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# SEISMIC BEHAVIOUR OF RECTANGULAR R/C BRIDGE COLUMNS UNDER BIDIRECTIONAL EARTHQUAKE COMPONENTS

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## ABSTRACT

Modern bridge design codes and regulations generally require that the seismic demand on bridge columns under bidirectional earthquake ground motions be determined using the 30%-Rule of the effects of each component computed independently using response spectrum analysis. A research project consisting of a comprehensive analytical and experimental study has been undertaken to examine the adequacy of the 30%-Rule to predict the seismic demand on R/C bridge columns subjected to bidirectional earthquake components for two North American sites in areas of moderate seismic hazard: Montreal, in the East, and Vancouver, along the West coast. Results of the analytical study show that the combination rule is tributary of both ground motion and bridge characteristics and suggest that a lower percentage for eastern sites and a higher percentage for western sites would be more appropriate compared to the 30%-Rule currently prescribed by codes and regulations. A new combination rule with varying weighted percentage, 20% for eastern sites and 40% for western sites, is proposed to account for the differences observed for the two sites. The objective of the experimental program described in this paper is to validate the proposed combination rule through the testing of large scale rectangular R/C bridge columns under bidirectional ground motions.

## Introduction

The prediction of the seismic demand on structural elements subjected to bidirectional ground motion earthquakes can be achieved using the response spectrum dynamic analysis method. A unique ground motion spectrum is usually adopted and input independently in each of the two orthogonal directions and the structure is analyzed accordingly. The critical seismic demand is then estimated by combining the two maximum demand values computed in each of the two orthogonal directions using combination methods. These methods are the Percentage Rule (Newmark 1975, Rosenblueth and Contreras 1977), the SRSS Rule (Rosenblueth 1951), or the CQC3 (Lopez and Torres 1997, Menum and Der kiureguian 1998).

For bridge columns, whose responses depend on the interaction of several forces (e.g. axial force and bending moments), rigorous advanced response-spectrum-based methods for combining the effects of ground motion components have been developed (Menum and Der Kiureghian 2000). These methods underlie complex theories and imply cumbersome calculations

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that are beyond the normal day-to-day practice for design engineering firms. As an alternative, the Percentage Rule represents a simpler procedure for combining the effects of ground motion components for bridge columns, especially for the common case of regular bridge structures. Consequently, the Percentage Rule has been widely accepted and is now prescribed in most seismic bridge design codes.

In North American bridge design codes (e.g., CSA 2006, ATC 2003, AASHTO 1996), the critical seismic response $R$ in bridge columns is obtained by combining the maximum responses $R_1$ and $R_2$ associated to each component of the ground motion earthquake, using the Percentage Rule:

$$R = R_1 + \alpha R_2 \tag{1}$$

$$R = \alpha R_1 + R_2 \tag{2}$$

where $\alpha$ is the weighted percentage defining the Rule. A unique value of $\alpha$ is typically prescribed. However, there is no general acceptance on the value of $\alpha$ among codes and regulations; while some codes prescribe $\alpha = 0.3$ (e.g. CSA 2006, AASHTO 1996), as suggested by Rosenblueth and Contreras (1977), others prescribe rather $\alpha = 0.4$ (e.g., ATC 2003), as suggested by Newmark (1975). Past studies related to the adequacy of the Percentage Rule generally indicate that the Rule can either underestimate or overestimate the critical response by as much 30% when compared to the exact response obtained from time-history analyses (e.g., Wilson and al. 1995, Menum and Der Kiureghian 1998). However, these studies were conducted for single response quantities from which the adequacy of the Percentage Rule cannot be generalized to the case of multiple response quantities that characterize structural elements such as bridge columns. Furthermore, none of these studies addressed the issue of the effect of the structure or the ground motion characteristics on the Percentage Rule.

