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SEISMIC VULNERABILITY OF REINFORCED CONCRETE BRIDGE COLUMNS IN CANADA

C. Yalcin[1] and M. Saatcioglu[2]

ABSTRACT

Bridges are essential lifeline infrastructures that must remain in service after strong seismic events. Recent design codes implement performance-based design methodologies which may call for increased seismic demands. However, most of the existing infrastructure in Canada was built prior to the enactment of modern seismic codes of the post-1980 era. Recent earthquakes revealed seismic vulnerability of bridge structures with a number of deficiencies in regards to low seismic design force levels, inadequate column confinement and lack of column shear capacity. The objective of this study is to assess the vulnerability of reinforced concrete bridge columns in Canada. Computer software DRAIN-RC, developed for non-linear dynamic analysis of reinforced concrete structures, was used to determine the deformation demands of bridge columns under selected Eastern and Western Canadian ground motions. Deformation demands were subsequently compared with available research data in the literature on column deformation capacities to assess seismic vulnerabilities. Results exhibit different levels of performance for existing bridge columns in different regions of Canada, with bridges in western Canada showing higher vulnerabilities.

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ABSTRACT

Bridges are essential lifeline infrastructures that must remain in service after strong seismic events. Recent design codes implement performance-based design methodologies which may call for increased seismic demands. However, most of the existing infrastructure in Canada was built prior to the enactment of modern seismic codes of the post-1980 era. Recent earthquakes revealed seismic vulnerability of bridge structures with a number of deficiencies in regards to low seismic design force levels, inadequate column confinement and lack of column shear capacity. The objective of this study is to assess the vulnerability of reinforced concrete bridge columns in Canada. Computer software DRAIN-RC, developed for non-linear dynamic analysis of reinforced concrete structures, was used to determine the deformation demands of bridge columns under selected Eastern and Western Canadian ground motions. Deformation demands were subsequently compared with available research data in the literature on column deformation capacities to assess seismic vulnerabilities. Results exhibit different levels of performance for existing bridge columns in different regions of Canada, with bridges in western Canada showing higher vulnerabilities.

Introduction

A large proportion of existing bridges in Canada belongs to pre 1980's inventory. These bridges lack seismic detailing, and thus, possess inadequate inelastic deformabilities [1]. The current investigation focuses on seismic vulnerability of reinforced concrete bridge columns, with an emphasis on inelastic drift and ductility demands in eastern and western Canada.

Drift demands of bridge columns were investigated through dynamic inelastic response history analysis. Computer software, DRAIN-RC was chosen for this purpose [2]. The software is a modified version of the general purpose computer software, DRAIN-2D, developed at the University of California, Berkeley [3]. The sectional properties of reinforced concrete members were determined by computer software COLA [4], which provided input data for DRAIN-RC.

Dynamic Analysis

Non-linear dynamic analyses were performed on a number of single-degree-of-freedom (SDOF) bridge models representing different structural properties for bridges. The bridges were analyzed under actual and artificial ground motion records, representative of the seismicity of eastern and western Canada. The ground motions were applied in the horizontal direction.

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The following subsections describe the software DRAIN-RC, bridge modeling and the preparation of input data for dynamic analyses.

Description of Computer Software DRAIN-RC

DRAIN-RC is two-dimensional dynamic inelastic response history analysis software, modified specifically for use for reinforced concrete structures. It uses step-by-step integration technique, assuming constant acceleration during each time step. It includes hysteretic models for flexure [5], axial load-moment interaction [6], shear [7], anchorage slip [8], infill panels with truss elements [9], and improvements for incorporating push-over analysis and P-Δ effects [10].

The program calculates ductility factors based on chord angles. Ductility factors, defined as maximum chord angle divided by the angle at initial yield, are listed for each deformation component, i.e., flexure, shear and anchorage slip, as well as for total deformation. The program further calculates energy dissipation factors as the ratio of plastic to elastic energy, where the energy is computed as the area under the force-deformation hysteretic relationship.

Modeling of Bridges

The inventory of bridges in Canada was first established to classify different types of bridges with different structural properties [1]. It was then assumed rigid bridge decks supported by columns, which were connected through bridge bearings. This resulted in a SDOF model with two springs connected in series. The mass represented the total bridge mass consisting of those of the superstructure and a portion of the columns. The springs reflected the stiffnesses of the columns, as well as the bearings. The columns were assumed to be fully fixed at their base and free against rotation at bearings. The bearing stiffness also included those associated with abutments. Figure 1 illustrates the SDOF model. The bearings were assumed to have rigid resistances followed by yielding, as in the case of rusted rollers or rollers with debris, representing existing bridge conditions.

