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PLAN ECCENTRICITY SENSITIVITY STUDY FOR PERFORMANCE BASED SEISMIC ASSESSMENT AND RETROFIT

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ABSTRACT: A two-part study considering the effect of plan eccentricities on buildings subjected to seismic events was performed. The principal objective of these analyses was to determine the effect of a plan eccentricity on the probability of drift exceedance of a simple concrete shear wall structure subjected to a suite of ground motions. The first part of the study considered the resistance required by the structure to meet collapse prevention performance objectives under different degrees of geometric eccentricity. The second part of the study investigated the effect of the plan geometry and its relationship to the degree of eccentricity of the structures. The results comprised a set of guidelines that can be used to design or retrofit such a structure based on its aspect ratio and the level of plan eccentricity present.

1. Introduction

Structures with plan asymmetries in either stiffness or mass are typically very sensitive to torsional effects under lateral loading. This asymmetry will create an eccentricity between the center of mass and the center of resistance of the structure, which will induce a torsional moment between the inertial and resisting forces in the structure. To resist this moment, the demands on one side of the lateral deformation resisting system (LDRS) will increase to equilibrate the induced moment. This is known as torsional coupling and can increase deflections of the structure and even cause failure of the LDRS if unaccounted for in design. Structures with this type of deficiency are more prone to excessive drifts and are more likely to be damaged during significant seismic events (Tso and Smith, 1999; Chandler, 1991; and Humar and Kumar, 2006).

The most typical cause of plan eccentricities is an asymmetric layout of the LDRS, which shifts the center of resistance of the structure away from its center of mass towards the eccentric LDRS component(s). This is herein referred to as a geometric eccentricity, since it is due to asymmetry in the plan geometry of the structure. Also possible is a resistance eccentricity, which is caused by one side of the LDRS being stiffer than the other. This draws more force into the stiffer component which will shift the center of resistance towards that side of the structure. A mass eccentricity, which causes a shift in the center of mass of a structure rather than the center of resistance, is also possible if the mass distribution of a story is asymmetric.

In order to quantify the effect of an eccentricity using a performance based methodology, the conditional probability of drift exceedance (CPDE) was used to determine the performance of a model. The CPDE defines the probability that the maximum drift in a structure will exceed its design drift under a suite of applied ground motions. The ground motions are scaled to a code level of shaking, i.e. 2% probability of exceedance in 50 years. The design drift is the level of drift that ensures the structure will be able to meet its performance objectives; this study considers a collapse prevention as the performance objective.

In this paper, the sensitivity of the CPDE of a one story typical reinforced concrete building with respect to its level of eccentricity is studied. As well, a simplified method for the design of such structures with plan eccentricities is developed based on a series of sensitivity analyses. This study only considers the effects of geometric eccentricities of a LDRS. Resistance eccentricities and mass eccentricities are not considered.

Previous studies which investigated the effect of torsional coupling on multistory structures, have concluded that the effects can be predicted through simplified, one story models, such as that used in this investigation (Tsicnias, 1981; Reinhorn and Rutenberg 1979; Kan and Chopra 1977). All major building codes, including the National Building Code of Canada (NBCC), have provisions to account for torsional coupling based on simplified one story parametric investigations (Chandler and Hutchinson, 1986; Humar et al., 2003). Many of these investigations have been based on spectral analysis using idealized response spectra such as Dempsey and Irvine (1979), Kan and Chopra (1977), Tso and Dempsey (1980), and Elms (1976).

Most codes account for the effect of structural eccentricities by applying the lateral earthquake force at an eccentricity relative to the to the story's center of stiffness (Chopra and Goel, 1991). According to Tso and Meng (1982), this eccentricity is specified as the maximum of:

$$e_d = \alpha e_s + \beta b$$

$$e_d = \delta e_s - \beta b$$

Where e_s is the calculated eccentricity, α and δ are dynamic amplification factors, typically 1 or 1.5 and 1 or 0.5, respectively (Tso and Meng, 1982). b is the plan dimension in the direction of the eccentricity, and β is typically 0.05 or 0.1 (Tso and Meng, 1982). The first term represents the lateral-torsional response due to the asymmetry in the floor plan, while the second term accounts for any accidental or unaccounted for eccentricity. The NBCC uses 1.0, 1.0, and 0.1 for α, δ, and β, respectively.