A research project consisting of a comprehensive analytical and experimental study has been undertaken by the authors to examine the adequacy of the 30%-Rule to predict the seismic demand on regular R/C bridge columns subjected to bidirectional earthquake components for two North American sites in areas of moderate seismic hazard: Montreal, in the East, and Vancouver, along the West coast. This paper summarizes the key findings of this study. The adequacy of the 30%-Rule is assessed throughout elastic and nonlinear dynamic analyses on a series of common regular bridge models. A new Percentage Rule that takes explicitly into account the ground motion and the bridge characteristics is proposed. The test set up and procedure used for the multi-axis testing of rectangular bridge piers designed with the proposed Percentage Rule and subjected to bidirectional seismic loadings is also briefly discussed.

## Earthquake ground motion records

Montreal and Vancouver were chosen as representative cities for eastern and western Canada, respectively. The selection of earthquakes representative of these regions was made based on the deaggregation of the seismic risk at each site in terms of most likely magnitude (M) and epicentral distance (R) scenarios for a probability of exceedance of 2% in 50%. The predominant M-R scenarios are M6.0 at 30 km, M6.5 at 50 km, and M7.0 at 70 km for Montreal, and M6.5 at 30 km and M7.2 at 70 km for Vancouver. Seven and nine pairs of orthogonal ground motion records were selected for Montreal and Vancouver, respectively. The earthquakes consist of recorded historical events as well as simulated earthquakes (SIM) provided by Prof. G. Atkinson (Personal communication 2005).

The site condition for the recorded and the simulated earthquakes are representative of site Class C, corresponding to an average shear-wave velocity of about 560 m/s, except for the Saguenay and Nahanni earthquakes which were recorded on hard rock. Site response analyses were first performed to modify the Saguenay and Nahanni recordings and make them appropriate for Class C site conditions. Finally, the horizontal components of all the selected earthquakes were transformed into their principal directions according to the Penzien and Watabe approach (Penzien and Watabe 1975).

## Effectiveness of the 30%-Rule

The adequacy of the 30%-Rule to predict the seismic demand on bridge columns subjected to bidirectional earthquake components was examined (Khaled and al. 2009). Nine (09) two-span generic bridge models (Fig.1) were considered. The prototype bridges used to develop the generic bridge models are regular bridges that are representative, in terms of characteristics, of a large number of bridge structures encountered in Montreal and Vancouver highways and consist of: (i) straight bridges, (ii) skewed bridges with 22$^{o}$ skew angle, and (iii) curved bridges with 30 m radius of curvature. The bent systems of these models are single column bents and multi-columns bents with circular, rectangular, and wall type columns. The columns are 8.0 m tall. They are fixed at the base and pin-connected at the top. The geometric characteristics as well as the fundamental periods of vibration along the longitudinal and transverse directions of the bridge models considered in this study are summarized in Table1.

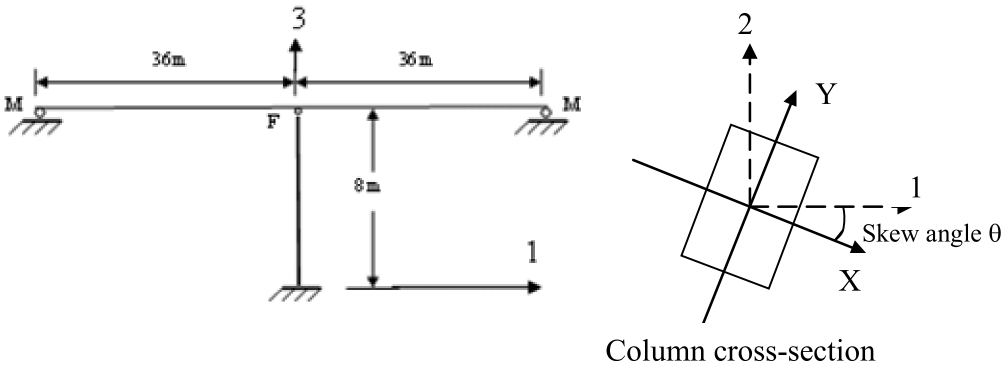


Figure 1. Typical elevation view of the generic bridge models.

