Vertical acceleration and torsional effects on the dynamic stability and design of C-bent columns

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2014 NZSEE Conference

ABSTRACT: C-bent columns are cantilever columns with an off-centred beam. These are used to support bridge decks where a column cannot be placed directly under a bridge span. Due to eccentricity of gravity loads caused by the beam offset, these columns tend to predominantly deform in the direction of the eccentricity in seismic events. Guidelines to reduce this tendency have been recently recommended, but do not consider vertical acceleration and torsional effects. This study examines the influence of these effects on the response of C-bent columns using ground motion records in all three lateral directions, and whether the recommended guidelines are adequate. For simplicity the axial, flexural, shear and torsional strength interaction was ignored. It was found that the inclusion of vertical accelerations caused an even greater tendency for the column to deform more in one direction. However the recommended guidelines still provide the most optimal design overall. The maximum torsional demand observed in analyses was only 11% of its capacity, and a maximum total rotation of less than 0.53^{o} was observed for a 10m tall column. This indicates that torsional response was unlikely to have a significant influence on the overall performance of the column, and that the recommended guidelines appear to be sufficient.

1 INTRODUCTION

C-bent bridge columns are cantilever columns which are loaded asymmetrically. These columns are usually used where space is limited to build the column concentrically. An example of such a column is shown in Figure 1, where the column had to be shifted to accommodate a right-turning lane. As the right cantilever beam is longer than that of the left, loading eccentricity will occur.

Figure 1. Example of C-Bent column

Due to the eccentric loading, C-bent columns are generally designed stronger on the tension/least compression side (under static loading) by a strength difference ratio, β, according to Equation 1.

$$M_y^+ = M_y^- + \beta M_E \qquad (1)$$

Where M_y^+ is the yield moment capacity in the direction of the eccentricity, M_y^- is the absolute yield moment capacity in the opposite direction, and M_E is the eccentric moment applied to the column (equal to the deck load, P multiplied by the lever arm, e).The general configuration of these columns is shown in Figure 2.

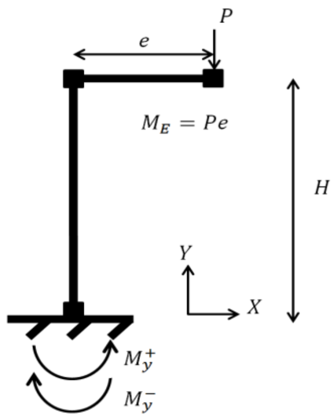


Figure 2. C-bent Column

The Japanese Road Code (1990) recommends a β value of 1 to use in design. However, experimental studies of C-bent columns (e.g. Ogasawara et al. (1999), Otsuka et al. (2004) and Kawashima et al (2010)) showed that columns designed for $\beta = 1$ tend to predominantly deform more in the direction of the eccentric loading, indicating that $\beta = 1$ is not sufficient to optimize dynamic stability. MacRae and Kawashima (1993) developed and applied the "Hysteretic Centre Curve" concept to bilinear responding C-bent columns, and found that $\beta = 2$ provided optimal dynamic stability when *P*-delta effects were ignored. Yeow et al. (2013) conducted further analytical studies on bilinear responding C-bent columns and found that the optimum β including *P*-delta effects can be given by Equation 2. Here *H* is the column height, *E* is Young's Modulus, and *I* is the column's moment of inertia.

$$\beta_o = \frac{2}{1 - \dfrac{PH^2}{2EI}} \qquad (2)$$

In these analytical previous studies however, the effects of vertical ground motion accelerations and torsional effects on these columns were ignored. This study examines the influence of these effects on the performance of several case study columns subjected to realistic ground motion records in all three lateral directions. The aim of this study is to identify if (i) vertical and torsional effects on the columns are significant, and (ii) whether the design approach using Equation 2 is valid if these effects are considered.

2 METHODOLOGY

The analytical framework utilized in this study is shown in Figure 3 and was executed using MATLAB (The Maths Works Inc, 2012). The base column model was based off Kawashima et al. (2010). The C-bent column's height (*H*) was 10 m, with a square cross section of 3.4m widths. The weight of the deck (*P*) was 6545kN, and the distance to the mass centroid (*e*) was 4.3m. The design elastic moment demand, *M*(*R*=1), was 72,000 kNm. The capacity reduction factor of the system (*R*) was assumed to be 4.0. The period of the column was varied between 1.0 and 1.5 s, and the value of β was varied from 1 to 3.