Critical review of the NBCC and similar code methods shows that the methodology is unnecessarily conservative for buildings with large eccentricities and unconservative for structures with small eccentricities and for structures with lateral and torsional modes with similar periods (Tso and Dempsey, 1980; Tso and Meng, 1982; Tso, 1983; and Chandler and Duan, 1993). Other investigations; such as Humar and Kumar (1998a and b), and Humar and Kumar (2006); have concluded that these provisions are very conservative for the design of the flexible side of the structure, yet sometimes unconservative for the stiffer side.

This paper introduces a novel approach using a performance based methodology to quantify the effect of plan eccentricity in the design of structures. In the approach presented herein, a single story shear wall structure comprising line elements with concentrated inelastic shear springs to represent the walls is considered. The model was used for nonlinear dynamic analysis using a suite of 13 bidirectional ground motions. The results are used to determine the effect that an induced eccentricity has on the collapse prevention performance of the structure. This was determined by calculating the CPDE of the structure to the suite of motions. The CPDE defines the probability that collapse prevention drift limits will be exceeded under design level ground motions, and can be used to determine the performance of a structure. The location of the structure was considered as Vancouver, BC, Canada, and the ground motions were scaled to the Vancouver 2% in 50 year spectrum.

The results of this study were used in the Seismic Retrofit Guidelines, 2nd Edition (SRG2) (APEGBC, 2013), which is a performance-based set of guidelines developed to simplify and accelerate the task of retrofitting high-risk schools in the Lower Mainland of British Columbia.

2. Model Description

The prototype model was a one-story square 22m x 22m reinforced concrete building, with a 3m storey height. The building was designed for Vancouver, BC Site Class C seismic demands. The prototype plan layout was varied throughout the analyses by adjusting the location of the walls.

The LDRS of the sample structure comprised four squat concrete shear walls – two in each orthogonal direction (Fig. 1). The walls were modeled with concentrated plasticity elements, with nonlinearity concentrated in a shear spring placed at the middle of the element. The shear springs were modelled with the nonlinear and hysteretic behaviour illustrated in Fig. 2. The base of the structure was fixed in all degrees of freedom and the roof was modeled as a rigid diaphragm, which meant that all LDRS components were coupled and the amount of force resisted by each wall was proportional to its stiffness.