Two series of dynamic analyses were performed on the selected bridge models using the SAP2000 program (CSI 2006). In the first series, time-history analyses were performed to determine the critical seismic response, $R_{TH}$, of the bridge columns under the simultaneous action of orthogonal earthquake principal components. The input angle of the two orthogonal earthquakes components was varied from 0$^{o}$ to 180$^{o}$ in 30$^{o}$ increments. In the second series, response spectrum analyses of the bridge models were performed using the 5% damped acceleration spectra of the selected earthquakes to determine the maximum response in each direction. The probable response, $R_{30\%}$, is then estimated using the 30%-Rule.

Table 1. Characteristics of the generic bridge models.

| Bridge Model | Bridge Type | Bent System | Column Cross-Section ($m^2$) | $T_x$ (s) | $T_y$ (s) |
|---|---|---|---|---|---|
| DPCU | Straight | Single Column | Circular (Ø 2.2 m) | 0.764 | 0.338 |
| DPRU | Straight | Single Column | Rectangular (1.4×2.8) | 1.005 | 0.284 |
| DPM | Straight | Wall-Type Column | Rectangular (0.8×10) | 1.250 | 0.109 |
| DPCM | Straight | Multi-Columns | Circular (Ø 1.2 m) | 0.747 | 0.322 |
| DPRM | Straight | Multi-Columns | Rectangular (0.8×1.6) | 1.024 | 0.257 |
| BPRU | Skewed | Single Column | Rectangular (1.5×3.0) | 0.886 | 0.265 |
| BPRM | Skewed | Multi-Columns | Rectangular (0.9×1.8) | 0.714 | 0.233 |
| CPRU | Curved | Single Column | Rectangular (1.6×3.2) | 0.770 | 0.190 |
| CPRM | Curved | Multi-Columns | Rectangular (1.0×2.0) | 0.575 | 0.227 |

The critical responses $R_{TH}$ and $R_{30\%}$ were identified, through a design process, as the ones producing the largest failure surface of the columns. The adequacy of the 30%-Rule at predicting the seismic response is investigated by comparing $R_{30\%}$ to $R_{TH}$, in terms of interacting moments ($Mx$, $My$) at the base of the columns. For the nine bridge models and the sixteen ground motions considered, a total of 144 graphs, representing the seismic response of the bridge columns to bidirectional earthquakes at both sites were obtained and analyzed. Typical results are presented in Fig. 2 for Montreal (east site) and Vancouver (west site).

Analysis of the results indicate that the critical seismic demand on bridge models located in Vancouver (west site) tend to be underestimated by the 30% - Rule, whereas for bridge models

(a) BPRU model under Saguenay EQ (b) DPCU model under Whittier Narrow EQ

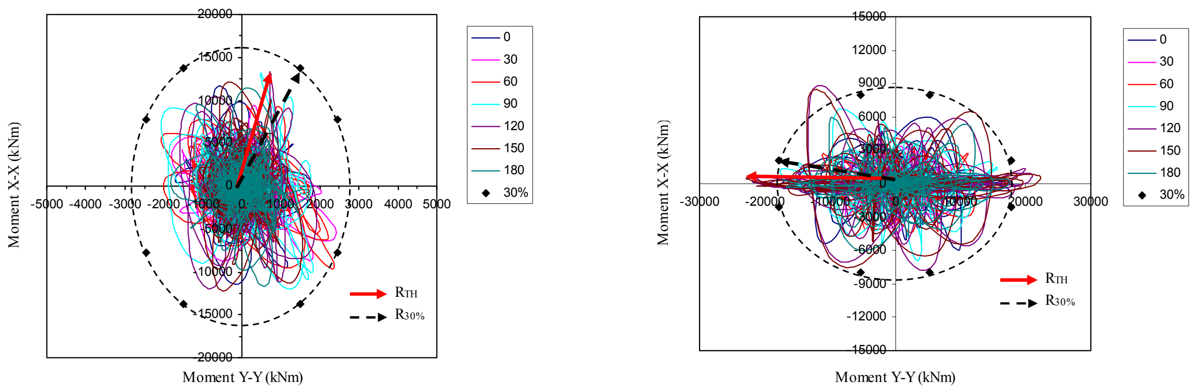


Figure 2. Comparison of time-history ($R_{TH}$) and response spectrum ($R_{30\%}$) results for: (a) Montreal (east site), (b) Vancouver (west site).

located in Montreal (east site) the 30%-Rule tends to overestimate on average the seismic response. The use of the 30%-Rule introduced a mean absolute error of the order of 7% when compared with time-history results. In some cases, the 30%-Rule was found to underestimate or overestimate the exact response by more than 21% and 19%, respectively. These results show a difference in the demand expected from earthquakes expected in eastern and western sites and suggest that a lower value of α (in Eqs. 1 and 2) for eastern Canada and a higher value for western Canada could yield more accurate results compared to the unique 0.3 value currently prescribed by the majority of bridge design codes.

