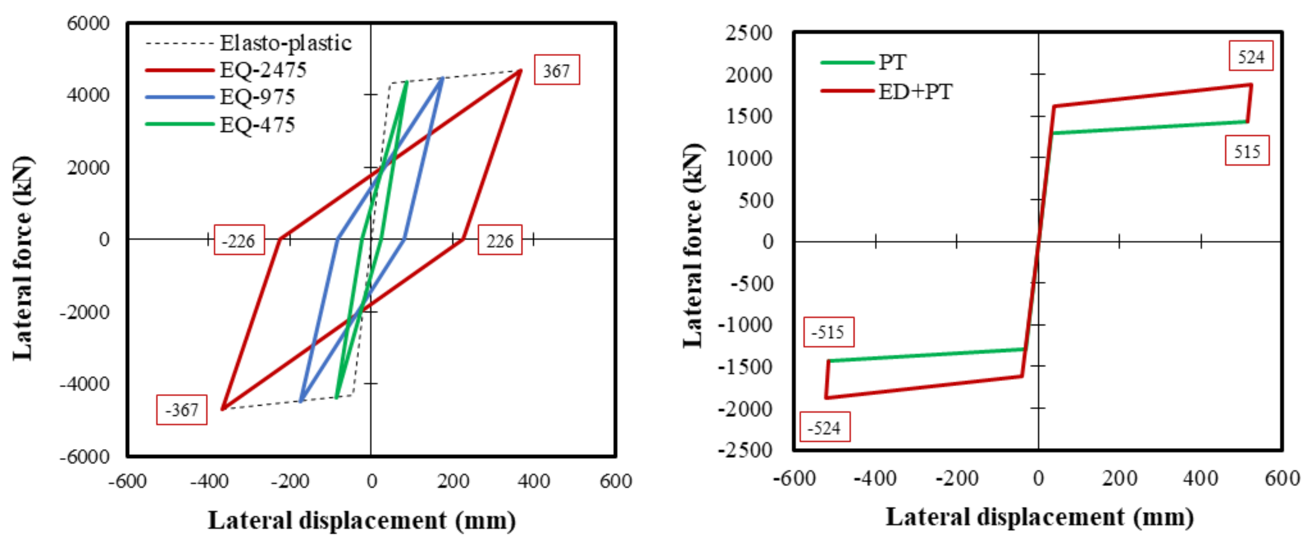
(a) *(b)*

Figure 8. Backbone curves for DCR column: (a) moment-rotation, (b) axial force-displacement.

Two types of DRC models were analyzed, elastic model using effective section properties calculated per CHBDC Clause 4.4.5.3.3, and boundary non-linear model using user-defined general links. Rubber and coefficient of friction are very sensitive to temperature; therefore, the LRB and FPB models were investigated for both summer and winter conditions. The DCR model was investigated with and without EDs in order to capture post-earthquake resistance capacity of the structure. Therefore, a total of 8 models were analyzed in order to summarize upper and lower bound results.

IDEALIZED HYSTERESIS LOOPS

Idealized hysteresis loops (IHL) of plastic hinge, rocking surface, lead rubber bearing, and friction pendulum bearing are developed for DRC, DCR, LRB and FPB bridge systems. IHLs are developed for both abutment and pier columns using ISPA; however, only pier column IHLs will be presented and discussed. Thin Modified Takeda rule [7] for plastic hinge of reinforced concrete columns and Flag-shaped rule for interface of rocking columns are used. IHL of DRC and DCR systems are presented in Figure 9. Maximum and residual displacements are also shown in the figures.



(a) *(b)*

Figure 9. Idealized hysteresis loops: (a) reinforced concrete pier column, (b) double rocking pier column.

Eight 1050 mm diameter lead rubber bearings or 1570 mm diameter friction pendulum bearings are used for both abutments and pier. Bilinear rule is followed for developing IHLs for both LRB and FPB at summer and winter condition. IHL of LRB at summer and FPB at winter are presented in Figure 10.

