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A NEW METHODOLOGY FOR DESIGNING MULTI-STORY ASYMMETRIC BUILDINGS

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ABSTRACT :

Traditional code torsional provisions are based on the assumption that the stiffness of lateral force resisting elements (LFREs) is independent from their strength. These provisions are mainly based on building linear responses and they distribute strength among LFRESs by static equilibrium based on predefined stiffness. An alternative approach for designing asymmetric buildings is using proper configuration of centers. Proper configuration of centers is a promising technique to control asymmetric buildings torsional responses. To use this method in seismic design, one has to find centers proper configuration and then distribute strength among LFREs such a way that results to that proper configuration. In this study a new methodology for designing asymmetric buildings is proposed. This method instead of using traditional static equilibrium, distributes the strength freely among LFREs, then strength of some LFRES are adjusted in a way to shift centers to their proper locations. To evaluate the method against traditional torsional provisions, some building models are designed by both traditional and proposed method. A comparison of nonlinear dynamic responses of these models displays the ability of proposed method for limiting building torsional responses.

KEYWORDS: Asymmetric buildings, torsion, D-type elements, stiffness eccentricity, strength eccentricity.

1. INTRODUCTION

Conventional seismic codes use the concept of design eccentricity to overcome issues raised by asymmetry. This concept is applied along with static equilibrium to distribute seismic lateral loads among lateral force resisting elements (LFREs). For static equilibrium the stiffness of LFREs was considered a constant value proportional to cubic of LFREs height and remained unchanged during design process when the strength of elements changes. This method increases building total lateral strength also building torsional strength and stiffness, on the other hand it doesn't efficiently improve building torsional responses. An alternative approach is to distribute strength freely to LFREs in a way that controls the torsional responses (Paulay 2001). This goal can be achieved by a strength distribution that results in proper configuration of centers of mass, strength and stiffness relative to each other. In the studies carried out by Myslimaj and Tso (2002) the balance configuration was recommended as a configuration that center of strength and stiffness were located in opposite side of center of mass. Aziminejad and Moghadam (2006) suggested proper configuration of centers in different limit states for each response parameter of single story buildings. Also to extend this methodology to multistory buildings (Aziminejad and Moghadam 2008) approximate definitions for center of strength and stiffness based on characteristic of each individual story in building was used. These definitions provide simple methods for determination of the centers location in each story specially when the stiffness of each LFREs is a function of its strength and can change during design cycles (Priestley and Kowalsky 1998, Paulay 2001). Based on these definitions the strategies for changing centers configuration in building stories were proposed which are capable in controlling undesirable effects of torsional responses.

To determine the proper configuration of centers in a multistory building first the designer must estimate the probable amount of nonlinear behavior in the building. It can be estimated by a pushover analysis of simplified reference symmetric model. Then the proper configuration of centers for single story building for that level of nonlinear behavior is considered. In design of new buildings the use of this single story proper configuration for drift response in all stories (SSPC for interstory drift responses) can be recommended (Aziminejad and Moghadam 2008). This configuration is the most stable configuration and can result in almost uniform distribution of displacement and drift demands along height of the building. Also it has the nearest values of drift and displacement responses to the reference symmetric model. For this configuration, probability of exceeding assumed limit state at both sides of building is very similar. The proper configuration for other response parameters such as ductility demand is also discussed in that reference mentioned above.

After recognition of proper configuration of centers and amount of strength needed for each story, the strength should be distributed among LFREs such a way that results in proper configuration of centers in the stories. For this purpose a proper strength distribution technique is needed. Two methods for strength distribution are proposed by Myslimaj and Tso (2004 and 2005) which results in suitable configuration of centers. These methodologies are mainly generated for single story or multistory building with similar center configuration. In this paper a new methodology for distributing strength among LFREs is proposed. This methodology is based on dividing elements in three groups and changing strength of each group such that results in proper configuration of centers. The method applies simplified definition of the centers for multistory buildings (Aziminejad and Moghadam 2008). To compare this method with traditional design eccentricity method some multistory torsionally restraint and unrestraint buildings are designed based on torsional provisions of ASCE-07, National Building Code of Canada (NBCC 1995) and the proposed method. To compare advantages and disadvantages of each method, nonlinear dynamic responses of buildings subjected to earthquake ground motion records are conducted.