## Improved Percentage Rule

An improved combination rule for predicting the seismic demand on regular bridge columns is developed. The improved combination rule implicitly accounts for both the bridge and ground motion's characteristics by specifying a variable weighted percentage. The required column reinforcement ratios of nine regular bridge models with varying characteristics (Table 2 ) were determined using the combination rule with different values of the weighted percentage α (0, 0.3, and 1.0) and compared to those obtained from multiple elastic time-history analyses to identify the bridge characteristics that influence the most the combination rule.

### Scaling of the earthquake ground motions

The two orthogonal principal components of the selected ground motion earthquakes listed in Table 1 were scaled to 2%/50 year uniform hazard spectra (UHS) using a loose spectral technique. The two resultant spectra were then separated by scaling up and down the response spectra to have a spectral ratio of the minor to the major component of 0.75 (Lopez et al. 2006). The spectral accelerations at T = 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0, and 4.0 s are equal to, respectively, 0.65, 0.71, 0.69, 0.5, 0.39, 0.34, 0.14, 0.048 and 0.024 for Montreal and to 0.80, 0.95, 0.96, 0.84, 0.74, 0.66, 0.34, 0.18 and 0.09 for Vancouver.

Table 2. Characteristics of the bridge models.

| Bridge model | Type | Bent system | Number. of spans | Column height (m) | Column cross-section ($m^2$) |
|---|---|---|---|---|---|
| DPCU | Straight | Single column | 2 | 6.0 | Circular: Ø 1.2 m |
| DPRU | Straight | Single column | 2 | 6.0 | Rectangular : 1.2×2.4 |
| DPM | Straight | Wall-type | 2 | 6.0 | Rectangular: 0.8×6.0 |
| BPRU | Skewed | Single column | 2 | 6.0 | Rectangular : 1.2×2.4 |
| BPM | Skewed | Wall-type | 2 | 6.0 | Rectangular: 0.8×6.0 |
| CPRU | Curved | Single column | 2 | 6.0 | Rectangular: 1.6×2.8 |
| DPRI | Straight | Multi-columns | 4 | 6.0 / 10.0 | Rectangular: 1.2×2.4 |
| IRR-C | Skewed/Curved | Multi-columns | 5 | 6.0 / 10.0 | Circular: Ø 1.8 m |
| IRR-R | Skewed/Curved | Multi-columns | 5 | 6.0 / 10.0 | Rectangular: 1.2×2.2 |

## Analysis and design procedures

Elastic response spectrum analyses of the bridge models were performed independently in each of the longitudinal and transverse directions using the NBCC 2005 design spectrum (Table 3) and the critical combined biaxial moments (*Mx, My*) were estimated using the combination rule given by Eqs. (1) and (2). Three values of $\alpha$ were considered: (a) $\alpha = 0$, (b) $\alpha = 0.3$, and $\alpha = 1.0$. The critical combined biaxial moments were also computed using multiple linear modal time-history analyses with the pair of the scaled components of the earthquake ground motion earthquakes as input.

