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Technical Note

An investigation of torsionally irregular multi-story buildings under earthquake loading

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Abstract. It is well known that torsionally unbalanced buildings are more vulnerable to earthquake hazards than are the regular structural systems. In this paper, a parametric investigation is presented, in order to observe the amplification in the internal forces, when increased eccentricities are used instead of the ones corresponding to the 5% accidental eccentricity. A series of five, ten-story framed and walled structures, with rather high torsional irregularity coefficients, are selected and a numerical test procedure is applied. Numerical results show that the maximum amplification in the internal forces at the most critical beams and columns at the flexible sides of the structures is about 10%. It is concluded that, more serious measures in the codes are needed in the case of this rather dangerous type of irregularity.

Key words: irregular structures; torsional irregularity; earthquake resistant design; seismic code; seismic response.

1. Introduction

Numerous studies on different types of structural irregularities have been carried out worldwide in recent years where most of them are concentrated on torsionally unbalanced systems, such as: Chandler *et al.* (1996), Duan and Chandler (1997), Rutenberg *et al.* (1995). Despite these efforts, there is not yet any universal agreement among researchers or any unique or accurate procedure advised for common practice in the seismic codes for the evaluation of the torsional effects. The main reason for this may be that the complex effects of various parameters governing the seismic response of torsionally unbalanced structures are not yet fully understood.

The seismic analysis procedure of a 3-D system depends on various parameters, such as the type and the location of the considered building, the positions and stiffness distributions of its structural members, the selection of the proper elastic model for the structural and the non-structural elements. The input earthquake motion, type and degree of the structural irregularity, the code requirements for the computation of the increased eccentricity value as well as the type of structural analysis affect the analysis procedure.

Most of the seismic codes in various countries have put some dissuasive limits on the use of various structural irregularities in buildings such as an increase in design forces or the requirement

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of 3D-dynamic analysis. Despite these punitive measures, torsional irregularities in buildings are sometimes inevitable because of architectural reasons; therefore its effect must be carefully taken into consideration in design.

The main objective of this paper is to observe the change of the internal forces in torsionally irregular multi-story buildings due to the increased eccentricity, as compared with the 5% accidental eccentricity (Çalım 1999). The research work is also aimed at investigating the variation of the "Torsional Amplification Factors" along horizontal and vertical axes for various "Sample Structures".

2. Code provisions for torsional irregularity

According to the Uniform Building Code of U.S.A. (UBC 1997), torsional irregularity exists when the *torsional irregularity coefficient*, η_{bx}, exceeds 1.2 for any story of a structure. η_{bx} is defined as

$$\eta_{bx} = \frac{\delta_{\max}}{\delta_{avg}} \tag{1}$$

Here, $\delta_{\max}$ and δ_{avg} denote the maximum displacement and the average of the displacements of the extreme points of the structure at the x^{th} level, respectively. When torsional irregularity exists, the effects are accounted for by increasing the accidental torsion (i.e., eccentricity) at each level by an amplification factor, A_x, determined by the following formula:

$$A_x = \left[\frac{\eta_{bx}}{1.2}\right]^2 \tag{2}$$

The increased eccentricity ε_x at the x^{th} level is then computed by

$$\varepsilon_x = 0.05\, A_x \tag{3}$$

It must be noted that, in almost all of the recently developed seismic codes, the above outlined procedure is adopted with slight modifications [Turkish Earthquake Code (1997) and Earthquake Resistant Regulations: A World List (1996).]

In this paper, a series of sample structures with varying torsional irregularities is selected and the effect of increased eccentricity is investigated using the analysis procedure given in UBC'97.

3. Procedure for the parametric study

A parametric investigation is carried out on various multi-story framed and walled structures with rather high torsional irregularity levels. The comparison and evaluation procedure is based on the numerical approach utilised by Özmen *et al.* (1999).

