METHOD OF PERFORMANCE BASED SEISMIC EVALUATION FOR IRREGULAR PLANE REINFORCED CONCRETE FRAME STRUCTURES

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ABSTRACT :

The relationship between inter-story torsion angle and torsion deformation ratio is deduced base on the rule of irregular plan structures in China tall building technical specification. Considering the inter-story drift ratio limitation of different performance levels under different earthquake hazard levels, the ratio of torsion angle to height of floor is calculated. Then a series of torsion angle demand curves are established and a new method named as torsion angle capacity spectrum method is put forward for the performance based seismic evaluation of irregular plan frame structures. Examples are presented to explain the method principle and to demonstrate the applicability and utility of the proposed methodology. It is concluded that the new method can identify the torsional displacement not only between stories but also among structure members in a story. The new method promotes a lot the performance based seismic design theory.

KEYWORDS: performance based seismic design, irregular plan structure, torsion angle demand curve, torsion angle capacity spectrum method

1. INTRUDCTION

The torsion effects caused by irregularity of plan layout of seismic structures have been emphasized for seismic design in some codes. However with the development of performance-based seismic design theory lots of method and theory are propose for regular structures, such as capacity spectrum method (Freeman 1998), yield point spectra method (Aschheim et al. 2000) and direct displacement-based method (Sullivan et al. 2003), while few method of performance-based design is researched about irregular plan structure. The researches about irregular plan structure are mainly focus on effect parameters of structure on seismic performance (Dai Junwu 2002; Goel et al. 1991), calculation of response of torsional vibration (Xu Peihu et al. 2000; Wei Lian et al. 2005) and so on. In this paper based on the rule of irregular plan structures in China Code for Seismic Design of Buildings (2001) and Technical Specification for Concrete Structures of Tall Buildings (2002) considering the inter-story ratio limitation of different performance levels under different earthquake hazard levels suggested by Men Jinjie (2007) a series of torsion angle demand curves are established and a new method named as torsion angle capacity spectrum method is put forward for the performance based seismic evaluation of irregular plan frame structures. Examples are presented to explain the method principle and to demonstrate the applicability and utility of the proposed methodology.

2.TORSION ANGLE CAPACITY SPECTRUM METHOD

2.1. Relationship between torsion deformation ratio and inter-story torsion angle

At present there isn't any specification for inter-story torsion angle in two main civil engineering codes of Code for Seismic Design of Buildings (2001) and Technical Specification for Concrete Structures of Tall Buildings (2002). And few experiment results have given a proper value of inter-story torsion angle for seismic design and evaluation. However a prescript of torsion displacement for torsional irregular structures is described in the two codes, that is, for torsional irregular structures torsional irregularity should be considered and the maximum story drift or inter-story drift at one end of the structure transverse to an axis is not more than 1.5 times the average of the story drifts or inter-story drifts at the two ends of the structure. Then a new parameter named torsion displacement ratio μ_t can be defined from the above prescript and a criterion can be expressed as

$$\mu_t = \frac{\Delta_{\max}}{\Delta_a} \le 1.5 \tag{2.1}$$

where $\Delta_{\max}$ is the maximum story drift and Δ_a is the average drift of the story.

A formula for calculating the inter-story torsion angle of irregular plane structures can be obtained on the based of Eqn. 2.1. The detail deducing procedure is as follows. Generally the stiffness of floor is assumed to be infinite, and then all the members in the floor have the same additive inter-story drift Δ_{ti}. The additive inter-story drift can be expressed with the product of inter-story drift ratio θ_t and the distance from torsion centre to members r_i, which is shown in Eqn. 2.2.

$$\Delta_{ti} = r_i \theta_t \tag{2.2}$$

The total drift of member *i* is expressed as

$$\Delta_i = \Delta_a + \Delta_{ti} = \Delta_a + r_i \theta_t \tag{2.3}$$

Clearly the additive inter-story drift and the total drift of the end member is the maximal among all the members in the same story, which is expressed in Eqn. 2.4.