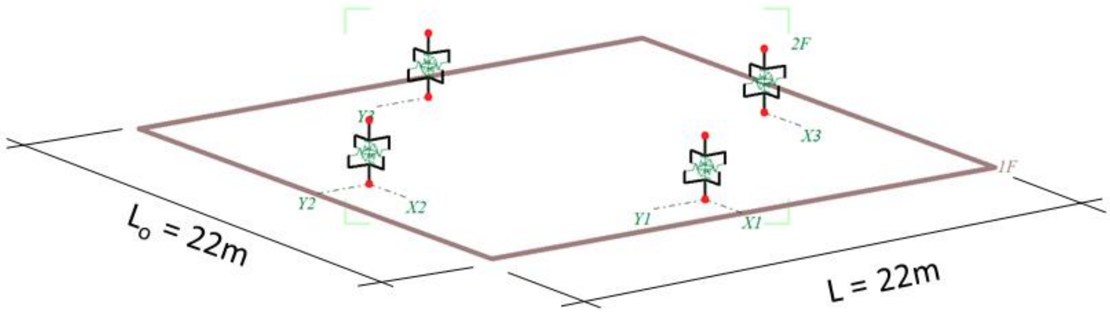
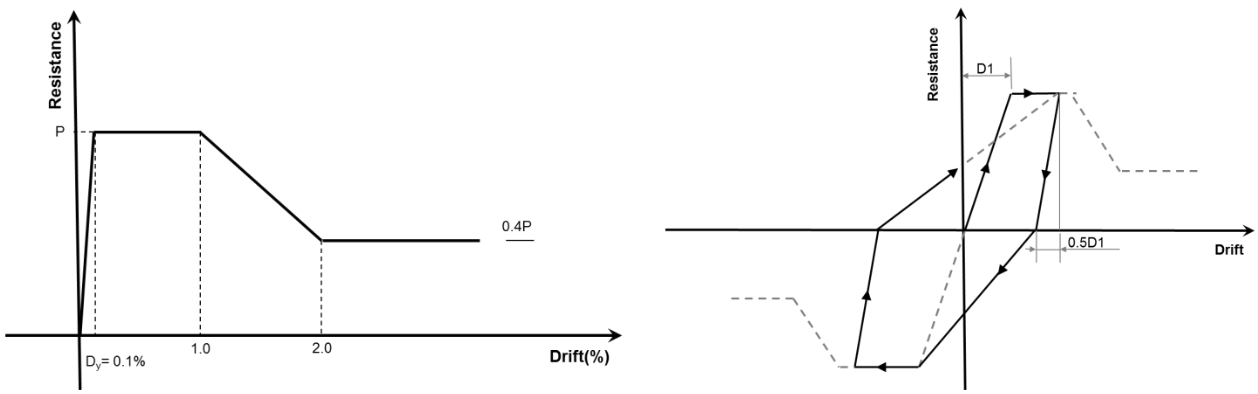


Fig. 1 – Prototype Model Layout



(a) **(b)**

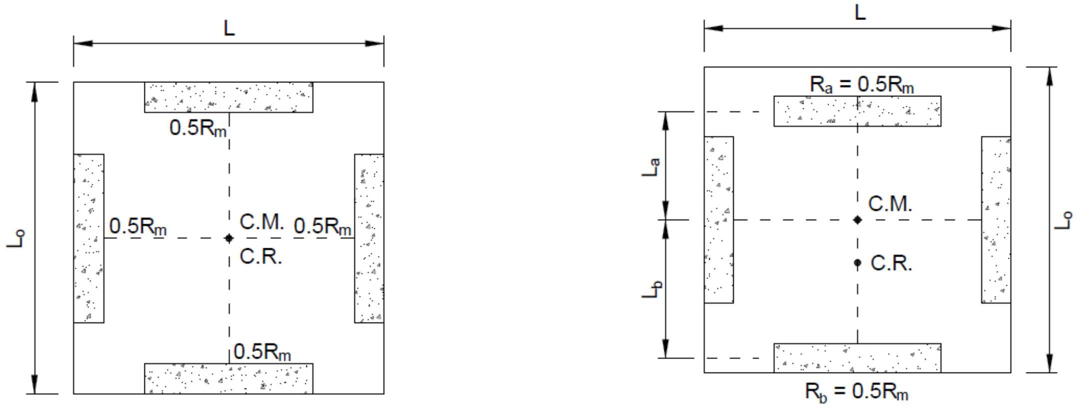
Fig. 2 – Shear Spring (a) Backbone and (b) Hysteretic Behaviour

The model was subjected to 13 bi-directional ground motions applied as time-history records. The ground motions were scaled to the design spectrum of the structure between 0.2 to 1.5 seconds. The walls were designed to meet life safety performance under a symmetric building layout.