The analytical model is shown in Figure 4a. A flexural rotational spring at the base of the column (between nodes 1 and 3) was used to model the column's plastic moment-rotation assuming bilinear hysteretic behaviour (post-elastic force-displacement bilinear factor of 4% assumed). The initial rotational stiffness was idealised as infinitely stiff to minimize additional flexibility in the column prior to yielding (i.e. rotation occurs only when the base yield moment is exceeded). Other column and beam elements (elements connecting nodes 2 to 3 and 2 to 4) were represented using elastic elements.

The torsional capacity of the column was obtained using recommendations from the American Concrete Institute (1995), and was determined to be 500 MNm. Inelastic torsional behaviour was modelled using a torsional rotation spring at the base of the column assuming bilinear hysteresis rule.

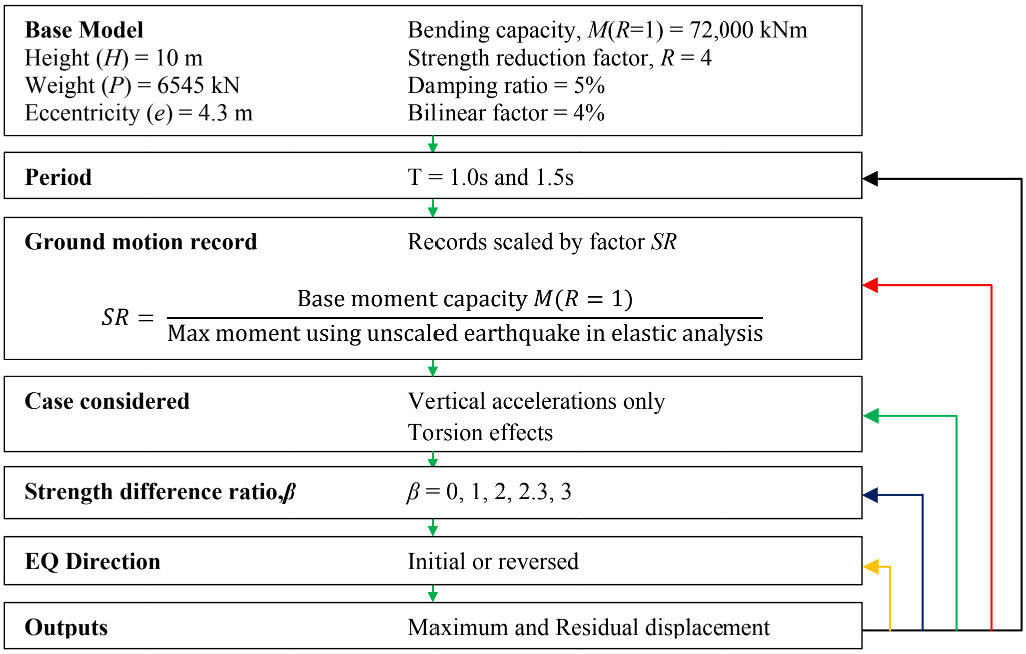
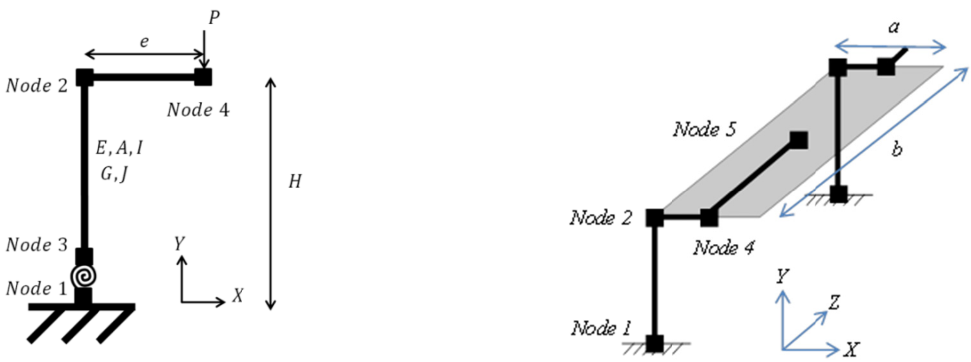


Figure 3. Analysis procedure.



(a) Front elevation **(b)** Plan view

Figure 4. C-bent column model with rotational spring.