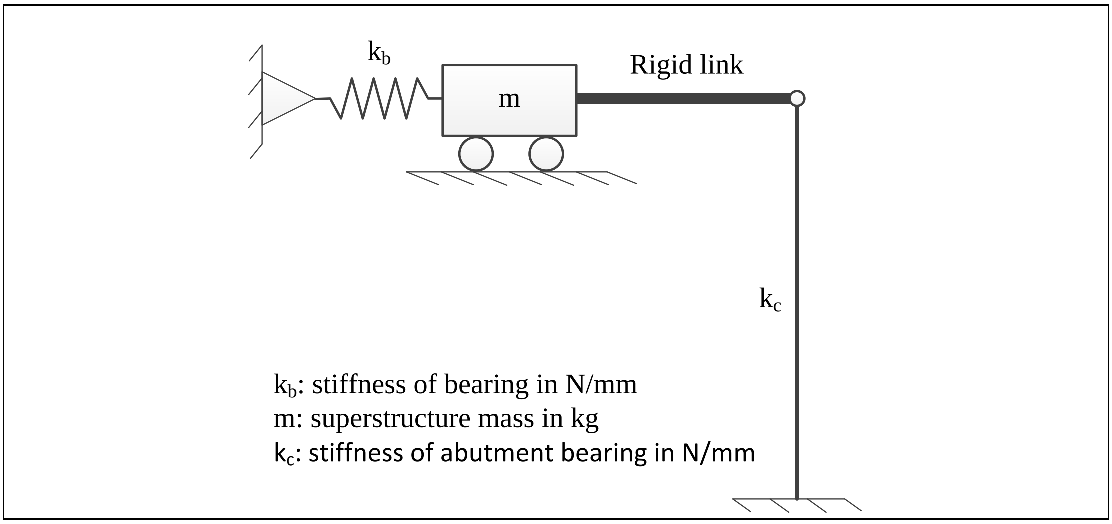

Figure 1. A SDOF model representing a bridge structure.

Preparation of Input Data

The structural properties of bridges were taken from a comprehensive Canada-wide bridge survey [1] and consisted of superstructure type (continuous or simply supported decks), number of spans, span lengths and widths, as well as column types and detailing. Therefore, a range of structural mass, stiffness and strength values were established on the basis of the survey.

Column Spring Properties: Computer software COLA was utilized to calculate primary force-displacement relationships, which were required as input for DRAIN-RC. This information was computed for both flexural and anchorage slip springs. The primary curve was established for a level of axial compression equal to 15% of column concentric capacity with initial effective elastic stiffness equal to 60% of uncracked stiffness and yield moment equal to 3.25 times the cracking moment. The ultimate moment was assumed to occur within the descending branch of the primary curve after the peak resistance, at 87% of yield moment. For the shear spring, a value of 0.5 was assumed for the ratio of post-cracking to elastic shear stiffness. All post-yield stiffness values were assumed to be 0.05 of the effective elastic stiffness.

Bearing Properties; Bearings provide connections between bridge superstructure and substructure, and transmit forces between these two media. Thus, they play an important role in the analysis of bridges and may dictate the behavior during a seismic activity. Therefore, they must be modeled properly. In this study, only sliding bearings were selected with different levels of sliding resistance, reflecting different levels of corrosion or debris accumulation. The coefficient of friction was considered to vary between 0.05 and 0.20 depending on the sliding surface condition. Bearing hysteretic relationship is shown in Figure 2.

