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ANALYSIS OF CRITERION FOR TORSIONAL IRREGULARITY OF SEISMIC STRUCTURES

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SUMMARY

The torsion effects caused by irregularity of plan layout of seismic structures have been emphasized for seismic design in some codes. When and how to consider torsion effects is depended on the criterion and relative regulations for torsional irregularity. There are some differences between the criterions from one code to another. In this paper, the differences between the codes of China, USA and Europe are studied. Through analyzing series of structures with eccentricity in one and two directions, the corelation between torsion effects and the criterion adopted by the different codes is obtained. According to the analysis results, it can be indicated that torsion effects has no dependency relation with the criterion adopted by the codes mentioned above and some regulations in the code are not reasonable.

INTRODUCTION

With the development of the theory of seismic design, the viewpoint is approved popularly that the torsion effects resulting from the irregular layout of the structure should be considered. The criterion and some relative regulations for torsional irregularity have been put forward in Code for Seismic Design of Buildings of China (called GB50011-2001 for short)[1], United Building Code (version1997)(called UBC97 for short) of USA [2], while the criterion for regularity of structures have been regulated in Structural codes of Europe [3] (called EC8 for short). The rationality and practicability of these criterion and relative regulations in these codes will be investigated in this paper.

In these three codes, for structures with torsional irregularities, the torsion effects should be considered in two aspects, (1) The analysis models of structures should be spatial; (2) The modal analysis considering torsion coupling should be adopted for seismic design. For the structures with extreme irregularities in layouts of mass and stiffness, the torsion effects under seismic action in two directions should be considered simultaneously. That is to say that the criterion for torsional irregularity of the seismic structures can be further taken as the one for the irregular structures considering seismic action in two directions simultaneously, thus the criterion for torsional irregularity becomes a keystone for the selection of different design methods in the seismic design of the structures.

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COMPARISON AND ANALYSIS OF PROVISIONS ON TORSION IRREGULARITY IN GB50011-2001, UBC97 AND EC8

In GB50011-2001, UBC97 and EC8, the criterion for torsional irregularity of the structures is approximately in the same form as shown in Figure 1. Torsional irregularity should be considered when maximum story drift (or inter-story drift) at one end of the structure transverse to an axis (δ_2) is more than 1.2 times the average of the story drifts (or inter-story drifts) at the two ends of the structure .The criterion is expressed in Equation (1).

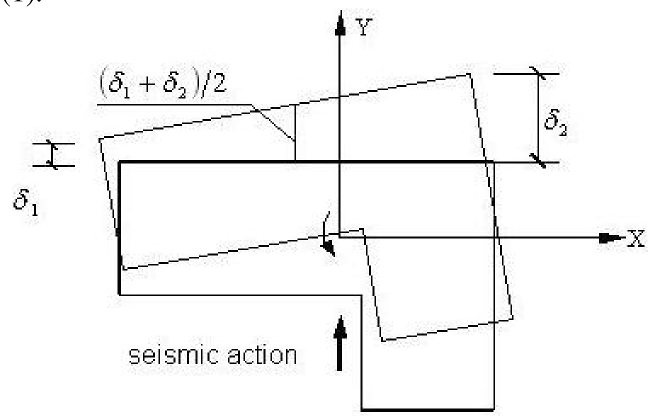


Figure 1. Graphic of torsional irregularity in GB50011-2001 and UBC97

$$\delta_2 \Big/ \left(\frac{\delta_1 + \delta_2}{2} \right) > 1.2 \quad (1)$$

$$\theta = \delta_2 \Big/ \left(\frac{\delta_1 + \delta_2}{2} \right) \quad (2)$$

Where δ_1 and δ_2 are the story drifts (or inter-story drifts) at the two ends of the structure respectively. θ is the parameter of the criterion.