$$\Delta_{t\max} = r_{\max}\theta_t,\ \ \Delta_{\max} = \Delta_a + \Delta_{t\max} = \Delta_a + r_{\max}\theta_t \tag{2.4}$$

In this paper the average drift of the story is defined to be a product of parameter ξ and the limitation value of inter-story drift Δ_u, which is expressed in Eqn. 2.5. Substituting Eqn. 2.5 into Eqn. 2.1, a new equation to calculate μ_t is obtained which is shown in Eqn. 2.6.

$$\Delta_a = \xi\,\Delta_u \tag{2.5}$$

$$\mu_t = 1 + \frac{r_i}{\Delta_a}\theta_t = 1 + \frac{r_i}{\xi\Delta_u}\theta_t \tag{2.6}$$

The value of ξ is less than 1 and the value of Δ_u is given in literature [9]. Furthermore Δ_u is expressed as the product of inter-story drift ratio $[\theta]$ and story height *h*, and then Eqn. 2.6 is transformed to Eqn. 2.7.

$$\frac{\theta_t}{h} = (\mu_t - 1)\frac{\xi}{r_i}[\theta] \tag{2.7}$$

For a building has been constructed, the story height and the distance from torsion centre to members are all known. The inter-story drift ratio limitation value of different seismic performance is given by Men Jinjie (2007). Now the question to be solved is to confirm the proper value of parameter ξ.The maximum value of inter-story drift of structure must meet the correlative rule in seismic design code, which is express in Eqn. 2.8.

$$\Delta_a + \Delta_{t\max} \le \Delta_u \tag{2.8}$$

When the equal mark is selected Eqn. 2.8 can be transformed to

$$\Delta_{t\max} = \Delta_u - \Delta_a = \Delta_u(1-\xi) \tag{2.9}$$

Based on Eqn. 2.1, 2.8, 2.9, torsion displacement ratio μ_t can be rewritten as

$$\mu_t = \frac{\Delta_{\max}}{\Delta_a} = \frac{\Delta_a + \Delta_{t\max}}{\Delta_a} = 1 + \frac{1}{\xi}\cdot\frac{\Delta_{t\max}}{\Delta_u} = 1 + \frac{1}{\xi}(1-\xi) \tag{2.10}$$

$$\xi = \frac{1}{\mu_t} \tag{2.11}$$

Substituting Eqn. 2.11 into Eqn. 2.7 the relationship between torsion deformation ratio and inter-story torsion angle is obtained:

$$\frac{\theta_t}{h} = (1-\frac{1}{\mu_t})\frac{1}{r_i}[\theta] \tag{2.12}$$

2.2 Torsion angle demand curve

When the torsion deformation ratio and the inter-story drift ratio are confirmed, the relation between θ_t/h and r_i can be calculated from Eqn. 2.12. And then based on the seismic performance levels under different earthquake hazard levels, a series of torsion angle demand curves are established which are expressed with the relation of θ_t/h and r_i.