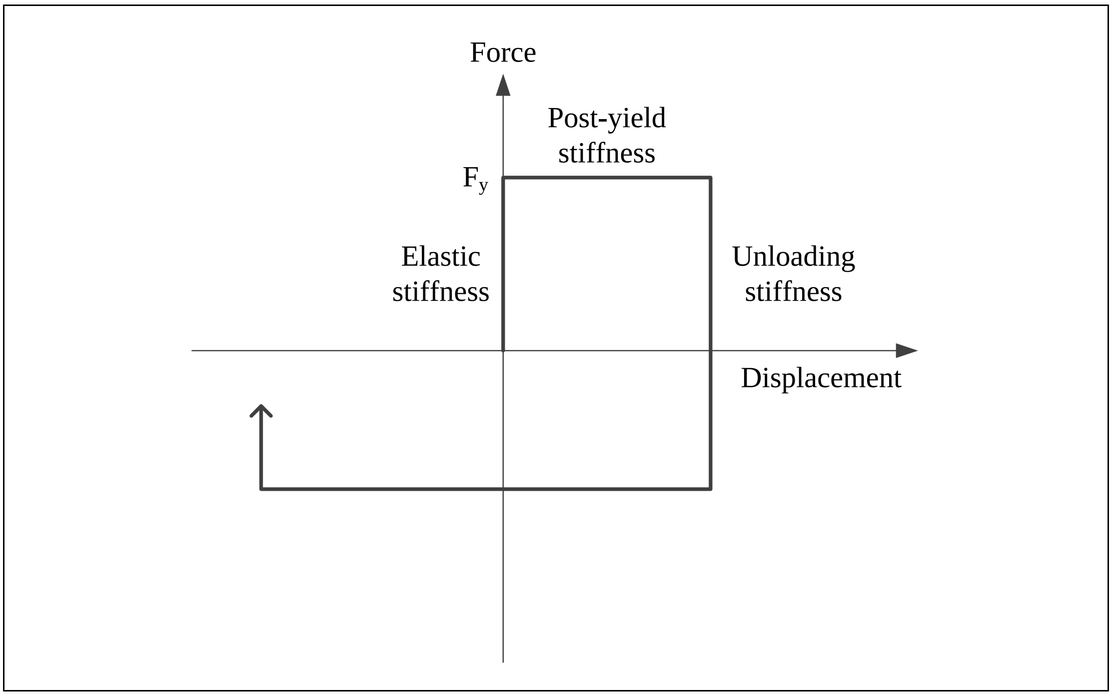

Figure 2. Bilinear hysteretic relationship for roller and rocker bearings.

Structural Parameters: The structural parameters of the SDOF bridge model considered included strength, stiffness and mass. In the inelastic range, post-yield properties and ductility characteristics also gained importance. For elastic response, stiffness and mass could be combined and represented in the form of fundamental period. The period of a typical highway bridge falls between 0.7 sec. and 4.8 sec. with an average period range of 1.5 to 2.0 sec [11]. Each column was designed to have 2% longitudinal reinforcement ($\rho = 0.02$).

Parametric Investigation

The effects of frequency content and intensity of ground motions on bridge response were investigated by considering a total of 17 earthquake records. The artificial records [1] used in the analyses yielded approximately the same response as those based on the uniform hazard response spectra (UHS) of the corresponding region with a 10% probability of exceedance in 50 years equivalent to a 15% probability of exceedance in 75years with a return period of 475years as recommended by CAN/CSA-S6-06 Canadian Highway Bridge Design Code (CHBDC) [12]. Hence, the response generated by these records may be viewed as those that are compatible with code-recommended design earthquakes. In addition to these artificial records actual earthquake records representing western and eastern Canadian seismicity were used. Among the records considered; one artificial and one actual earthquake records with critical spectral values were selected separately for eastern and western Canada. The characteristics of these records are given in Table 1.

The analyses were then conducted under actual and amplified intensity levels, as well as two different bearing yielding levels of 0.05W and 0.20W, where W represents the weight of the bridge. The amplification of records reflected possible soil amplification effects and corresponded to peak ground accelerations of 30% and 60% of “g”. The results were presented in the form of horizontal drift and ductility demands for bridges within a typical range of fundamental periods.

Table 1. Ground motion characteristics used in the analyses.

Ground Motion Record	Ground Motion Duration (Sec.)	% “g”
Saguenay, 1988 (for eastern Canada)	21	12.55%
Eastern Long Artificial Event #2	26	8.78%
El Centro, 1940 (for western Canada)	20	18.56%
Western Long Artificial Event #2	20	8.48%

Drift and Ductility Demands of Columns

The results of time history analyses are presented in Figures 3 through 6 for eastern and western Canada for two different levels of bearing frictional resistance (f = 0.05W and f = 0.20W). The results indicate that the bridges in eastern Canada remained elastic in all cases. The amplification of records up to 60% of “g” did not generate inelasticity in the columns, even with bearings having a small sliding resistance of 5% of weight. For western Canadian bridges, though they generally remained elastic, the columns of bridges with less than 1.5 sec. period developed yielding under the 1940 El Centro record, and exhibited up to a displacement ductility ratio of about 2.0 when the sliding resistance of the bearings was reduced to 5% of bridge weight. When the same record was amplified to match 30% of “g”, with the same bearing condition, the bridges in the west developed increased ductility demands, approaching a ductility ratio of 3.0 within the entire range of fundamental periods.