In order to model torsional response, the effect of the bridge deck needs to be considered. In Kawashima et al. (2010), the deck span was 12m wide (*a*) and 30m long (*b*). It was assumed the deck span was fixed at one column and is on rollers at the connecting column. Figure 4b shows the location of the centre of mass of the deck (node 5). The torsion rotational masses were obtained using Equations 3-5, where *M* was the mass of the deck span.

$$m_{xx} = \frac{M}{12} \times \left(\frac{b}{2}\right)^2 \tag{3}$$

$$m_{yy} = \frac{M}{3} \times \left[\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2\right] \tag{4}$$

$$m_{zz} = \frac{M}{12} \times \left(\frac{a}{2}\right)^2 \tag{5}$$

Inelastic dynamic response history analyses were conducted in OpenSees (McKenna et al, 2000) using the constant acceleration Newmark integration scheme. The SAC suite of realistic near fault ground motions (SAC, 2000), which are representative of a 1 in 475 year event for seismic zone 4 conditions (in the US), were used in the analyses. This suite consists of ten sets of ground motion records, each with one vertical and two orthogonal horizontal components. These were used as near fault ground motions generally have higher vertical accelerations, which provide a 'worst case scenario'. The ratio of the average vertical and horizontal peak ground accelerations was calculated to be 0.64.

To minimise the effects of directionality, each analyses was repeated by reversing one horizontal component of the ground motion. The maximum and residual drifts (including signs) obtained from running each set of records were averaged and plotted against β. The β value corresponding to a maximum or residual drift of 0 (e.g. same response in both directions) was considered the optimum β. Note that axial, flexural, shear and torsional strength interaction was ignored in this study for simplicity, as this study is exploratory in nature to examine the possible influence of vertical acceleration and torsion on the response of the column.

3 RESPONSE OF C-BENT COLUMNS TO VERTICAL GROUND MOTION EFFECTS

3.1 Effect of vertical mass on the global C-bent column behaviour

The base moment versus deck displacement (relative to ground) response of an elastic C-bent column (T = 1.5 s) considering in-plane horizontal (x-direction) and vertical masses/ground motion records, and excluding P-delta effects, is shown in Figure 5. It can be seen that the response is highly non-linear, despite the column remaining elastic. This effect is attributed to the presence of two distinct bending moment patterns along the column caused by (i) horizontal accelerations acting on the horizontal mass and (ii) vertical accelerations acting on the vertical mass. This is shown in Figure 6. The moments caused by horizontal and vertical action is shown in Equations 6 and 7 respectively.

$$M_h(t) = m_h a_h(t) H \tag{6}$$

$$M_v(t) = m_v a_v(t) e \tag{7}$$

Where m and a are the mass and acceleration of node 4, M is the base moment demand, and the h and v subscripts represents horizontal and vertical directions respectively.

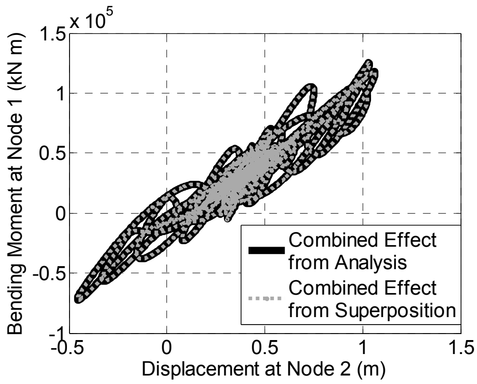


Figure 5. Stiffness variation due to interaction between horizontal and vertical mass. (*R* = 1.0, *T* = 1.5 s)

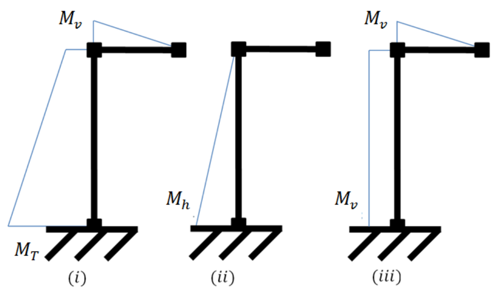


Figure 6. Bending moment diagrams: i) combined, ii) effect of horizontal mass, iii) effect of vertical mass.