3. Eccentricity Definition

Fig. 3a shows a rigid slab with lateral resistance, R_m, in each direction with plan dimensions L x L_o. The center of mass and center of rigidity are both located at the geometric center since no eccentricity exists. A primary geometric eccentricity is introduced by changing the plan geometry of the LDRS by shifting one component of the LDRS orthogonally to its primary direction, as shown in Fig. 3b. The eccentricity this induces is calculated as:

$$e = \frac{R_A L_A - R_B L_B}{(R_A + R_B) L_o}$$



(a) **(b)**

Fig. 3 – (a) Symmetric Plan Geometry and (b) Typical Geometric Eccentricity

In this case, the resistance of the components: R_A and R_B, are equivalent and equal to half of the total resistance in the considered direction: R_m. L_A and L_B are defined as the respective distances to each component measured from the center of mass of the structure.. Additionally, the distance between the orthogonal walls in the other direction can be varied to change the torsional resistance of the structure. This is referred to as an orthogonal eccentricity.

Fig. 4 illustrates the components of an eccentric building plan and introduces a key term: β, which is defined as the distance in the primary direction between the orthogonal components of the LDRS and the center of rigidity. It is of importance due to its effect on the torsional resistance of the orthogonal components of the LDRS.

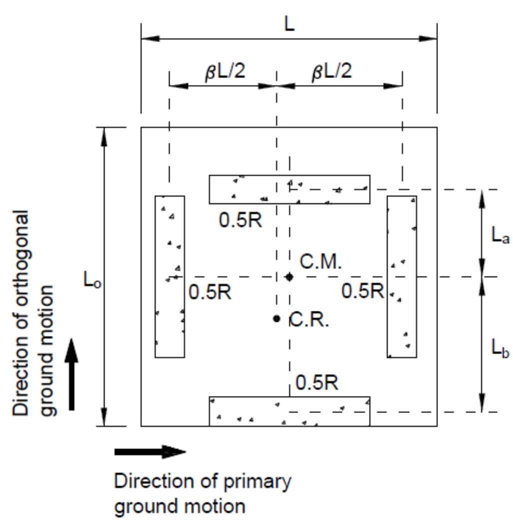


Fig. 4 – Eccentricity Components

4. Ground Motions

Thirteen bi-directional ground motions were selected and applied as acceleration time histories to the models. The geometric mean (geomean) of the ground motions was scaled to the target design spectra of Vancouver, on Site Class C, over a period range of 0.2 to 1.5 seconds. The scaled ground motions, target spectrum, and geomean of the selected ground motions are shown in Fig. 8.