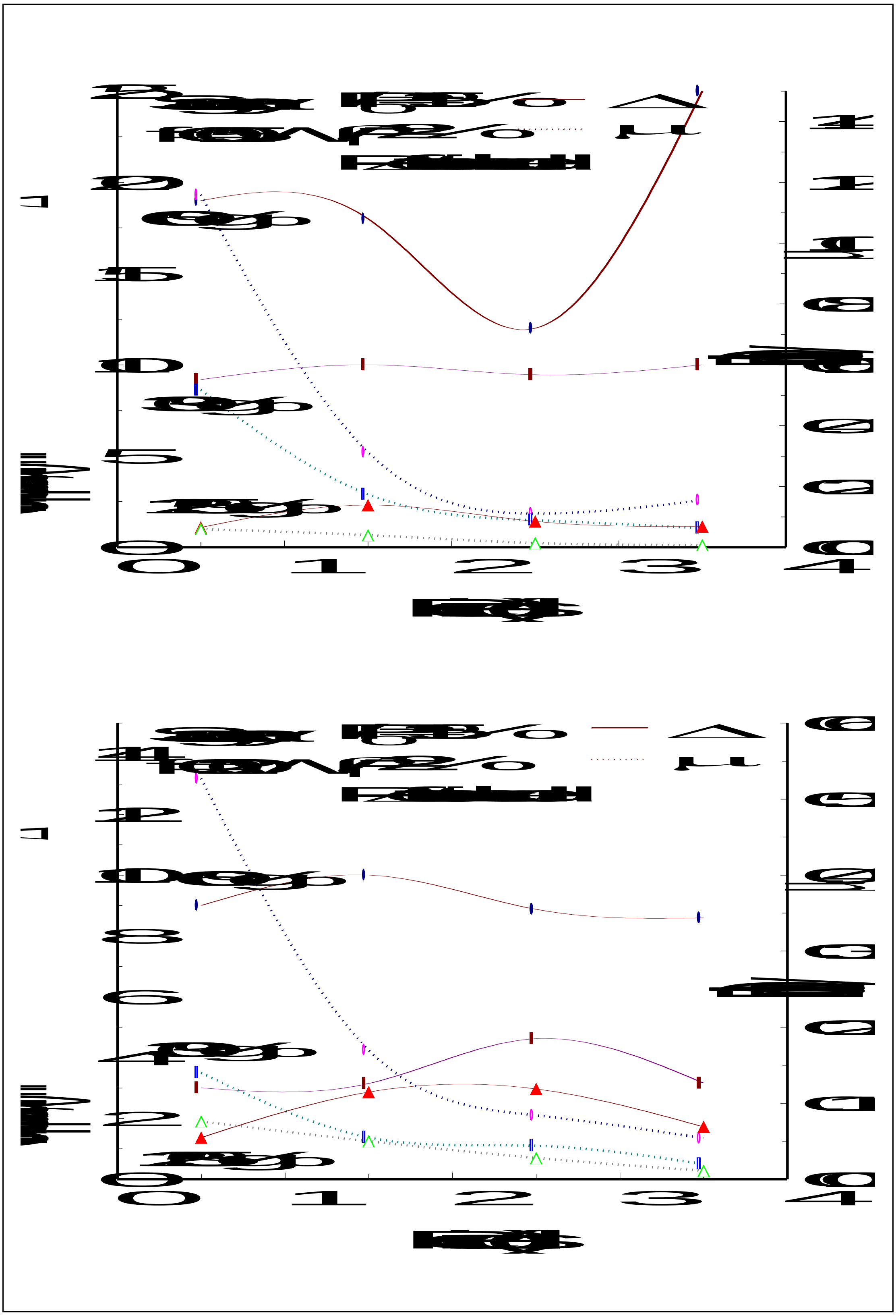

Figure 3. Saguenay Earthquake response of bridges with roller or rocker bearings with P-Δ effect.