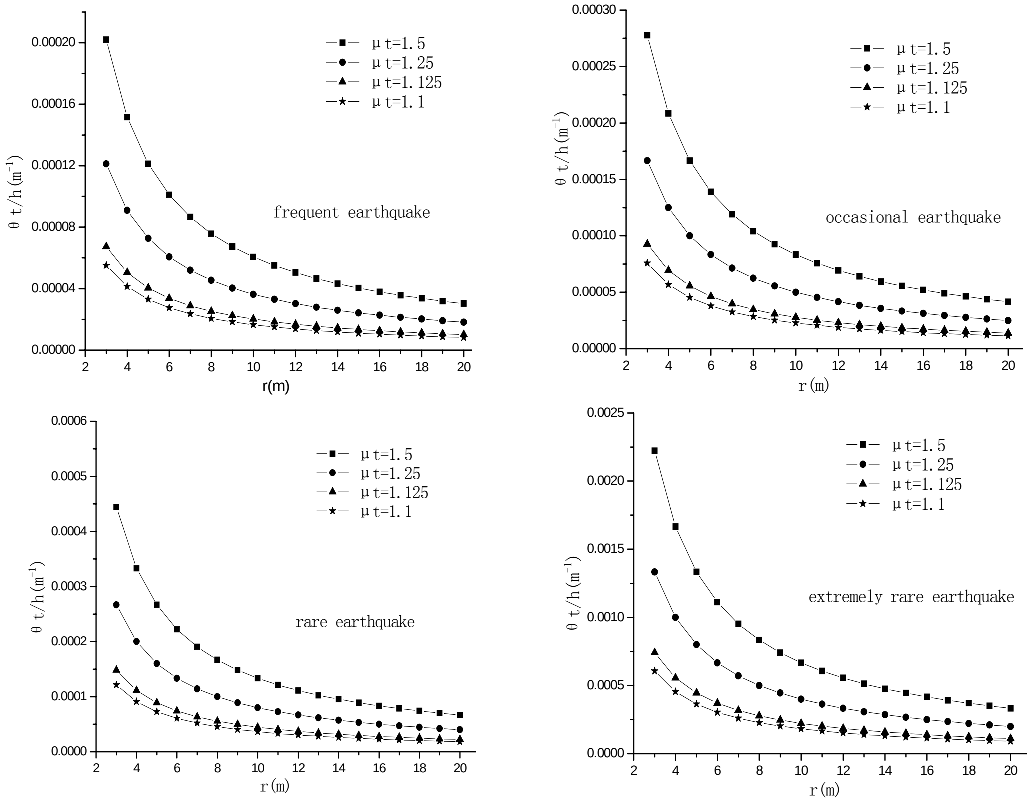

Figure 1 Torsion angle demand curves

When the inter-story drift ratio of reinforced concrete frame structure is equal to 1/550, 1/400, 1/250 and 1/50 under frequent, occasional, rare and extremely rare earthquake respectively and when the torsion deformation ratio is equal to 1.5, 1.25, 1.125, 1.1, four group of torsion angle demand curves are shown in Figure1. The torsion angle demand curves can be applied to irregular plan structures with different degree irregularity under different earthquake hazard levels.

The torsion angle demand curves in this paper denote the torsion angle demand of members from various distances to the torsion center. It is shown from Figure 1 that the farther the distance is the value of torsion angle of member is more less under the identical level earthquake and the identical torsion deformation ratio. It means that the torsion displacement of the farther member is limited more strictly in the same story. Even torsion displacement of the member close to the torsion center satisfies the demand, however torsion displacement of the member far away from the torsion center can not satisfy the demand.

2.3 Calculation method of torsion angle

Irregular plan structure occur torsion vibration even under horizontal earthquake, moreover the torsion vibration is coupling with the horizontal vibration. The equation of motion for irregular plan structure can be written as

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=-[M]\{\ddot{U}_g\} \tag{2.13}$$

in which $\{U\}$, $\{\dot{U}\}$, $\{\ddot{U}\}$represent the relative displacement matrix, the relative velocity matrix, the relative acceleration matrix, respectively. And the relative displacement matrix can be expressed as

$$\begin{aligned}\{U\}&=\left[\{x\}^T\{y\}^T\{\theta\}^T\right]^T\\&=\left[x^{(1)}x^{(2)}\cdots x^h\vdots y^{(1)}y^{(2)}\cdots y^h\vdots\theta_t^{(1)}\theta_t^{(2)}\cdots\theta_t^{\,h}\right]^T\end{aligned} \tag{2.14}$$

in which θ_t^i refers to the torsion angle of story i, $\{\ddot{U}_g\}$represents the relative acceleration matrix of ground motion, and $[K]$ represents the stiffness matrix which is component of the anti-torsion stiffness matrix $[K_{\theta\theta}]$, the anti-drift stiffness matrix $[K_{xx}]$, $[K_{yy}]$, $[K_{x\theta}]$, $[K_{y\theta}]$, in which $[K_{\theta\theta}]$ can be expressed as

$$[K_{\theta\theta}]==\begin{bmatrix}K_\theta^{1,1} & K_\theta^{1,2} & \cdots & K_\theta^{1,r} & \cdots & K_\theta^{1,h}\\ K_\theta^{2,1} & K_\theta^{2,2} & \cdots & K_\theta^{2,r} & \cdots & K_\theta^{2,h}\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ K_\theta^{r,1} & K_\theta^{r,2} & \cdots & K_\theta^{r,r} & \cdots & K_\theta^{r,h}\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ K_\theta^{h,1} & K_\theta^{h,2} & \cdots & K_\theta^{h,r} & \cdots & K_\theta^{h,h}\end{bmatrix} \tag{2.15}$$