Some differences between the terms of torsional irregularity are given as following,

1) δ_1 and δ_2 can be story drifts or inter-story drifts in GB50011-2001, and the maximum θ from the two results of story drifts and inter-story drifts should be adopted, while these can only be inter-story drifts in UBC97 and story drifts in EC8;

2) θ is calculated considering not only actual eccentricity, but also accidental eccentricity of ±5 percent of the length of the structure in UBC97 and EC8, while in GB50011-2001 only actual eccentricity needs to be considered; and

3) In the code of GB50011-2001, the maximum of θ is 1.5 while there is no similar provision in code of UBC97 and EC8.

When the criterion are used in practice, some problems should be pointed out,

1) It is not convenient for engineers to determine θ at the beginning of the design. θ must be calculated through the global analysis of structure;

2) The relative eccentricity is usually considered as the important factor influencing torsion effects, the relationship between θ and relative eccentricity should be studied;

3) Story drifts (inter-story drifts) of different floors may be different. So θ may be different between different floors. It is not clear that θ of which floor should be adopted in GB50011-2001, UBC97 and EC8; and

4) If θ is a proper criterion for torisonal irregularity, whether it can further be taken as the criterion for considering seismic action in two directions simultaneously should be studied.

Therefore, there are some unclearness and inconvenient in the criterion of torsional irregularity. The above problems have been investigated by example analysis by Zheng [4] and the contents are extracted here.

EXAMPLE STRUCTURES ANALYSIS

Although the criterion for torsional irregularity looks simple, but the application of it has some confusions and it is necessary to investigate the details of it and make it easy to use. For the factors influencing torsion effects, many scholars approve the relative eccentricity is an important factor. The relationship between θ and relative eccentricity and the relationship between torsional effects and θ are respectively investigated by examples analysis of structures with eccentricity in one and two directions. Based on these analyses, the applicability of the criterion will be evaluated, the superiority of story drift and inter-story drift to calculate θ will be evaluated and the value of θ for different stories will be compared.

Method for analysis

The example structures are analyzed through modal analysis by SAP2000. The response spectrum is adopted given by GB50011-2001 as shown in figure 2, here $\alpha_{\max}$ is 0.16, T_g is 0.45s, η_1 is 0.02, η_2 is 1 and γ is 0.09. The spatial model and the postulate that the floor is rigid are adopted. Three degree of freedom (two for lateral translation and one for torsion rotate) for every story are considered and the first 15 mode shapes are combined by the complete quadratic combination method (CQC) for torsion rotate and lateral translation coupling model.

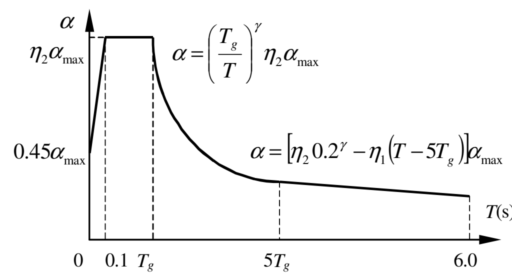


Figure 2. Seismic effect coefficient curve

Design of example structures

Two type of structures with torsional irregularity are designed, one with eccentricity in one direction and the other with eccentricity in two directions. The relative eccentricity along X direction of structures with eccentricities in two directions keeps invariable when the relative eccentricity along Y direction varies from 0.0 to a value. To investigate the influence of plan size to the torsional effects, three kinds of plan sketch that the ratios of long size and short size are respectively 1:1, 3:1 and 5:1 (for short called correspondingly as Str.11, Str.31 and Str.51) are designed. All elevation layouts are regular. The structures are 5 stories and the height of the ground floor is 4.6m and the above is 3.6m each. The cross section is 500×500mm for columns and 300×700mm for beams. The center of rigidness (C_S) of floor is located on the center of floor and the center of mass (C_M) is variable with the variation of mass distribution, so the total mass and total lateral resisting stiffness keep invariable. Here only the plan layout of Str.31 is shown in figure 3, where ex , ey are the eccentricity along x and y direction.