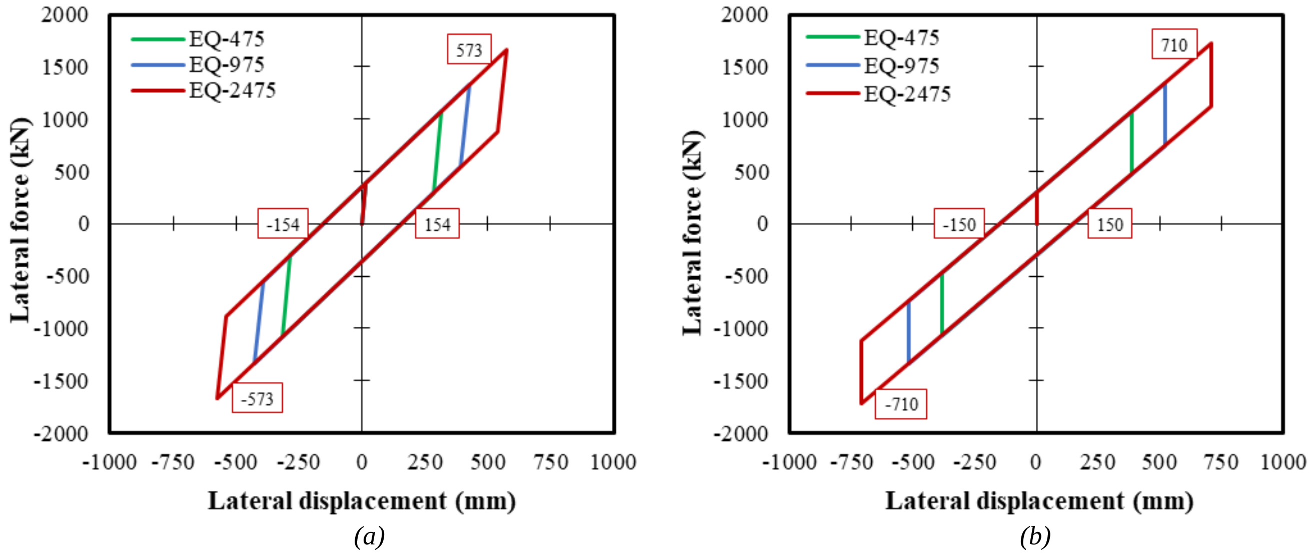


Figure 10. Idealized hysteresis loops: (a) lead rubber bearing at summer, (b) friction pendulum bearing at winter.

BILINEAR PUSHOVER CURVES

Bilinear pushover curves are developed to compare seismic performance between four different seismic resistance systems. Ratios of lateral force (base shear) and weight acting on each column or device (V/W) are plotted against the corresponding percent drift of the column. These plots are presented below in Figure 11.

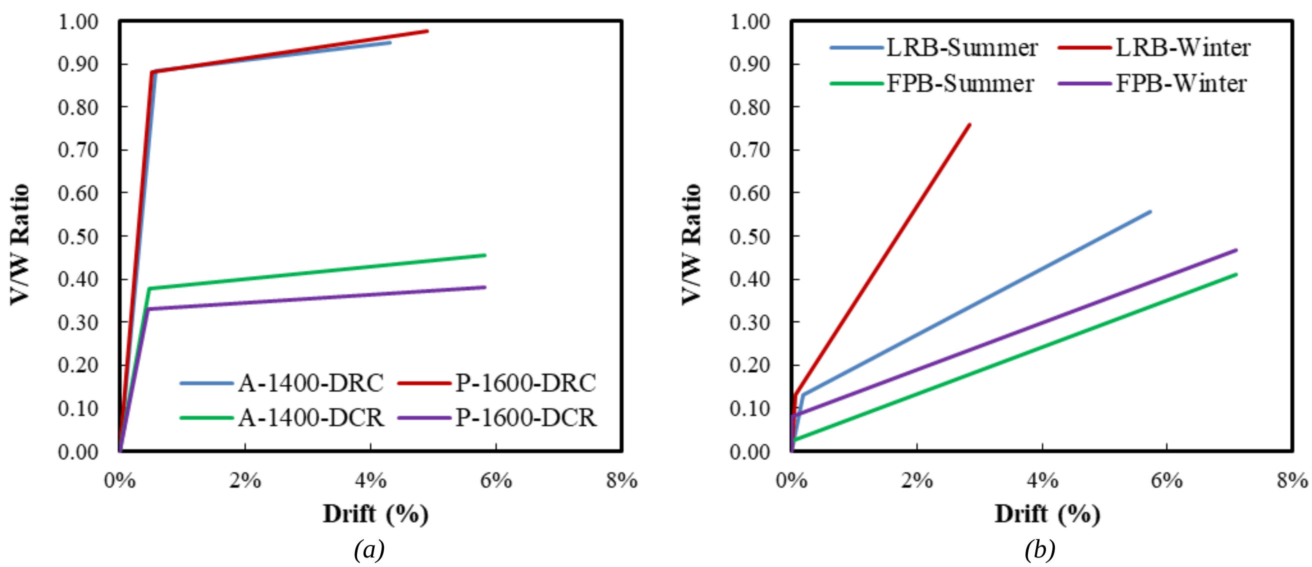


Figure 11. Bilinear pushover curves: (a) ductile and rocking columns, (b) lead rubber and friction pendulum bearings.