It is concluded from the equation of motion and the stiffness matrix that the torsion angle can be calculated and is relative to the stiffness matrix. When the structure gets into inelastic stage under earthquake the torsion angle of members can be calculated by modifying the stiffness matrix. Generally the stiffness of floor is assumed to be infinite thereby the torsion angle of the story is the same.

The method to calculate the torsion angle includes discrete modal method, finite element method and some approximate method. However the procedure of these methods is mostly complicated. Nowadays some software, such as SAP2000, ETABS provides simple and convenient procedure to calculate the torsion angle of structures. In this paper the value of θ_t/h, as the structure and member capacity parameter, is obtained on the result of software ETABS. Then the result of θ_t/h-r_i is used to establish the torsion angle capacity curves of stories, which are horizontal line in a story under the presupposition that the stiffness of floor is infinite.

2.4 Seismic evaluation process of torsion angle capacity spectrum method

By using of torsion angle capacity spectrum method the processes of performance-based seismic evaluation for irregular plane structures are as follows:

(1) Establishing the mechanics model of the structure. (2) Confirming the earthquake hazard level including frequent earthquake, occasional earthquake, rare earthquake and extremely rare earthquake and the torsion displacement ratio the value of which is from 1 to 1.5, then establishing the torsion angle demand curve from Eqn.2.12 or selecting directly from Fig.1. (3) Calculating the inter-story torsion angle of members in all floor under the earthquake action and rewriting as θ_t/h-r_i which are the torsion angle capacity curves of members. (4) Drawing and comparing the torsion angle demand curve and the torsion angle capacity curve obtained from above step (2) and (3) in a coordinate system then evaluating the torsion displacement and the seismic performance of members, stories and structure.

3. ILLUSTRATIVE EXAMPLE WITH TORSION ANGLE CAPACITY SPECTRUM METHOD

The floor plan of a R.C frame with 7 story is shown in Figure 2. The section dimension of A axes columns is 500×500mm, of B and C axes columns is 400×400mm which comprises 8 longitudinal reinforcement bar with diameter of 25mm, strength grade of HRB335. The section dimension of beams is 300×600mm which comprises 4 longitudinal reinforcement bars with diameter of 18mm, strength grade of HRB335. The concrete strength grade of beams and column is C30. The height of each story is 3.3m. The seismic fortification intensity is 8, the design group of ground motion is the first group and the site type is typeⅡ.

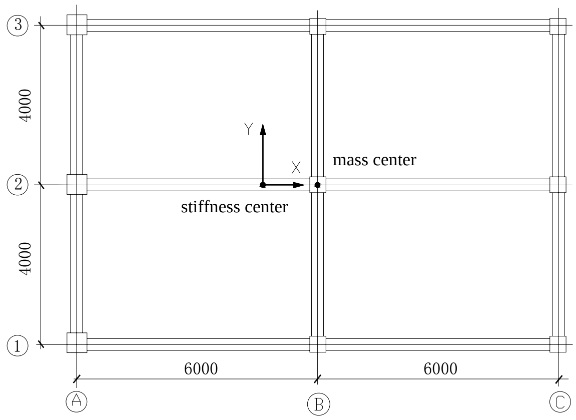

Figure 2 Layout of irregular plan structure

3.1 Structure analysis

Structure model is established by use of software ETABS and the story drift is obtained under frequent, occasional, rare and extremely rare earthquake respectively. It is concluded that the maximum story drift at one end of the structure transverse to an axis is more than 1.2 but less than 1.5 times the average of the story drifts at the two ends of the structure which accord with the specification of irregular plan structure. the story drifts at the two ends (δ_1, δ_2) and the average of the story drifts ($\overline{\delta} = (\delta_1 + \delta_2)/2$) under frequent earthquake are shown in table 3.1. In addition the mass of the frame is symmetric while it has eccentricity in x direction because of the asymmetrical stiffness of the column. The stiffness center is offset from A axes of 4.91m in story 2 to 7 and of 4.64m in story 1 and the relative eccentricity is 1.09m in story 2 to 7 and 1.36m in story 1.