The bridge columns were designed for both sites based on the seismic requirements of the CSA-S6-06 standards (CSA 2006). The specified strength *f'c* and the modulus of elasticity *Ec* of the concrete were set equal to 35 MPa and 26 000 MPa, respectively, whereas the yield stress *fy* = 400 MPa and the modulus of elasticity *Es* = 200 000 MPa, were assumed for the steel reinforcement. The critical seismic induced biaxial moments were reduced by the appropriate reduction factor *R*, as prescribed by the CSA-S6: *R* = 3.0 for *Mx* and *My*, for single or multiple ductile columns and 2.0 for *My* for wall-type piers. The required reinforcement ratio $\rho$ was determined for a combination of (*P, Mx, My*), where *P* is the axial load in the column. For each bridge model and site, the optimum required longitudinal reinforcement ratios $\rho_{0\%}$, $\rho_{30\%}$, $\rho_{100\%}$, and $\rho_{TH}$ were computed adopting $\alpha = 0$ for $\rho_{0\%}$, $\alpha = 0.3$ for $\rho_{30\%}$, $\alpha = 1.0$ for $\rho_{100\%}$, and based on time-history analysis results for $\rho_{TH}$.

The results show that the required reinforcement ratios for the bridge columns designed at the Montreal site, with $\alpha = 0$ and $\alpha = 0.3$, varies between 0.35% and 0.73%. These values are below the lower limit of 0.8% specified in CSA-S6. That lower limit requirement is met for all bridges located in Vancouver. The results also show that for both sites, the computed value of $\rho_{0\%}$ and $\rho_{30\%}$ are nearly equal for the bridge models without skewed columns (DPCU, DPRU, DPM, CPRU, and DPRI), the increase in steel being less than 4% among all cases when applying the 30%-Rule (average increase = 1.7%). This difference is more pronounced in the case of the bridge models with skewed columns (BPRU, BPM, IRR-C, and IRR-R) with an average increase of 21% and 19% for Montreal and Vancouver, respectively. This suggests that the skew angle $\theta$ of the bridge columns may have a significant influence on the weighted percentage $\alpha$ used in the combination rule.

## Effect of the column skew angle on the combination rule

To assess the significance of the effect of the column skew angle on the weighted percentage $\alpha$, a second series of analyses and designs were performed on a two spans simple column skewed bridge (BPRU type bridge) by varying the column skew angle $\theta$ from 0° to 45° and following the same procedure used previously. The results are summarized in Table 3.

The required reinforcement ratios $\rho_{0\%}$, $\rho_{30\%}$, and $\rho_{100\%}$ are compared to $\rho_{TH}$ for both sites in terms of the relative error given by:

$$Relative\ Error = \left( \frac{\rho_{\%}}{\rho_{TH}} - 1 \right) \times 100 \quad (\%) \tag{3}$$

Table 3. Required reinforcement ratio of the bridge column for different values of θ.

| Bridge | Montreal (east site) | | | | Vancouver (west site) | | | |
|---|---|---|---|---|---|---|---|---|
| | $\rho_{0\%}$ | $\rho_{30\%}$ | $\rho_{100\%}$ | $\rho_{TH}$ | $\rho_{0\%}$ | $\rho_{30\%}$ | $\rho_{100\%}$ | $\rho_{TH}$ |
| BPRU_0° | 0.54 | 0.56 | 0.67 | 0.56 | 1.56 | 1.60 | 1.75 | 1.75 |
| BPRU_10° | 0.54 | 0.60 | 0.79 | 0.56 | 1.56 | 1.70 | 2.15 | 1.75 |
| BPRU_20° | 0.52 | 0.63 | 0.90 | 0.56 | 1.51 | 1.75 | 2.43 | 1.80 |
| BPRU_30° | 0.48 | 0.63 | 0.96 | 0.56 | 1.36 | 1.70 | 2.60 | 1.80 |
| BPRU_35° | 0.38 | 0.60 | 0.98 | 0.56 | 1.26 | 1.65 | 2.71 | 1.80 |
| BPRU_45° | 0.40 | 0.56 | 0.98 | 0.56 | 1.07 | 1.51 | 2.71 | 1.80 |

At both site, the relative error generally increases when increasing the skew angle to reach approximately 30% for Montreal site and 40% for Vancouver site. For Montreal, the 30%-Rule slightly overestimates the required amount of steel with a maximum relative error of 12.5% for θ = 30°, whereas for Vancouver the 30%-Rule underestimates the required amount of steel with a minimum relative error of -16.1% for θ = 45°.