2. PROPER CONFIGURATION OF CENTERS

For LFREs such as shear walls and moment resisting frames, the stiffness of each element is depended on its strength (Priestley and Kowalsky 1998, Paulay 2001) and will be modified during strength assignment. These LFREs are called D-type elements. The code design procedure in buildings with D-type LFREs lacks the ability to enforce simultaneous yielding among LFREs. In general before 1997 most of the studies on asymmetric buildings considered only single story buildings with K-type elements. In those researches, with the assumption that the location of center of strength remains unchanged during design procedure, the proper location of center of strength was examined. For these types of buildings Tso and Ying (1992) suggested that strength eccentricity should be zero or near to zero in order to reduce ductility demand on flexible edge element for buildings that has non-uniform stiffness distribution. Rutenberg et. Al. (1992) and De Stefano et. al. (1993) tried to find optimum location of center of strength relative to center of mass and center of rigidity for minimizing ductility demand. They concluded that the best location of center of strength is at the middle of centers of mass and stiffness.

Paulay (2001), based on plastic mechanism analysis considered the behaviour of single story asymmetric structures with D-type elements. He suggested that an arbitrary strength distribution strategy can be more effective for superior performance of asymmetric structure in ultimate limit state. Similar to Tso and Ying (1992), he proposed that an appropriate location of center of strength is somewhere near the center of mass. Myslimaj and Tso (2002) demonstrated that the response of asymmetric structures during the earthquake excitations depends on the location of both center of strength and center of stiffness relative to center of mass. They proposed that the best configuration of center of mass, strength and stiffness is a configuration in which the center of mass is between centers of strength and stiffness. This configuration was called as balance configuration. According to their study, balance configuration will improve the interstory drift and diaphragm rotational responses of a building, but it can cause an increase of ductility demand on elements in the stiff side of structure. Based on these findings and to recognize proper configuration of centers Aziminejad and Moghadam (2005, 2008) examined performance of single story and multistory shear and flexural type buildings. In these studies more accurate configurations of centers which improve the performance of asymmetric buildings to their maximum value was identified for general response parameters such as story rotation, interstory drift, displacement, ductility demand and plastic rotation. This configuration is called proper configuration of centers. The proper configuration of centers can be identified by the ratio of strength eccentricity to yield eccentricity (ev/ed). For example, in buildings consist of LFREs with strain hardening equal to 2% of their stiffness the configuration of centers with ratio of ev/ed= 0.25 could properly control diaphragm rotation, interstory drift and plastic rotation of LFREs, provided that average ductility demand LFREs are between 2~4.5. For extending the results of one story

buildings center configuration to multistory buildings a new definition for center of rigidity and center of strength based on shear center is proposed. Center of strength of a story is defined here as the point that if resultant of lateral forces act through it and story reaches to mechanism, no rotation happens in that story, when all the degrees of freedoms of lower stories are restrained. It is a more general form of definition that was used by De la Llera and Chopra (1995) for shear buildings that can be used for both shear and flexural buildings. For center of rigidity similar definition was used with linear behaviour assumption. A similar concept is used for defining yield center, the point on story diaphragm that first moment of yield displacement of LFREs elements is zero when all elements degree of freedom in lower stories are restraint.
By using these definitions for centers, one of the strategies that can be used for controlling torsional responses is using proper configuration of single story models in all stories, considering amount of nonlinear behaviour in each story (SSPC strategies).

3. ELEMENT GROUPING METHOD

When the designer had selected a proper scheme for configuration of center in building stories, a technique for strength distribution is needed that leads to that proper configuration of centers. In this part a methodology based on dividing LFREs in three groups in each direction is proposed. The first and second groups are elements that designer has ability to change their strength and the third group are elements that because of detailing or code limitations their strength is pre-determined and designer couldn’t change them. In this method the designer distributes strength among the LFREs using any desirable rule, for example proportional to square of elements length or element yield displacement. Then the total strength of these two groups is adjusted such a way that results in proper configuration of centers in each story. To do this the story plan of sample building is shown in Figure 1. The LFREs are divided to three groups. Total strength of story shown by V and total strength of each group by V0, V1 and V2. Based on equilibrium condition the story total strength is:

$$V=V0+V1+V2 \qquad 3.1$$

The designer’s selected rule for each group can be assumed as following:

$$\begin{cases} \gamma 1_i = \dfrac{V1_i}{V1} \\ \gamma 2_j = \dfrac{V2_j}{V2} \end{cases} \qquad 3.2$$