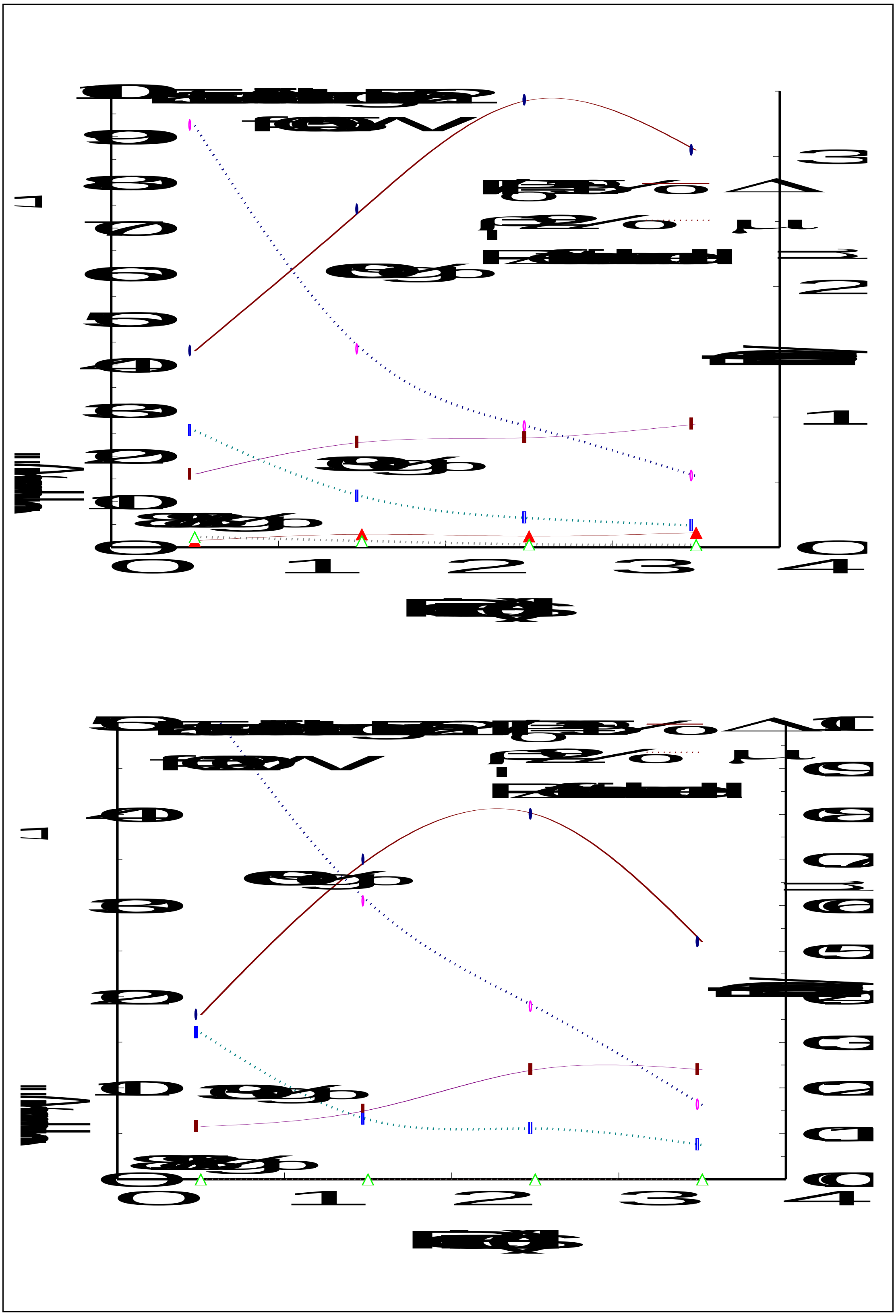

Figure 4. Eastern Artificial Long Event #2 Earthquake response of bridges with roller or rocker bearings with P-Δ effect.