As the eccentricity of the mass is comparable to the height of the column, these two moments are similar in magnitude. In addition, the stiffness of the column against horizontal action is 1.5 times that of the stiffness against vertical action. Due to this, the superposition of the moments and displacements caused by the horizontal and vertical action will be non-linear (unless the ratio of α_h and α_v remains constant throughout shaking). The validity of this effect was investigated by separating the bending moments into its two components. The total moment demand was recorded at nodes 1 and 2 throughout the analyses. This corresponds to the total base moment demand (M_T) and M_v respectively based on Figure 6. From this, M_h can be obtained as:

$$M_h(t) = M_T(t) - M_v(t) \tag{9}$$

Knowing M_h and M_v and the column stiffness for each of these bending moment patterns, the displacement resulting from horizontal and vertical actions were obtained. The moments and displacements were then superimposed together, the result of which matches the recorded moment-displacement exactly, as shown in Figure 5. This shows that the response against each individual component is still linear, despite the combined action being non-linear.

3.2 Vertical accelerations only

The average drift-β response of C-bent columns (R = 4) subjected to vertical accelerations and in-plane horizontal accelerations separately is shown in Figure 7. In this case, there is no yielding in the column when analysing using vertical ground motion components only. As such, the average drifts are always 0. This implies that its influence on the response is likely to be lower than that of horizontal components. The trend observed for horizontal ground motions only is similar to that observed in Yeow et al. (2013), where the column has a greater tendency to deform in the positive direction for low β values. While not shown here, these results were similar for other cases using different R, T, column geometries and ground motion record suites.

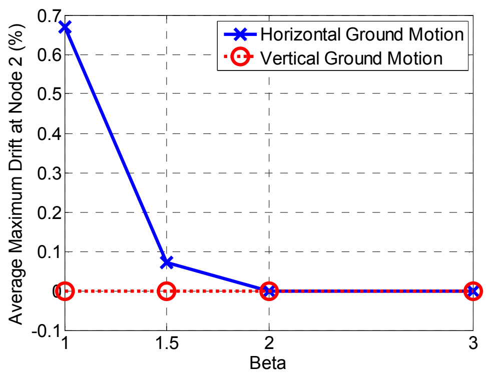


Figure 7. Comparison of vertical and horizontal ground motions. (*R* = 4, *T* = 1.5 s, P-Δ effects excluded)

3.3 Horizontal and Vertical Accelerations with Vertical and Horizontal Masses

The average drift-β response of C-bent columns (R = 4, T = 1.5 s) subjected to both vertical and horizontal ground motions simultaneously with horizontal and vertical masses attached is shown in Figure 8. It is shown that the averaged drifts are larger when vertical ground motions are considered (over 100% larger in the β = 1.5 case). However, from approximately β = 2.3 (obtained using Equation 2) there is very little change in the averaged drifts. This implies that at this value, the column does not have a tendency to deform in any one particular direction. This would suggest that recommendations provided by Yeow et al. (2013) is sufficient, even in cases were vertical accelerations were considered.

Additional results for other cases considering both vertical and horizontal ground motions and masses are shown in Figure 9. In all cases, there is a tendency for the column to deform more in the positive direction for smaller β values. As with Figure 8, the β value corresponding to the lowest averaged drifts is the same as that obtained from Equation 2. This suggests that the recommendations provided by Yeow et al. (2013) are applicable to the range of columns considered in this study.

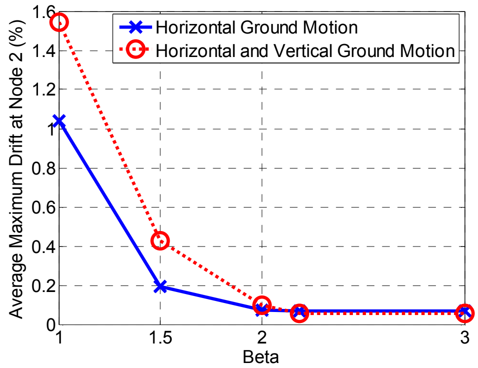
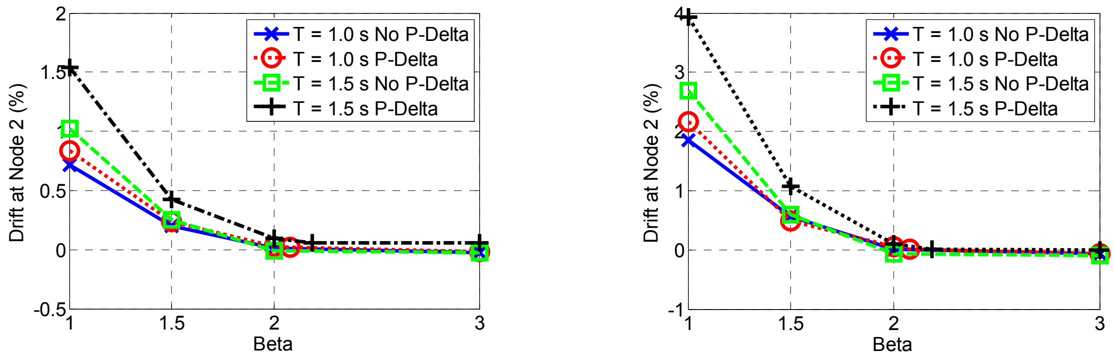