In these equations $V1_i$ and $V2_j$ are strength of i element in first group and strength of j element in second group. The strength eccentricity of each group could be calculated as following:

$$\begin{aligned} e0_v &= \frac{\sum_{h=1}^{l} V0_h x_h}{V0} \\ e1_v &= \frac{\sum_{i=1}^{m} V1_i x_i}{V1} = \sum_{i=1}^{m} \gamma 1_i x_i \\ e2_v &= \frac{\sum_{j=1}^{n} V2_j x_j}{V2} = \sum_{j=1}^{n} \gamma 2_j x_j \end{aligned} \qquad 3.3$$

Now the story could be modeled by an equivalent three element model that the strength of each element is equal to total strength of the group and its distance to mass center is equal to its strength eccentricity. This equivalent model has shown in Figure 2. The strength eccentricity of this model is equal to the main building:

$$e_V = \frac{V0.e0_v + V1.e1_v + V2.e2_v}{V} \qquad 3.4$$

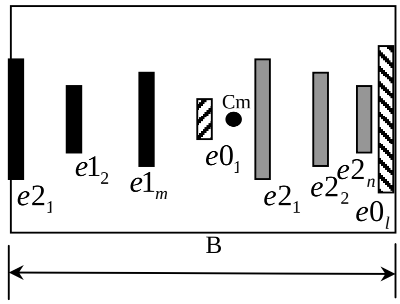

Figure 1 Sample Building Configuration

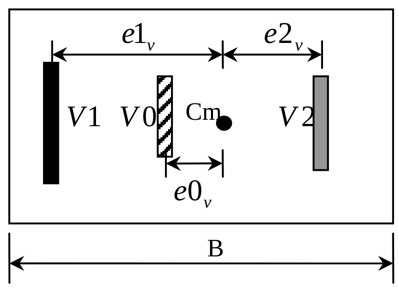

Figure 2 Equivalent three element model

By using equations 3.1 and 3.4 the total strength of elements group one and two can be calculated such that strength eccentricity is equal to e_v. V1 and V2 can be derived by the following formulas:

$$\begin{cases} V1 = \dfrac{V(e_v - e2_v) + V0(e2_v - e0_v)}{(e1_v - e2_v)} \\ V2 = \dfrac{V(e_v - e1_v) + V0(e1_v - e0_v)}{(e2_v - e1_v)} \end{cases} \qquad 3.5$$

The advantage of this method is that a designer could have his preferable strength distribution in each group and by adjusting the total strength of each group could achieve proper configuration for each story without affecting strength distribution of each group. However the ability of this method to generate desirable center configuration is a function of the form of element grouping. The proper configuration of centers could be achieved, if the location of desirable center of strength is located with enough distance between equivalent elements one and two (Figure 2).

For using this method in multistory shear wall buildings these steps should be followed:

1- Calculation of total flexural strength of each story in each direction based on code lateral loads.

2- Selecting desirable strength distribution rules in groups, for example strength distribution relative to element yield displacement or relative to second order of elements length.

3- To group elements in the neutral group (group 0) and two main groups (group 1 and 2). The grouping of elements should be in such a way that their centers of strength are on two sides of desirable location of center of strength of story and with enough space.

4- Center of strength of each group can be calculated using equations 3.2 and 3.3.

5- Total strength of groups one and two can be calculated by equation 3.5.

6- The total strength of each group are distributed based on group strength distribution rule using equations 3.2.

7- The strength limitation of elements should be checked and each element that its calculated strength is out of allowed range should be moved to neutral group and steps 2 till 7 is repeated again.