RESULTS AND DISCUSSIONS

Major observations and findings of the above parametric studies are summarized below:

- Free standing rocking (FSR) column has inherent characteristics of developing elasto-plastic moment-rotation and force-displacement curves; however, the negative slope of the plastic branch is not desirable. Adding an unbonded post-tensioning tendon (PT) at the center of the column can make this negative slope positive and provide self-centering capability of the system. Connecting columns with the base and cap of the bridge using mild steel long bolts can provide energy dissipating capacity to the system. These bolts are called energy dissipaters (ED). Tension-only (TO) EDs are used in this analysis and recommended for easy replacement. EDs are designed to elongate and fail at extreme seismic event to be replaced thereafter.

- The combination of PT with FSR columns can be called post-tensioning-controlled rocking (PCR) columns and further combining EDs with PCR columns can be called dissipative controlled rocking (DCR) columns. The moment-rotation and force-displacement curves of the FSR, PCR and DCR columns are presented in Figure 6 in order to demonstrate elasto-plastic behaviors of the column at each level.

- At 5.5% drift, the factor of safety against overturning of the rocking columns for pier and abutment are 2.87 and 2.50 respectively. However, the factor of safety can be further increased by increasing the design parameters such as diameter of the column, post-tensioning tendon, etc.

- Figures 7 and 8 illustrate backbone curves of different columns and bearings which are easy to generate in Excel and assign as "General Links" in the models using commercially available bridge analysis software.

- Based on idealized hysteresis loops (IHL), Shown in Figure 9 and 10, the maximum allowable displacements and their corresponding residual displacements are summarized below in Table 2. The analysis indicates that the maximum superstructure displacement is expected in friction pendulum bridge (FPB) system, and zero residual displacement in dissipative control rocking (DCR) with same boundary conditions at 2475-year seismic event.

Table 2: Maximum and residual displacements

Type	Maximum (mm)	Residual (mm)
DRC	± 367	± 226
DCR	± 524	0
LRB	± 573	± 154
FPB	± 710	± 150

- In accordance with the CHBDC, extensive damages are allowed for major-route bridges at 2475-year seismic event; however, the bridge shall be usable for emergency traffic after inspection and reparable to restore full service. The LRB and FPB bridges may be recentered in some extent; however, it is very challenging and costly or almost impossible in many cases to recenter the DRC bridges. Flag-shaped hysteresis loop of the DCR column indicates to self-center the bridge with almost no cost.

- The DCR column supported bridges can be designed to resist main-shock (MS) and after-shock (AS). Hysteresis loop of the DCR column, shown in Figure 8(b), indicates that the PT+ED (red line) will be able to resist MS. After damaging of EDs during MS, the bridge will remain elastic but behaving plastic and the PT (green line) will be able to resist AS.

- Figure 11(a) illustrates similar pattern of bilinear pushover behaviors of the DRC and DCR columns. Lateral to vertical load ratio (V/W) of the DCR column is almost 50% than that of the DRC column which indicate to reduce foundation costs of the DCR system with similar amount of target drifts.

- Without damages target drift or ductility of the DRC columns cannot be achieved; therefore, these columns shall be required to be repaired or replaced after extreme seismic event. On the contrary, no, or low damages are expected in DCR columns; therefore, it is proven to be a resilient earthquake resistant system compared to the traditional ductile system.

- Drift to V/W relationship of LRB and FPB, shown in Figure 11(b), indicate that performance of the LRB at winter in cold climate region is not favorable to reduce foundation costs of the bridge. The maximum base share of FPB and DCR column supported bridges are comparable. Therefore, the foundation costs of these two systems shall be same; however, the costs of four rocking columns shall be less than the costs of eight FPBs.

SUMMARY AND CONCLUSIONS

Ductile and rocking column, and lead rubber and friction pendulum bearing supported bridges have been studied analytically and numerically. Analytical results of free standing rocking column have been verified with the 3D finite element model results. Bilinear backbone curves of cap-column connections and bearings have been developed and applied in 3D bridge models. The analytical results of four different systems have been compared. No or low damage and self-centering behavior has been observed in the rocking column system. Therefore, rocking column supported bridges can be considered as cost-effective and resilient Accelerated Bridge Construction (ABC) solution.

More studies shall be performed to – 1) verify accuracy of the backbone curves, 2) compare results through elastic static analysis (ESA) for non-seismic loads and nonlinear time history analysis (NTHA) for seismic loads including soil-structure-integration (SSI), and 3) develop rocking interface and post-tensioning connection details.

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