Figure 8. Comparison of optimum *β* when including vertical ground motions – horizontal and vertical masses attached. (*R* = 4, *T* = 1.5 s, *P*-Δ effects included)



(a) Average maximum drifts

(b) Average residual drifts

Figure 9. Comparison of optimum design *β* from including vertical ground motions with horizontal and vertical masses attached.

As previously mentioned, axial-flexural interaction was ignored in this study. Further studies are required to check if consideration of this interaction has any effect on the overall column response. Also note that, as the drifts in Figure 10 are averages (including signs), it is valid for the average residual drifts to be higher than the average maximum drifts. This does not imply that the maximum drifts are lower than the residual drifts. While not shown here, the absolute maximum drifts obtained were always higher than the residual drifts.

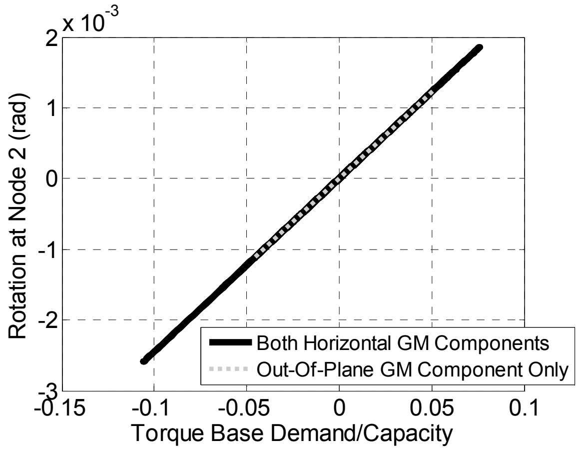
4 RESPONSE OF C-BENT COLUMNS TO TORSIONAL EFFECTS

Figure 10a compares the column's torsional response between using the out-of-plane horizontal component only (z direction) against using both horizontal components (x and z directions). The response using both horizontal components results in greater maximum torque. However, in both cases the torsional capacity was not exceeded (maximum demand was only 11% of its capacity).

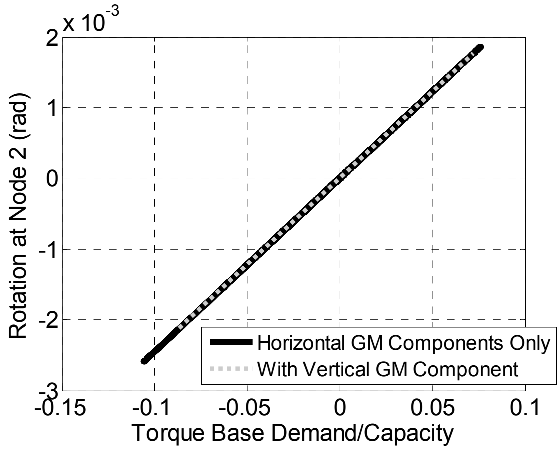
The response using all three components was compared against the case using both horizontal components and is shown in Figure 10b. Interestingly, the torsional response decreases when vertical acceleration was considered compared to using only the horizontal components. However the case with all ground motion components combined still exhibits a larger response than the case where only the out-of-plane horizontal component was considered. Again the resulting maximum torque does not exceed the torsion capacity of the column during either of the simulations.

Additional cases were analysed where the rotational stiffness and rotational mass was varied to consider other scenarios. The rotational stiffness and the rotational mass of the C-bent column were varied from 10 to 100% of its original value. The relationship between rotation at the top of the column and rotational stiffness/mass is shown in Figures 10c and 10d respectively. There is a clear relationship between the column's rotation and the rotational stiffness of the C-bent system, where the column's rotation decreases as the rotational stiffness of the column increases. However there is no clear relationship for the case where the rotational mass of the system is varied (all within 10% of the maximum rotation).