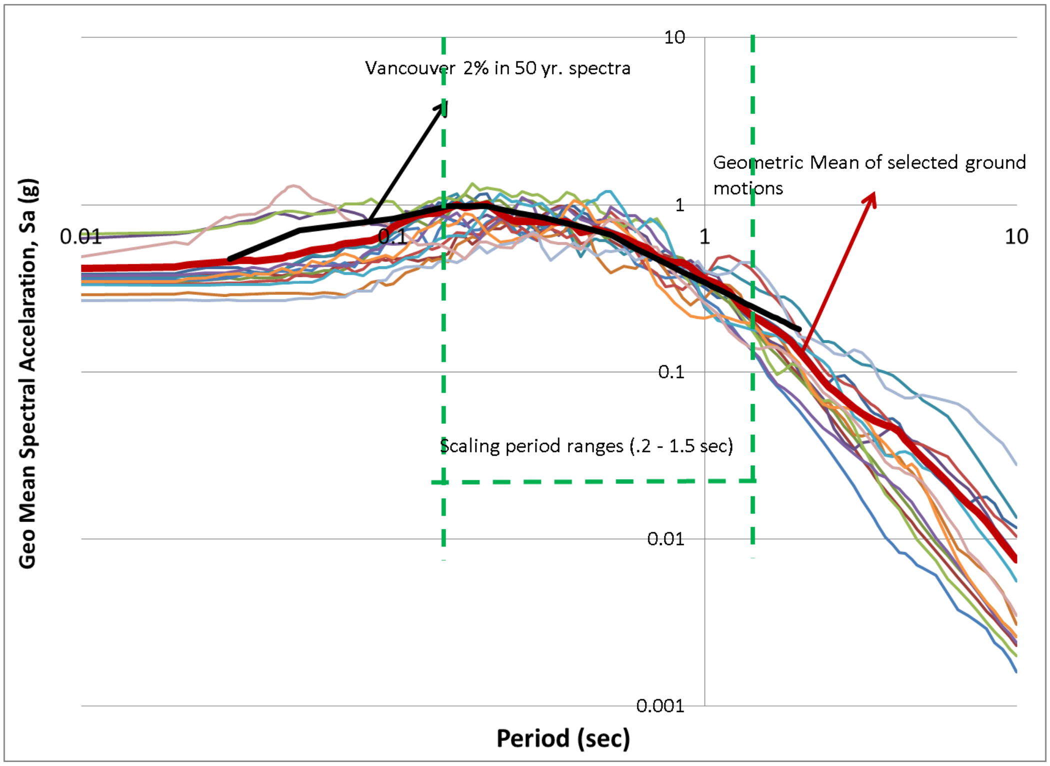


Fig. 8 – Scaled Ground Motions

5. Sensitivity of CPDE to Eccentricity Level

The CPDE of a suite of analyses, defined for a specific drift limit, can be defined by the percentage of runs that cause exceedance of the specified drift limit. To analyze the sensitivity of the CPDE to the degree of eccentricity in the model, both the eccentricity and orthogonal torsional resistance were varied. The orthogonal eccentricity was varied over a range of 0 to 25% by changing the position of one of the primary walls. This eccentricity was matched in the orthogonal direction by shifting the position of both of the orthogonal walls so that the total torsional resistance of the plan remained constant.

The orthogonal torsional resistance, defined by the amount of torsion resistance created by the orthogonal walls was increased by moving the orthogonal walls further apart to effectively increase the polar moment of inertia of the plan layout. The orthogonal torsional resistance, T_o, can be quantified as:

$$T_o = \frac{\beta L R_m}{2}$$

The strong component of each ground motion was applied to the structure in the primary direction. The average CPDE was computed in each component. The critical wall was selected and used to express the results of the system. The CPDE was calculated at a drift of 1%, which is when the walls begin to lose strength (Fig. 2). These results are summarized in Fig. 9.

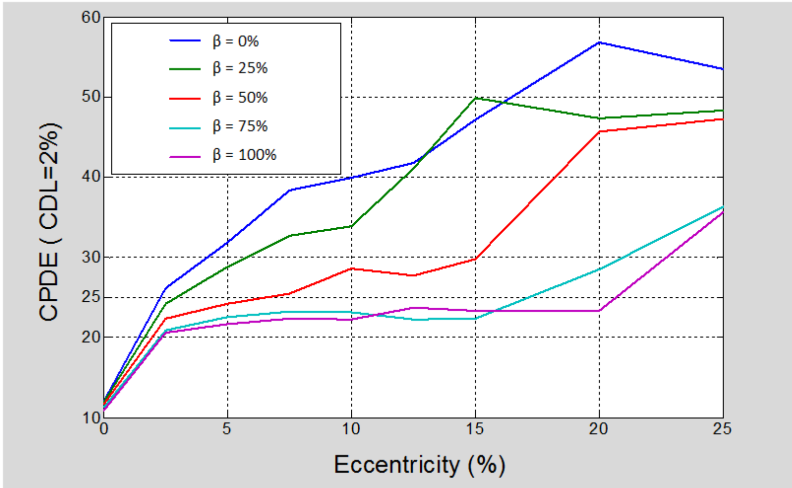


Fig. 9 – Eccentricity vs. CPDE at Varying Orthogonal Torsional Resistances

Considering the initial slope of each line in Fig. 9, it can be noted that there is a large sensitivity to even small eccentricities, regardless of the torsional resistance of the system. This is because the primary walls are designed for life safety (full capacity), and therefore, even a small in increase force to equilibrate the torsion induced by a small eccentricity will cause a sudden exceedance in the drift probability.