**Proposed weighted percentage α for regular skew bridges**

An ideal weighted percentage is derived by determining, by linear interpolation between the steel quantities $\rho_{0\%}$, $\rho_{30\%}$, and $\rho_{100\%}$, the percentage α that will give the value of $\rho_{TH}$ obtained from time-history analysis. For Montreal, the optimum weighted percentage increases nearly linearly from 0 to 30% with the skew angle of the bridge column, with an average value of 20%, whereas for Vancouver it remains almost constant, at an approximate value of 40%.

Based on the results presented in the previous sections, the following values of the weighted percentage are suggested for the combination rule for design of regular bridges located in eastern and western Canada.

*Eastern Canada:*

*For skew angles less or equal to 10°, $\alpha = 0\%$*

*For skew angles larger than 10°, $\alpha = 20\%$*

*Western Canada:*

*For skew angles less or equal to 10°, $\alpha = 0\%$*

*For skew angles larger than 10°, $\alpha = 40\%$*

## Validation of the proposed combination rule

Multi-directional cyclic testing has been performed on half-scale bridge columns to validate the proposed combination rule and the seismic design requirements for bidirectional seismic loading, with special interest in the difference in demand anticipated from earthquakes expected in eastern and western regions in North America. Four R/C 3000 mm tall bridge column specimens having a 600 × 1200 mm rectangular cross-section were tested in the Hydro-

Québec Structural Engineering Laboratory at Ecole Polytechnique of Montreal. The four specimens were divided in two sets. The first set, S1 and S2, representative of skewed columns ($\theta = 30^o$) located in Montreal (east site) were designed with $\alpha = 0$ and $\alpha = 0.3$, whereas the second set, S3 and S4, representative of skewed columns ($\theta = 45^o$) located in Vancouver (west site) were designed with $\alpha = 0$ and $\alpha = 0.4$. Table 4 summarizes the design results.

Table 4. Design of the column specimens.

| Column Specimen | Combination Rule | Axial Load Index | Provided Reinforcement Ratio (%) | Longitudinal Rebar ∗ | Transverse Reinforcement |
|---|---|---|---|---|---|
| S1 | 100%-0% | 0.06 | 0.41 | 42 - #3 | #3 @ 45 mm |
| S2 | 100%-30% | 0.06 | 0.57 | 32 - #4 | #3 @ 45 mm |
| S3 | 100%-0% | 0.06 | 0.94 | 34 - #5 | #3 @ 40 mm |
| S4 | 100%-40% | 0.06 | 1.72 | 32 - #7 | #3 @ 45 mm |

∗ Imperial bar sizes.

Two general bidirectional displacement-prescribed cyclic loading were developed based on results of nonlinear time-history analyses. The bidirectional displacement-prescribed cyclic loadings follow a “butterfly-type” path, as illustrated in Fig. 3(b), and were intended to reproduce the estimated average orbital displacement of the prototype bridges (Fig. 3(a)) under earthquakes expected in eastern and western regions of North America.

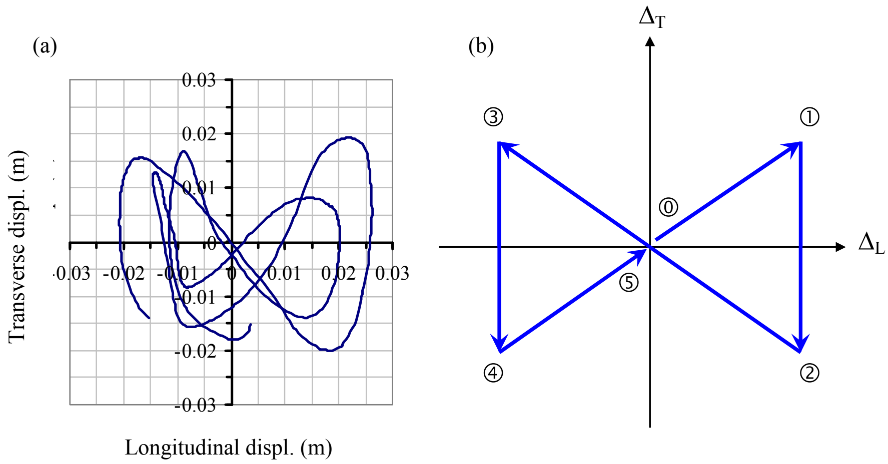


Figure 3. Bidirectional cyclic loading: (a) Orbital displacement of the prototype column; (b) Displacement-prescribed loading path used for cyclic testing.