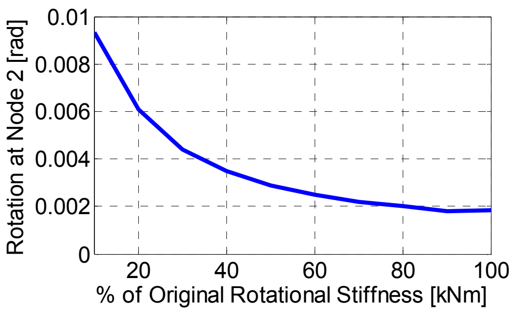
The maximum torsional rotation observed is 0.0092 radians or 0.53°. This rotation corresponds to a translation of 280 mm at the roller end of the bridge deck. This is less than 2.5% of the total cantilever beam length (12 m). As this displacement is relatively small, and that the maximum torsional demand was also small in comparison to its capacity, torsional effects are unlikely to influence the recommended guidelines proposed by Yeow et al. (2013).



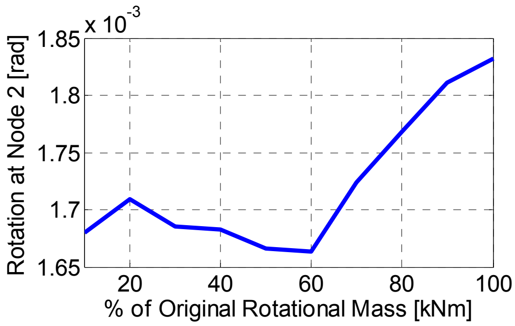
(a) Effect of including horizontal shaking components



(b) Effect of including vertical shaking components



(c) Effect of rotational stiffness



(d) Effect of rotational mass

Figure 10. Influence of ground motion components, rotational stiffness and mass on torsional response.

5 CONCLUSIONS

From the inelastic response history analysis conducted with the assumptions of bilinear hysteresis behaviour and ignoring axial, moment, shear and torsional interaction, it was found that:

- Inclusion of vertical ground accelerations in combination with horizontal ground accelerations can cause the column to have an even higher tendency to deform predominantly more in one direction over the other.
- Despite the increased response due to vertical accelerations, the expression derived by Yeow et al. (2013) (shown in Equation 2) still provides the optimal strength difference.
- Torsional effects caused a horizontal displacement of no more than 280 mm on roller end of the bridge deck (less than 2.5% of the C-bent column cantilever beam length). Also, the median torsional force was less than 11% of the torsional capacity so torsional inelasticity was not expected. Based on this, it is unlikely that torsion will have a significant influence on the general design of the column

REFERENCES

American Concrete insitute. (1995). Building Code Requirements for Structural Concrete (ACI318-95).

Japan Road Association. [1990], Design Specifications for Road Bridges Part V Seismic Design.

Kawashima, K., Nagata, S., & Watanabe, G. (2010). Seismic Performance of a Bridge Supported by C-Bent Columns. *Journal of Earthquake Engineering*.

MacRae, G. A. and Kawashima, K. (1993). The seismic response of bilinear oscillators using Japanese earthquake records. *Journal of Research of the Public Works Research Institute*, 30. Ministry of Construction, Tsukuba, japan.

McKenna, F., Fenves, G. L., Scott, M. H., & Jeremic, B. (n.d.). Open System for Earthquake Engineering Simulation (OpenSees). Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Ogasawara, M., Tsuno, K., Ichikawa, H., Maekawa, K., & Tsuchiya, S. (1999). Multi-Axis Flexure Behavior and Nonlinear Analysis of RC Columns Subjected to Eccentric Axial Forces. *Proceedings of JSCE (Japan Society of Civil Engineers)*, 131-143(.

Otuska, H., Takeshita, E., Yabuki, W., Wang, Y., Yoshimura, T., & Tsunomoto, M. (2004). *Study on the Seismic Performance of Reinforced Concrete Columns Subjected to Torsional Moment, Bending Moment and Axial Force.* Proc. 13th World Conference on Earthquake.

SAC [2000] “Suites of earthquake ground motions for analysis of steel moment frame structures.”Retrieved from http://nisee.berkeley.edu/data/strong_motion/sacsteel/ground_motions.htm

Yeow, T., MacRae, G. A., Sadashiva, V. K., & Kawashima, K. (2013). Dynamic Stability and Design of C-bent Columns. *Journal of Earthquake Engineering*.**17**. p 750-768.