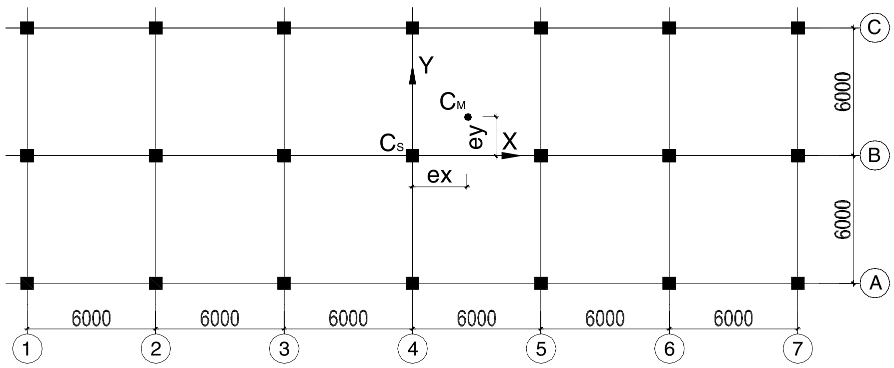


Figure 3. Plan layout of Str.31

For describing clearly, defining such parameters as,

$$exr = ex / r \tag{3}$$

$$er = \sqrt{ex^2 + ey^2} \; / \; r \tag{4}$$

$$r = \sqrt{\left(a^2 + b^2\right)/12} \tag{5}$$

Where exr is relative eccentricity for structures with eccentricity in X direction while er in two directions, r is the radius of torsion rotate of the floor. a , b are the length of structure along X and Y direction. The above information of all example structures are shown in table 1.

Table 1. Information of structures for analysis

Style of structure	Number×span		Structures with eccentricity in X direction		Structures with eccentricity in one ~ two directions	
	Xdirection	Ydirection	exr	Numbers	0.00～ exr ～ er	Number
Str. 11	6×6	6×6	0.00~0.34	8	0.00~0.23~0.41	6+7
Str. 31	6×6	2×6	0.00~0.56	8	0.00~0.37~0.46	6+8
Str. 51	10×5.4	2×5.4	0.00~0.45	11	0.00~0.31~0.34	8+9