(a) (b)

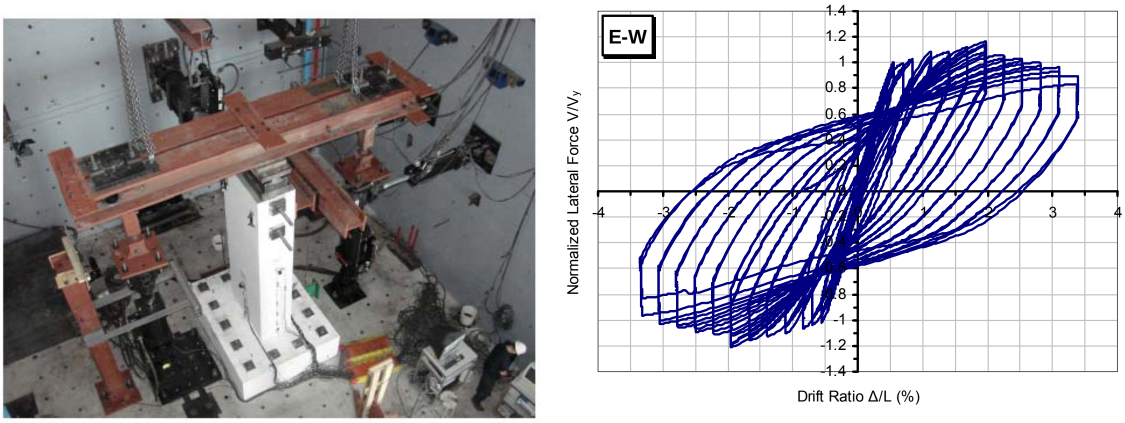


Figure 4. Experimental program: (a) Test setup; (b) Typical response of the column.

The test columns were subjected to a constant gravity load of 1566 kN and a simultaneous displacement-prescribed loading in the two orthogonal directions using five high performance structural actuators as illustrated in Fig. 4(a). In the test setup, constant gravity load was applied using 2-1000 kN vertical actuators. Lateral displacement protocols were imposed simultaneously along the X and Y axes (see Fig. 1) at the column top using three horizontal actuators reacting against a 10 m tall L-shaped reaction wall. In-plane torsional rotation of the column top was constrained to zero during the tests., such that response under the combination of the bending moments about both X and Y directions, as determined from previous time-history analyses could be examined. Typical response is shown in Fig. 4(b). The tests confirmed the adequate behavior of the column specimens under the effects of combined seismic actions in both orthogonal directions.

## Conclusions

A research project consisting of a comprehensive analytical and experimental study has been undertaken to examine the adequacy of the 30% combination rule to predict the seismic demand on R/C bridge columns subjected to bidirectional earthquake ground motion. This study is limited to regular bridge structures for which simple combination rules such as the Percentage Rule are likely to be used in conjunction with response spectrum analysis in design. Based on the results of this study, the following main conclusions were reached:

(i) The combination rule for predicting the seismic demand on regular bridge columns should account for the effect of the skew angle and ground motion characteristics.

(ii) The value of the weighted percentage varies linearly with the skew angle for a bridge located in eastern Canada (Montreal), whereas it remains nearly constant for a bridge located in western Canada (Vancouver).

(iii) For an adequate prediction of the seismic demand on regular bridge columns under multi-directional ground motion components, it is suggested to use a 20%-Rule for bridges located in eastern site and a 40%-Rule for bridges located in western site, when the column skew angle exceeds $10^{o}$.

(iv) Bi-directional testing was carried out that confirmed the adequacy of the proposed combination rule. The columns exhibited satisfactory inelastic cyclic bi-directional response up to high ductility levels way beyond the design level demand and were able to achieve their predicted nominal flexural capacities up to the last cycle before failure.

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