By modal analysis the first, second and third period of the structure is mainly in x, y and torsional direction, namely, T_1=0.908s, T_2=0.863s, T_3=0.732s. And the modal participate mass in x, y and torsional direction is of 82%, 67%, 67% respectively.

Table 3.1 Story drifts of structure under frequent earthquake action

Story	δ_1 (mm)	δ_2 (mm)	$\bar{\delta}$ (mm)	$1.2\bar{\delta}$ (mm)	$1.5\bar{\delta}$ (mm)
7	8.55	13.05	10.80	12.96	16.20
6	7.82	12.15	9.98	11.98	14.97
5	6.73	10.80	8.76	10.52	13.15
4	5.34	8.69	7.02	8.42	10.53
3	3.73	6.12	4.92	5.91	7.39
2	1.97	4.26	3.12	3.74	4.67
1	1.02	1.73	1.37	1.65	2.06

3.2 Seismic performance evaluation

The torsion angle demand curves calculated by Eqn.2.12 with torsion displacement ratio of 1.1, 1.2 ,1.3, 1.5 under frequent, occasional, rare and extremely rare earthquake action are plotted together with the torsion angle capacity curves calculated by software EATBS under the four level earthquake action which are shown in Figure 3. The demand curves are plotted with solid marks while the capacity curves are plotted with hollow marks.