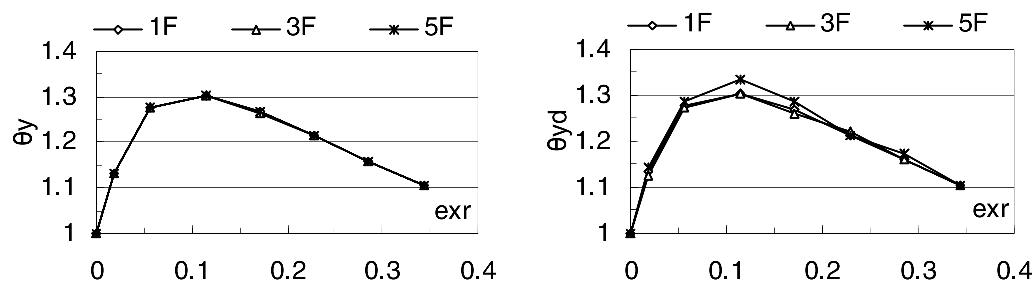
Results analysis

Relationship between θ and relative eccentricity

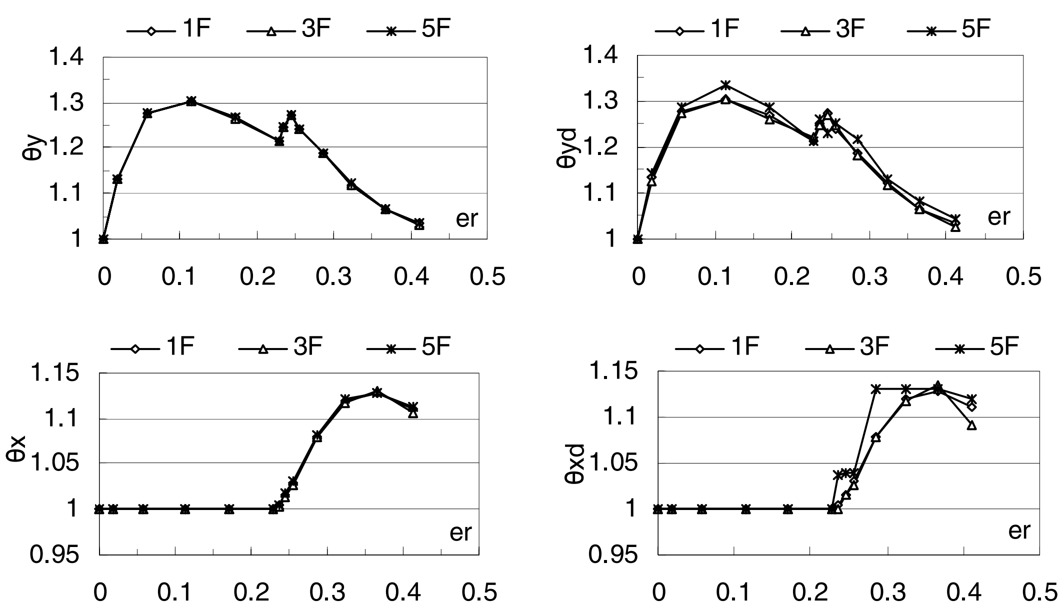
θ_y (θ_x) and θ_{yd} (θ_{xd}) are respectively calculated by story drifts and inter-story drifts under earthquake action in Y(X) direction. The relationships between θ and e are shown in figure 4. (1), (3) and (5) of figure 4 correspond to the structures with eccentricity in one direction, (2), (4) and (6) of figure 4 correspond to the structures with eccentricity in two directions. Based on figure 4, the following can be obtained,

1) θ_x and θ_y are almost same between different stories. θ_{yd} and θ_{xd} are different from one story to another, the θ of the top story is bigger than that of the other stories, but these differences are not obvious. The differences between θ_y and θ_{yd}, θ_x and θ_{xd} are little, which differences is biggest in the top story. Therefore, the difference of story drifts and inter-story drifts between GB50011-2001, UBC97 and EC8 can be neglected for design.

2) For regular structure, θ_x, θ_{xd}, θ_y and θ_{yd} are all equal 1, as shown in (1), (3) and (5) of figure 4. When exr varies from 0 to a small value, θ_y (θ_{yd}) varies dramatically from 1 to a value which exceeds the limit value of torsional irregularity 1.2. For example, when θ_y is 1.2, the corresponding exr of Str.11, 31 and 51 are all less than 0.05. Thus according to the criterion of torsional irregularity, torsion effects should be considered for the structure with a very little eccentricity which less than 0.05. That is to say any structure may be torsional irregular if accidental eccentricity of 5 percent the length of the structure is considered according to UBC97 and EC8.