After this initial large rise in CPDE, the models with higher orthogonal torsional resistance (T_o ≥ 37.5%) are less sensitive to eccentricity changes, due to the significant amount or torsional resistance provided by the orthogonal walls. Since the ground motions were always less intense in the orthogonal direction, the orthogonal wall had sufficient extra capacity to resist the additional forces induced by the eccentricity. The other models, which had lower orthogonal torsional resistance, were more sensitive since their primary walls, which were only designed to meet life safety performance requirements for the ground motions in one direction, provided the majority of the torsional resistance of the system.

In SRG2, a CPDE less than 25% is considered to provide sufficient safety against collapse at a code shaking level. This is not met for several design geometries of this sample building. To estimate the degree of additional resistance required for each layout to achieve an acceptable factor of safety against excessive damage, the LDRS resistance was increased from R_m to R_m^* so that the CPDE was reduced to 25% or lower. The percentage increase was plotted in Fig. 10, versus the amount of eccentricity of the system, to show how the variation of the resistance factor depends on the amount of eccentricity.

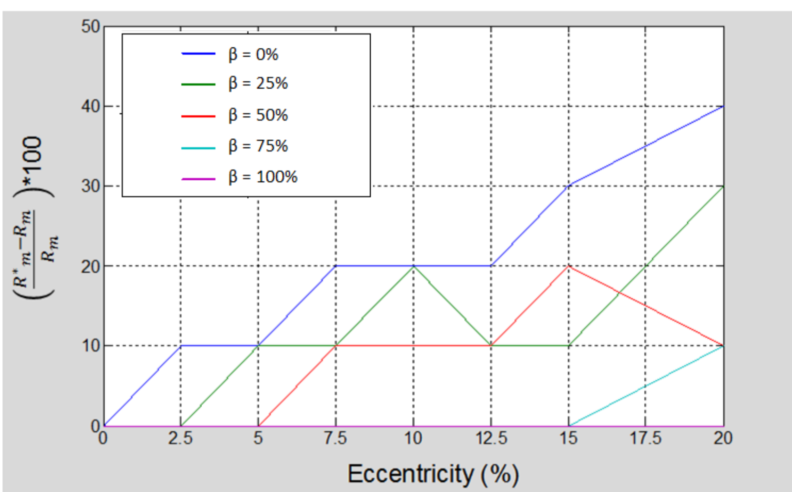


Fig. 10 – Required Resistance Factors for 25% CPDE

Depending on the torsional resistance provided by the orthogonal walls, the resistance factor can vary from 40% to 0% (0% meaning no increase in resistance is required) for the range of eccentricities shown above and a limiting CPDE of 25%. The jaggedness of the plots can be attributed to the particular ground motions used in the analyses, as well as the nature and uncertainties of nonlinear dynamic analyses in general.

6. Effect of Geometry

Next, the effect of the geometry of the sample structure was investigated by varying the aspect ratio (L:L_o) of the building.

The aspect ratio was modified from 1:3 to 3:1 in seven increments. In order to observe the effect of the aspect ratio, the degree of eccentricity had to be held constant. Two eccentricity levels: 5% and 10% were chosen. These levels were chosen because they are the common values used for accidental eccentricities (Tso and Meng, 1982).

Similar to before, the percentage increase in the LDRS required to meet a CPDE of 25% was considered. However, the increase is compared to a normalized orthogonal resistance ratio - defined as the orthogonal torsional resistance divided by the product of the orthogonal length (L^*) and the total LDRS resistance (C). This quantity can be calculated as follows:

$$\frac{T_o}{CL_o} = \frac{\beta L}{2L_o}$$

The results are summarized in Fig. 11.