These steps should be followed for each individual story using story needed flexural strength. Each element is designed by this flexural strength, its axial forces are calculated from traditional elastic analysis of vertical loads and shear forces that are calculated from lateral forces with a pattern similar to building lateral force and with amplitude that causes calculated flexural strength. Of course the elements lateral force pattern can only be corrected after preliminary design using appropriate analysis methods such as pushover methods.

4. ANALYTICAL MODELS

To compare performance of proposed design method with traditional seismic codes method, seven stories models with shear wall LFREs have been used. Buildings have two different layouts for walls, the first layout is torsional restraint and the second layout is torsional unrestraint (Figure 3). The models consist of seven stories buildings having rigid diaphragms with dimensions of 30m x 20m and three shear walls in each direction. Buildings are symmetric in x-direction and asymmetric in y-direction. The stories one till three of models are typical and have similar strength distribution and the stories four till seven also are typical and have similar strength distributions.

The design gravity loads of the models have been determined based on the Iranian standard 519 (1999). The design earthquake loads are calculated based on the Iranian standard 2800 earthquake provision (2007). A force reduction factor equal to seven is assumed in calculating seismic lateral loads. The length of the left and the right walls in y-direction are changed in a way that the model has a yield displacement eccentricity equal to 6.75 percent of the plan width in each story. Using traditional stiffness calculation based on LFREs length will result in 18.76 percent stiffness eccentricity. Six methods were used for strength distribution among LFREs and so six models for each layout were generated. Strength of the first model calculated based on design eccentricity of ASCE 7-05 (Similar to IBC and Iranian 2800 standard), second model based on NBCC 1995. Strength distributions of model three and four are done using grouping method. In model three the distribution in each group was proportional to square of elements length and in model four proportional to order four of element length. Models five and six are similar to models four and five, but in these models 5% accidental eccentricity was considered and related accidental torsional moment was calculated. These torques are applied on building stories and based on LFREs maximum reaction total lateral strength of models were increased. In Table 1 the total flexural strength of LFREs in models are shown. Application of torsional provision of seismic codes or accidental eccentricity will increase the total building base shear. For models under consideration the overstrength ratio has been shown in Figure 4. The overstrength ratio of model two that designed using NBCC (Canadian seismic code) is maximum among the six models. It is the consequence of larger design eccentricity of this code. To study performance of building models, nonlinear time history analyses are conducted.

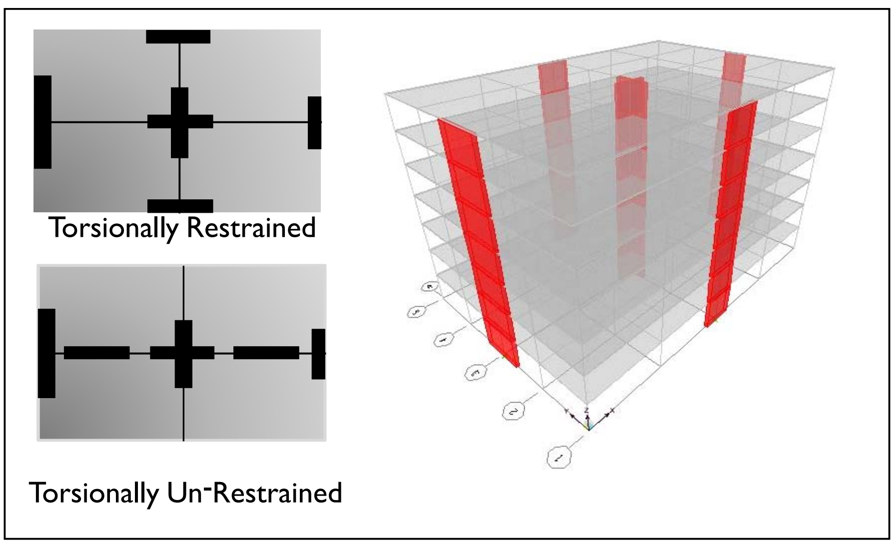

Figure 3 Configuration of torsionally restrained and unrestrained models

Table 1 Flexural strength LFREs in y direction (Ton.m)