The main steps of the parametric investigation procedure can be summarised as follows:

1. The considered sample structure is first analysed with 5% accidental eccentricity assuming the floor diaphragm is rigid. The computed internal forces in the structural members are defined as M_a.
2. The values of the torsional irregularity coefficient η_{bx} and the increased eccentricity ε_x are computed at each x^{th} story of the building.
3. The analysis is repeated for the increased eccentricity ε_x at each story, with rigid diaphragm

assumption again. The computed internal forces at the column and beam members are defined as M_i.

4. Then, the "Torsional Amplification Factor: *TAF*", defined in the following expression, is computed for each critical section.

$$TAF = \frac{M_i}{M_a} \tag{4}$$

5. The variations of *TAF* values along the horizontal axes as well as along the height of the structures are investigated by utilising the weighted-averages of *TAF* values, (TAF_{avg}).

4. Sample structures

The numerical investigations are carried out on five ten-story R/C sample buildings, which are designated as SS1, SS2, …, SS5. The schematic floor plans of those sample structures are shown in Fig. 1.

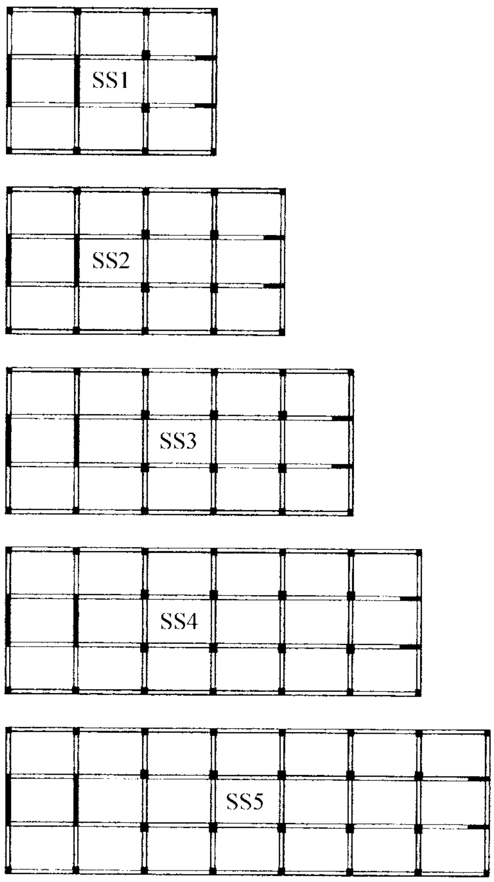

Fig. 1 Schematic floor plans of sample structures

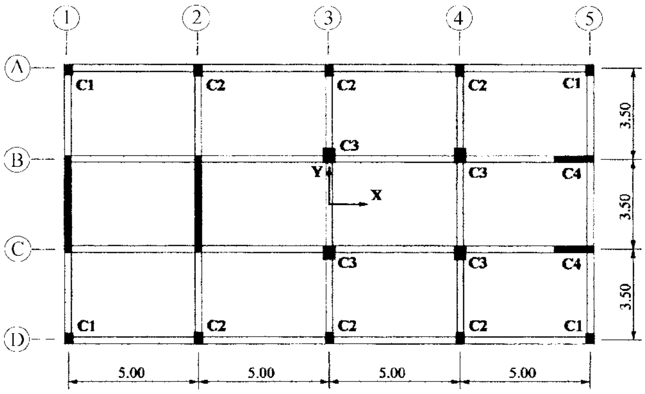

Fig. 2 Detailed floor plan of sample structure SS2

Table 1 Column sections

Story No.	C1 (cm × cm)	C2 (cm × cm)	C3 (cm × cm)	C4 (cm × cm)
10, 9	30 × 30	30 × 30	30 × 30	150 × 25
8, 7	30 × 30	30 × 40	40 × 40	150 × 25
6, 5	30 × 40	30 × 45	45 × 45	150 × 25
4, 3	30 × 45	30 × 55	45 × 60	150 × 25
2, 1	30 × 55	30 × 70	45 × 70	150 × 25

As can be seen in the figure, all sample structures have essentially the same structural configuration, with varying numbers of transverse frames. The floor heights are 4.00 m for the first stories and 3.00 m for the other stories of the sample structures.