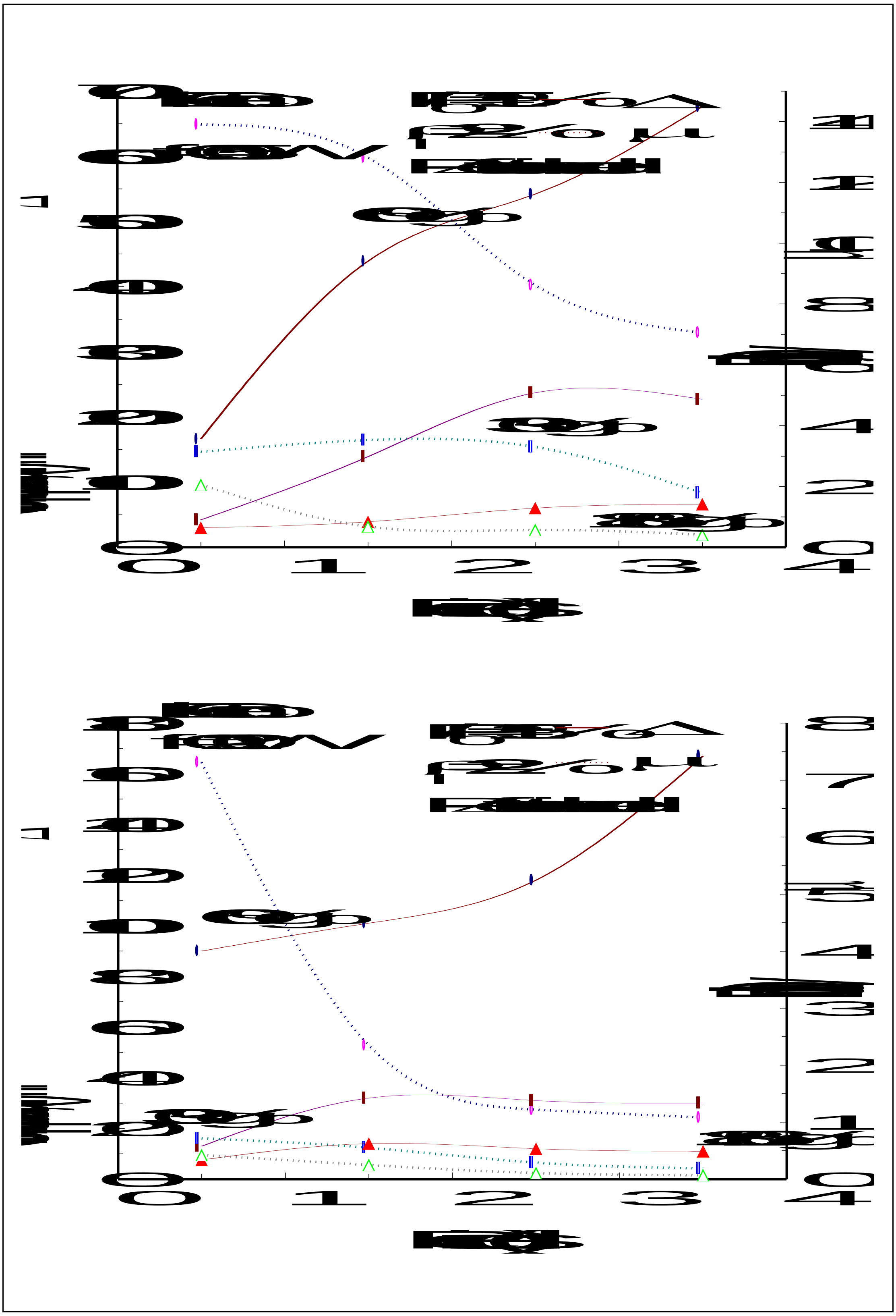

Figure 5. El Centro Earthquake response of bridges with roller or rocker bearings with P-Δ effect.