Model	Story 1~3			Story 3~7		
	Element Left	Element Middle	Element Right	Element Left	Element Middle	Element Right
2800-ASCE	2159.8	1904.2	1452.6	938.3	818.2	609.7
CANADA	2715.5	2097.1	1836.8	1173.4	903.3	769.2
CENTERS-I^2	1390.4	1686.5	2117.6	707.2	722.8	796.3
CENTERS-I^4	1488.0	1491.3	2215.2	749.0	639.2	838.1
CENTERS-I^2 (5% Eccentricity)	1533.3	1859.9	2335.3	750.2	766.8	844.7
CENTERS-I^4 (5% Eccentricity)	1634.8	1638.4	2433.8	793.6	677.2	888.0

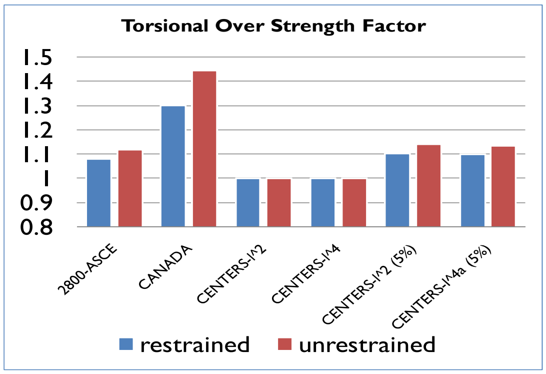

Figure 4 Torsional overstrength factor of designed models

5. ANALYTICAL RESULTS

Using the OPENSEES software (2005), the nonlinear dynamic analyses are performed. All six models are analyzed for fifteen, two directional ground motions (Table 2). As response parameters, diaphragm rotation and maximum interstory drift were considered. In Figure 5 the results of average of maximum diaphragm rotations are shown. All models with proper configuration of centers perform well in controlling maximum building rotations in all considered earthquakes intensities and in both case of restraint or unrestraint building configurations. The models with proper configuration of centers, independent of form of strength distribution or their total strength, adequately control the diaphragm rotations. In this case increasing building total strength has minor effect on diaphragm rotations. The results of interstory drift for models designed by traditional torsional provision and centers proper configuration are much closer than those for diaphragm rotations. It is logical as models under consideration are regular and uniform asymmetric models that great portion of their drift is the result of their translational deformation (Figure 6). For interstory drift, the performance of proper configuration of the centers is much better in the unrestraint models because in these models the influence of torsion in critical drift responses is more, however the performance of the Canadian code with about 30% to 40% overstrength is better than ASCE (model 1) in unrestraint case. In general models with poper configuration of centers perform well and they reduce the inerstory drift responses of buildings about 15% to 20% in PGA equal to 0.35g, compare to ASCE design methodology. Of course the buildings under consideration have only 6.75% yield eccentricity and it is predicted that in cases with larger yield eccentricity the proper configuration of centers perform even better.

6. CONCLUSION

Proper configuration of centers appropriately controls selected torsional responses in single story buildings. Using story independent definition for center of strength and rigidity, one can consider a multistory building as ensemble of single story buildings and use proper strategy to control critical responses of buildings. One of these strategies is using proper configuration of single story building in all stories (SSPC strategy). In this paper, a new strength allocation strategy which results to the proper configuration of centers in multistory buildings is proposed.

Table 2 Earthquak ground motion records

	Earthquake	Year	Magnitude(M)	Duration(Sec)	PGA Y (g)	Site	Dis. (Km)
1	Cape-Mendocino	1992	7.1m	36	0.229	Shelter Cove Airport	33.8
2	Chi-Chi	1999	7.6m	35	0.413	TCU047	33.01
3	Compano lucano	1980	6.9mw	35	0.14	Mercato san servino	48
4	Manjil	1990	7.4mw	25	0.184	Qazvin	49
5	Imperial Valley	1979	6.5m	40	0.169	Cerro Prieto	26.5
6	Izmit	1999	7.6mw	30	0.208	Gebze-arcelic	38
7	Kern county	1952	7.4mw	25	0.175	Taft	41
8	N. Palm Springs	1986	6m	20	0.228	San Jacinto	32
9	Northridge	1994	6.7m	20	0.256	LA - Century	25.4
10	San Fernando	1971	6.6m	20	0.324	Castaic	25
11	Whittier Narrows	1987	6.0m	20	0.299	Union Oil	25.2
12	Loma Prieta	1989	6.9m	25	0.233	Golden Gate Bridge	85.1
13	Northridge	1994	6.7m	20	0.404	Westmoreland	29
14	Chi-Chi	1999	7.6m	35	0.204	CHY086	35.43
15	N. Palm Springs	1986	6m	11.2	0.240	Hurkey Creek Park	34.9