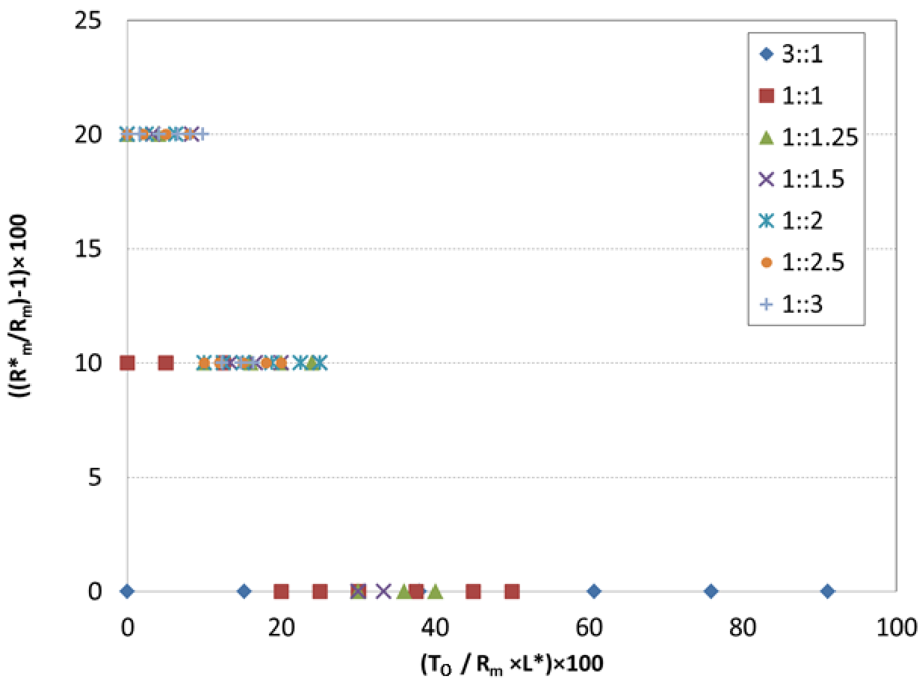


Fig. 11 – Resistance Factors Based on Orthogonal Torsional Resistance and Aspect Ratio for a 5% Eccentricity

It can be seen that both low orthogonal torsional resistance ratios and low aspect ratios contribute to a large required resistance factor. Based on the results presented in Fig. 11, the minimum resistance ratios shown in Table 1 are proposed for a plan with a 5% eccentricity to conform to a CPDE of 25% or less:

Table 1 – Resistance Factors for 5% Eccentricity

Minimum T_o	Minimum Resistance Factor
$\mathbf{T_o} < 0.15 \times C_t \times L_o$	$1.2 * C_t$
$0.15 \times C_t \times L_o < \mathbf{T_o} < 0.4 \times C_t \times L_o$	$1.1 * C_t$
$0.4 \times C_t \times L_o \le \mathbf{T_o}$	$1.0 * C_t$

Notes:

1. T_o – Torsional resistance in orthogonal direction
2. L_o – Orthogonal slab plan dimension
3. C_t – Sum of R_m values for all LDRSs in direction of shaking such that sum C / D = 1.0

A similar trend is observed in Fig.12 for a sample plan with a 10% eccentricity in both directions.