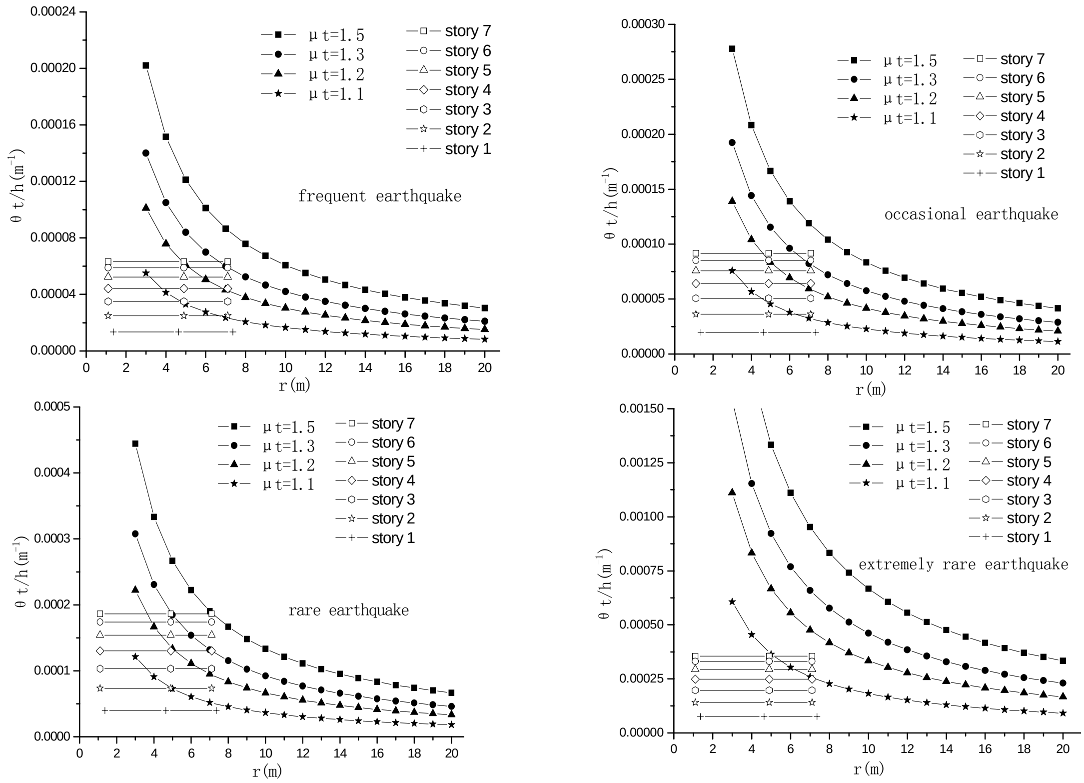

Figure 3 Seismic performance evaluation curves of a 7 story irregular plan structure

It is shown from Figure 3 that the inter-story torsion angle increase from the first story to the top story, but the increasing trend is slow. For example the inter-story torsion angle increases from 1/22381 to 1/4797 under frequent earthquake action and from 1/3979 to 1/853 under extremely rare earthquake action.

It is concluded that the torsion displacement ratio wouldn't more than 1.2 in story 1 to 3 and not more than 1.3 in story 4 to 7 under frequent earthquake action. The torsion displacement increases much under occasional earthquake action but the torsion displacement ratio wouldn't more than 1.4. Under rare earthquake action the torsion displacement increases much more in story 6 and 7 the maximum torsion displacement ratio of which is just close to 1.5. However the torsion displacement ratio of all stories is on the contrary less than 1.2 under extremely rare earthquake action. It is possibly because of two reasons. One is that elastic modal spectrum method is adopted to calculate the torsion displacement. The method doesn't take the inelastic displacement of structure into account which results in lower value of torsion angle capacity. The other reason is that the inelastic inter-story drift ratio of reinforcement concrete frame, 1/50, is used to establish the torsion angle demand curve under extremely rare earthquake action. The value of 1/50 maybe results in higher value of torsion angle demand for seismic performance evaluation of irregular plan frame structures

3.3 Result comparing

The peak ground acceleration of El-Centro earthquake is adjusted to 70gal, 101gal, 207gal and 400gal respectively which correspond to the maximum ground acceleration of time-history analysis when under frequent, occasional, rare and extremely rare earthquake action in seismic fortification intensity of 8. Then nonlinear time-history analysis is carried through. The maximum torsion displacement ratios of stories are obtained which are listed in table 3.2.

Table 3.2 Maximum torsion displacement ratio of time-history analysis result

Story	μ_t (frequent earthquake)	μ_t (occasional earthquake)	μ_t (rare earthquake)	μ_t (extremely rare earthquake)
7	1.323	1.361	1.486	1.283
6	1.324	1.359	1.488	1.282
5	1.329	1.365	1.507	1.276
4	1.332	1.375	1.529	1.265
3	1.340	1.399	1.536	1.260
2	1.352	1.428	1.540	1.258
1	1.369	1.462	1.545	1.282

It is concluded that the maximum torsion displacement ratio of time-history analysis result are accorded well with that of the torsion angle capacity spectrum method. The coincident conclusion is that the maximum torsion displacement ratio of structure under frequent, occasional, rare and extremely rare earthquake action wouldn't exceed 1.3, 1.4, 1.5 and 1.2 respectively. It needs to noticed that the torsion angle capacity spectrum method maybe overrate the torsional capacity of structure in the bottom story.

4. CONCLUSIONS

A new method named torsion angle capacity spectrum method is proposed for the performance-based seismic evaluation of irregular plan frame structures. Through deducing the relationship between inter-story torsion angle and torsion deformation ratio and considering the inter-story drift ratio of different performance levels under different earthquake hazard levels, torsion angle demand curves are established. By software ETABS torsion angle capacity curves are established. Plotting the demand curve and capacity curve of stories and members together in a coordinate system, the torsion displacement and seismic performance can be evaluated conveniently and availably. It is concluded from example that the new method can identify the torsional displacement not only between stories but also among structure members in a story. The result of the torsion angle capacity spectrum method accords well with that of nonlinear time-history.

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