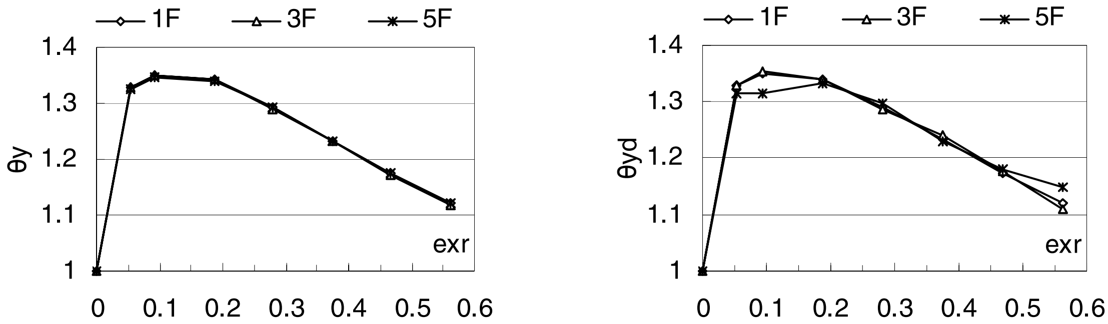


(1) Str.11 with eccentricity in one direction

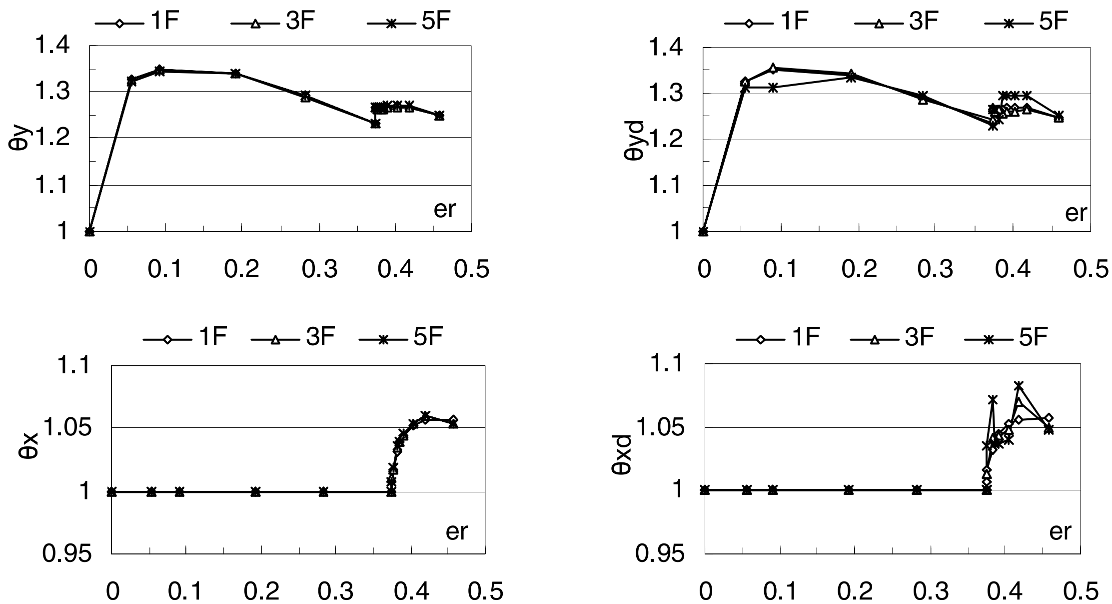


(2) Str.11 with eccentricity in one and two directions

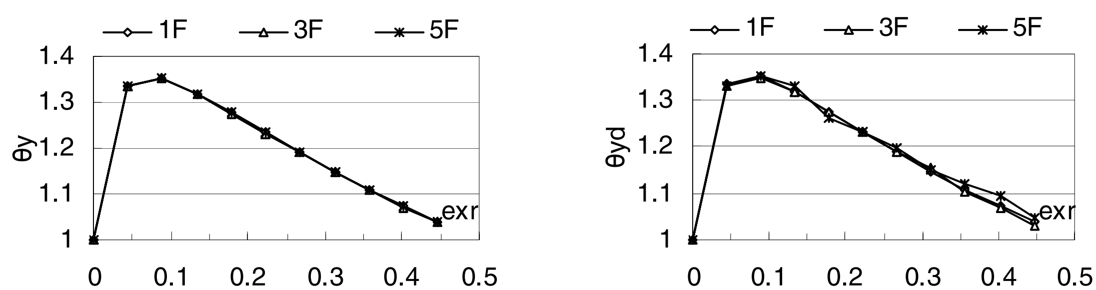
Figure 4. Variations of θ with $exr(er)$