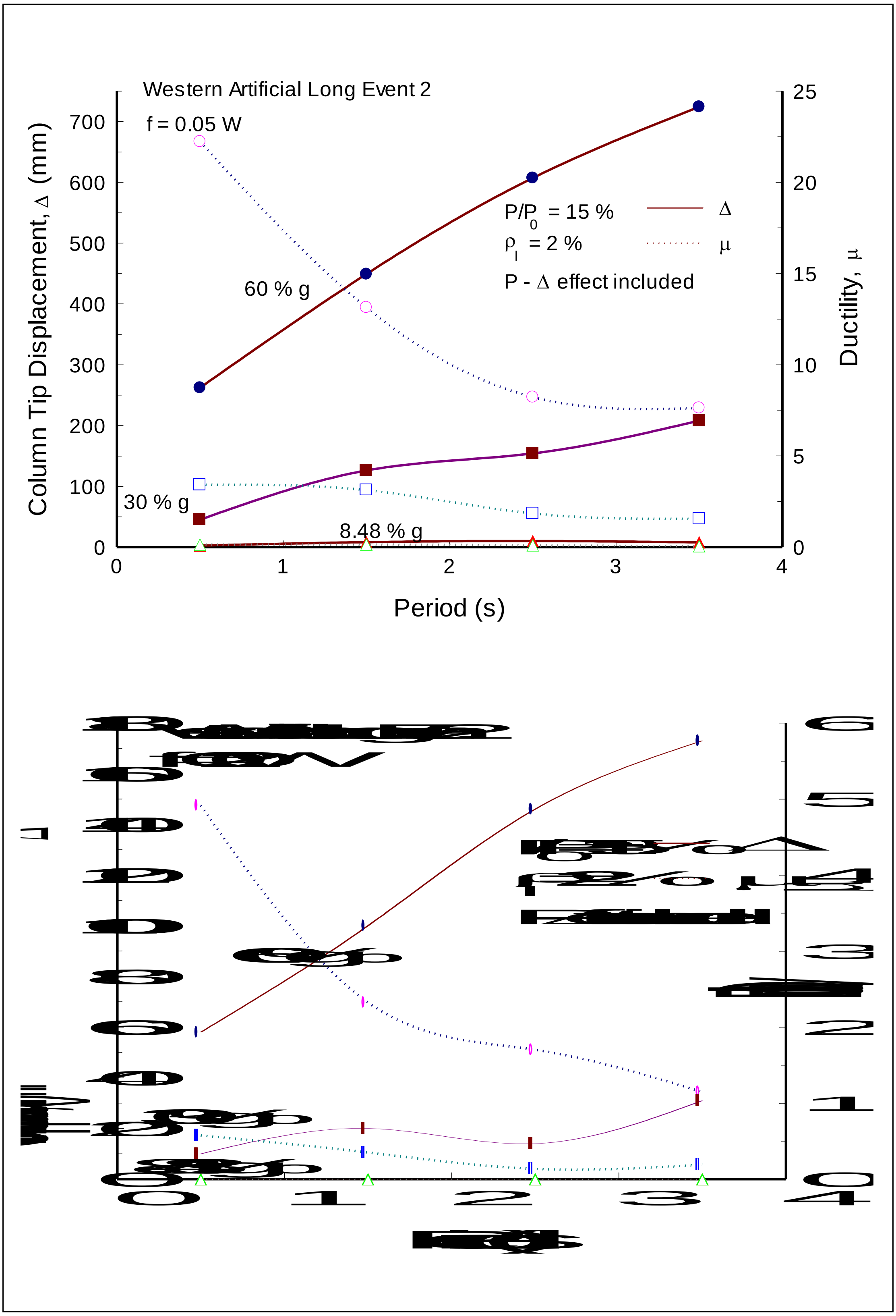

Figure 6. Western Artificial Long Event #2 Earthquake response of bridges with roller or rocker bearings with P-Δ effect.

The results also indicate that sliding properties of bridge bearings play a very significant role on bridge performance. When the onset of sliding was equal to 20% of bridge weight, the bridges remained elastic even under amplified ground motions of up to 30% g. When the sliding limit is reduced to 5% of bridge weight, inelasticity was observed under the same level of amplification. Increase in peak ground accelerations to match 60% g resulted in bridge failures (as indicated by unrealistically high displacement demands) when the sliding limit was 5% of bridge weight. At the same level of excitation, bridge bearings having a higher sliding force limit of 20% of bridge weight experienced high displacement demands, but remained intact, especially in the long period range.

Conclusions

The following conclusions can be drawn from this research project:

- The bridges can be modeled as a SDOF model for the purpose of dynamic analysis. The dominant parameter affecting structural response is the fundamental period, especially under intense earthquake records generating non-linear displacement response. It was found that the column tip deflection increases approximately linearly with increasing peak ground acceleration. Also, it was found that the relationship between ductility ratio and period is inversely proportional. This is expected because as the period increases, the spectral accelerations decrease along with ductility demands. This implies that bridge columns with low aspect ratios exhibit higher ductility demands.
- Among the critical earthquake ground motions considered, artificially-produced records generate higher displacement and ductility demands than recorded motions, especially in eastern Canada.
- Generally speaking, the majority of concrete bridges in Canada are expected to perform well during design level earthquakes if built on rock or firm soils. However, soil amplification associated with soft soil conditions result in significant increases in ductility demands in western Canada.
- Sliding properties of bridge bearings were shown to play a significant role on bridge response. If the onset of sliding is delayed to develop a lateral force resistance equal to 20% of bridge weight, the bridges remained elastic even under amplified ground motions of up to 30% g.

Acknowledgments

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