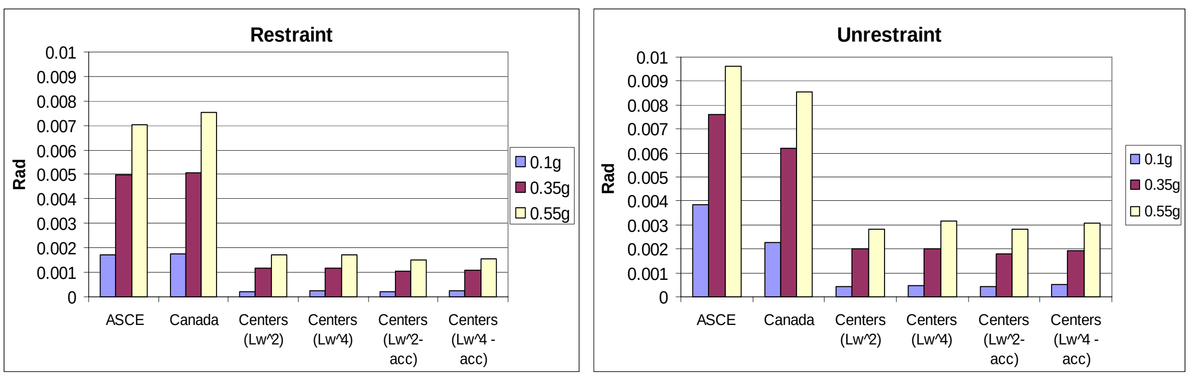

Figure 5 Maximum diaphragm rotations for torsionally restraint and unrestraint building models

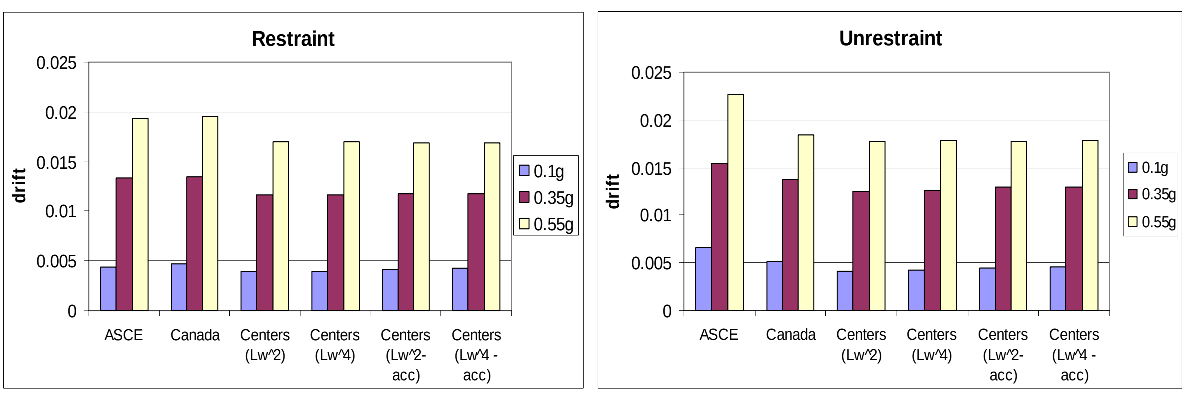

Figure 6 Maximum drifts for torsionally restraint and unrestraint building models

Using this methodology to achieve proper configuration of center in the building stories could help the building designer to control adverse effects of asymmetry and torsional moment. Considering the reliability of proper configuration of centers for controlling interstory drift as shown in previous studies and using SSPC strategy, in this study some sample building models are designed and their responses are compared with other models designed with traditional seismic codes torsional provisions. The results show that models with proper configuration of centers considerably better control critical drift or rotational responses.

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