(3) Str.31 with eccentricity in one direction

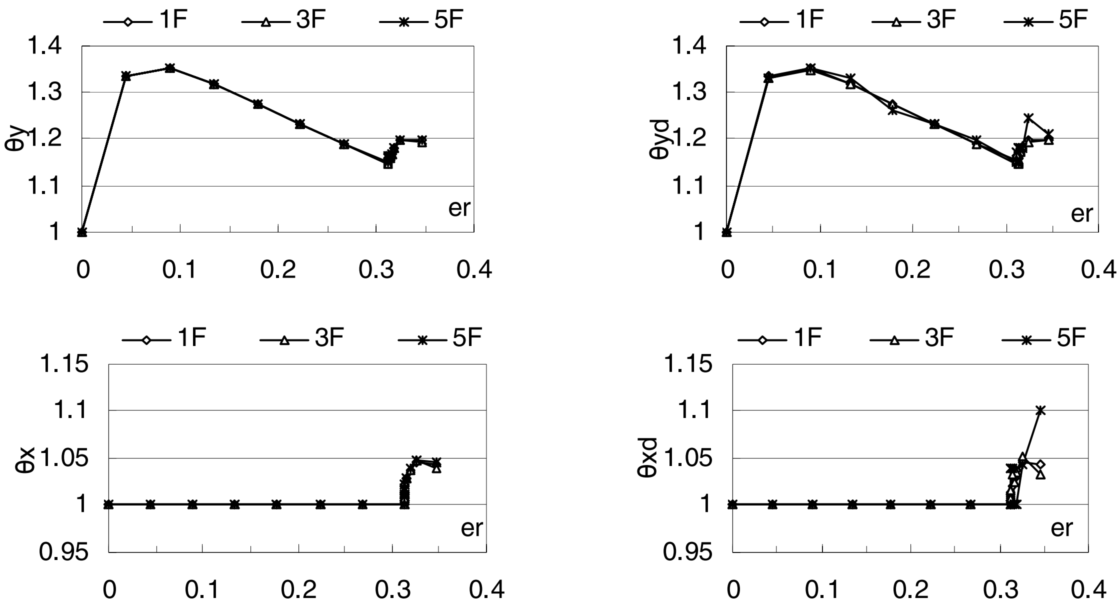


(4) Str.31 with eccentricity in one and two directions



(5) Str.51 with eccentricity in one direction

Figure 4. Variations of θ with $exr(er)$ (continue)



(6) Str.51 with eccentricity in one and two directions

Figure 4. Variations of θ with $exr(er)$ (continue)

3) After the quick increasing, θ_y of Str.11, 31 and 51 decrease with the increasing of exr. It is contradictory to the results that Wang [5] pointed out lager relative eccentricity, lager torsion effects. The boundaries of declining points are not same for the three categories of structures, which may attribute to the different sizes of the structures. The decrease ratio of θ_y is largest for Str.51. θ_y may be less than 1.2 for the structure with bigger eccentricity. According to the criterion, these structures are irregular and the torsion effects may be ignored. But this is obviously impossible.

4) As shown in (2), (4) and (6) of figure 4, with ey increasing but ex is constant, θ_y of Str.11 increases firstly and then decreases even less than the one of structure with only ex along X direction. When θ_y of Str.31 and 51 increases to some extent and the values of them are more than those of structures with ex. This is to say that one er may correspond to several θ_y with the variations of the size and eccentricity of the structures. The θ_y of the structures with eccentricities along two directions has not good relationship with er.

5) As (2), (4) and (6) in Fig. 4 shown, with eccentricity ey increasing but ex keeping constant, θ_x increases gradually. Contrasting with the phenomenon that big θ_y corresponds to little exr of structures with eccentricity in X direction, values of θ_x here are all less than 1.1. The factors influencing θ_x need be investigated furthermore.