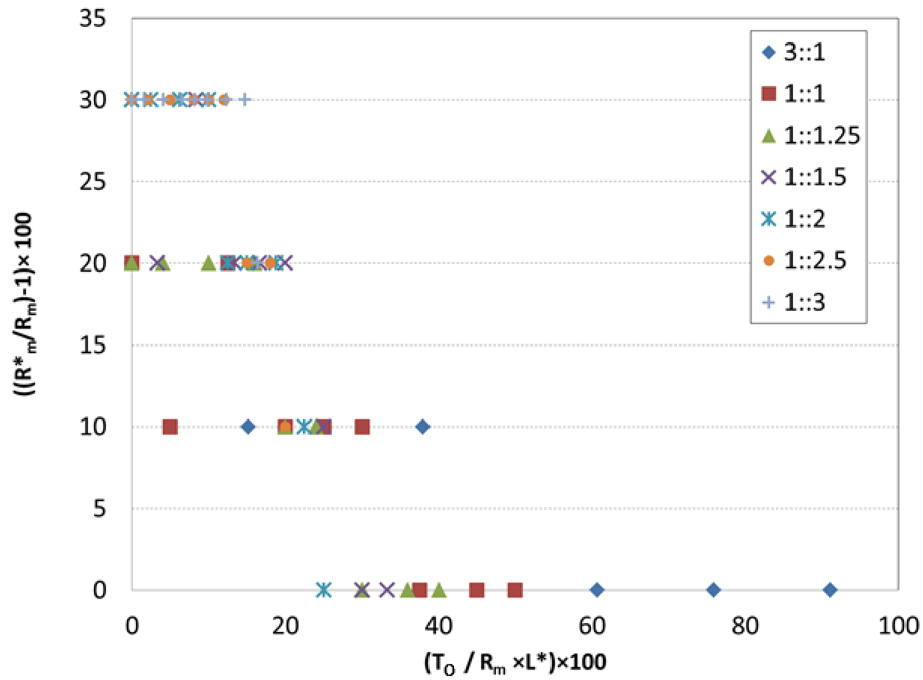


Fig. 12 – Resistance Factors Based on Orthogonal Torsional Resistance and Aspect Ratio for a 10% Eccentricity

However, in this case it was noticed that at low required T_o values, larger aspect ratios tended to increase the required resistance factor. For this level of eccentricity the following required minimum resistances summarized in Table 2 are proposed:

Table 2 – Resistance Factors for 10% Eccentricity

Minimum T_o	L_o/L	**Minimum Resistance Factor**
$\mathbf{T_o} < 0.15 \times C_t \times L_o$	≥ 1.5	1.3 * C_t
$\mathbf{T_o} < 0.15 \times C_t \times L_o$	< 1.5	1.2 * C_t
$0.15 \times C_t \times L_o < \mathbf{T_o} < 0.4 \times C_t \times L_o$	-	1.1 * C_t
$0.4 \times C_t \times L_o \leq \mathbf{T_o}$	-	1.0 * C_t

Notes:

1. T_o – Torsional resistance in orthogonal direction
2. L_o – Orthogonal slab plan dimension
3. C_t – Sum of R_m values for all LDRSs in direction of shaking such that sum C / D = 1.0

7. Conclusion

This study considered the effect of plan eccentricities on torsionally sensitive structures. A simple rectangular structure with two sets of shear walls comprising the LDRS in each direction and a rigid diaphragm was chosen for the study. The walls were modeled with inelasticity concentrated in shear springs. Thirteen ground motions were chosen for the time history analyses, which were scaled so that the geomean of the motions matched the Vancouver design spectrum from 0.2 to 1.5 seconds.

Two main studies were done on this test structure. First, the CPDE was compared to the level of eccentricity in the plan of the structure. This was analyzed at several ratios of orthogonal torsional resistance in order to determine the effects both variables had on the CPDE of the building. As expected, the CPDE increased as the eccentricity ratio increased. It was also observed that the torsional resistance of the components in the orthogonal LDRS had a large impact in the sensitivity of the CPDE.

Next, the effect of the geometry of the sample structure was investigated. This was done by varying the aspect ratio of the plan dimensions at fixed eccentricity values and observing the effect on the strength increase required to limit CPDE to 25% or less. Two eccentricity values were chosen as constants: 5% and 10%. At each of these levels of eccentricity, guidelines were proposed for the minimum required resistance. These guidelines were based on the orthogonal torsional resistance, orthogonal plan length, total resistance of the LDRS, and aspect ratio of the structure. The guidelines were designed to meet a CPDE of 25% or less. The proposed guidelines are suitable for the performance based design of torsionally sensitive structures providing the plan eccentricity be less than or equal to 10%.

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