According to above analysis, the criterion for torsional irregularity has not close relations with relative eccentricity exr and er. The parameter θ is not proper to represent the torsion effects of the structures and defined as the criterion of torsional irregularity.

The relationship between λ_{VX} and θ_y

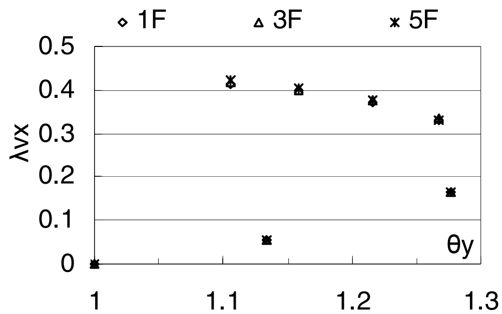
Defining λ_{VX} as following

$$\lambda_{VX} = V_{xy} / V_{xx} \tag{6}$$

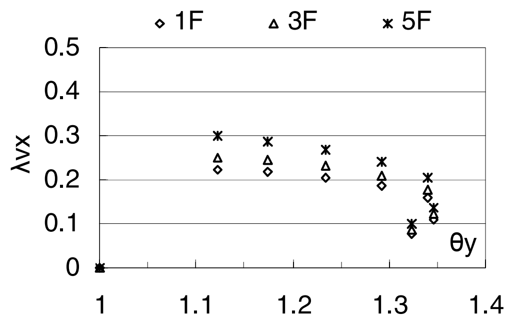
Where V_{xy} is the shear force in X direction under earthquake action in Y direction for structures with eccentricity in X direction. V_{xx} is the shear force in X direction under earthquake action in X direction. λ_{VX} denotes the torsion effects of structures with eccentricity in X direction.

For seismic design, V_{xy} should not be ignored when λ_{VX} increase to a prescribed value and the total shear in X direction should be combined by V_{xy} and V_{xx} no matter the structure has eccentricity in one directions or two directions, otherwise the design is not safety enough. Therefore λ_{VX} can be considered as the link of torsional irregularity and considering earthquake action in two directions simultaneously.

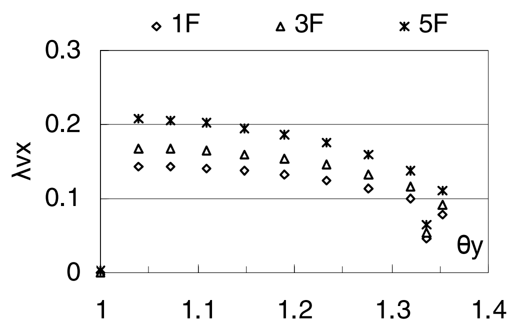
Correlations of λ_{VX} and θ_y of example structures with eccentricity in X direction are shown in Figure5.



(1) Str.11



(2) Str.31



(3) Str.51

Figure 5. Variations of λ_{VX} and θ

It can be seen that with the increasing of θ_y, λ_{VX} of different structures all decrease but the degrees of decrease are not same. When θ_y are in 1.3~1.4, the same θ_y may corresponds to several λ_{VX} for Str.31 and 51. And λ_{VX} increases with the increasing of story for Str.31 and 51. In a word, the correlation of torsion effects and the criterion for torsional irregularity is not definite. This criterion for torsional irregularity is not proper to decide considering earthquake action in two directions simultaneously or not.

CONCLUSIONS

In this paper, the criterion and relative regulations for torsional irregularity in GB50011-2001, UBC97 and EC8 are compared and analyzed from the theoretical and practical aspects. Through designing and analyzing the series of example structures with eccentricity in one direction and two directions, a elementary conclusion can be drawn that the corelationships between torsion effects and θ are not definite, although the criterion about θ is adopted by GB50011-2001, UBC97 and EC8 for torsional irregularity. This criterion is not proper to decide considering earthquake action in two directions simultaneously or not.

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