The detailed floor plan of the sample structure SS2 is shown in Fig. 2, wherein geometrical and structural frames, plan dimensions in metres and typical column designations (C1, C2, C3 and C4) are depicted. All beam dimensions are 25 by 50 cm/cm, and the thicknesses of all the structural walls are 25 cm. The column dimensions for the various stories are shown in Table 1.

The mass centres of sample structures are assumed to be at the geometrical centres of floor plans. To determine preliminary dimensions of the various structural elements of the considered sample structures, all structures were first analysed by using equivalent static loads computed according to the UBC’97, assuming the seismic zone as $Z = 3$, soil profile type S_B and the importance factor $I = 1.00$. The SAP90 Structural Analysis Package is utilised for the 3D analyses (Wilson and Habibullah 1992).

5. Results of the analyses and observations

As has been mentioned above, all sample structures are first analysed according to ±0.05 accidental eccentricities. Since the sample structures are all symmetric about X-axis, the lateral load analyses have been carried out only in the Y-direction.

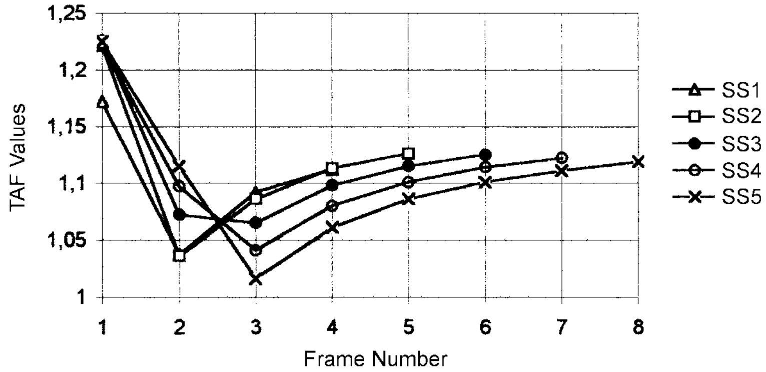

Fig. 3 *TAF* values for maximum beam end moments

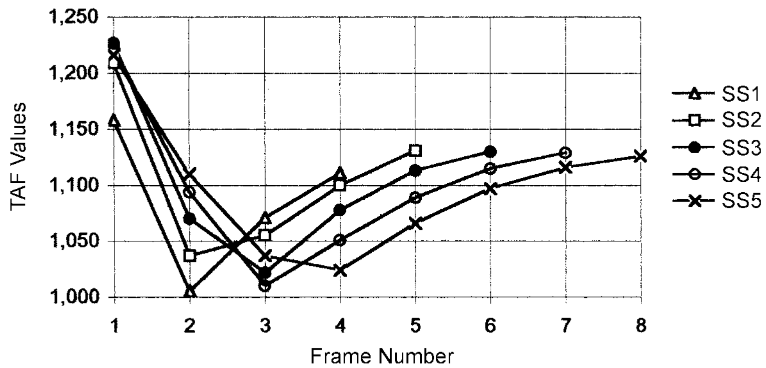

Fig. 4 *TAF* values for maximum column end moments

The torsional irregularity coefficients, η_{bx}, computed for the sample structures, vary between 1.578 and 1.944, which are higher than the upper limit of 1.2 given in the code. Hence, the analyses of sample structures are repeated by using increased eccentricities, which are computed according to Eqs. (2) and (3).

Then, the torsional amplification factors (*TAF*) for each end moment of all the structural elements are computed by using Eq. (4). *TAF* values for maximum beam and column end moments corresponding to the transverse frames of each sample structures are shown in Fig. 3 and Fig. 4, respectively.

The inspection of the those figures brings forth the following observations:

· As expected, the maximum amplifications occur at the end frames, i.e., the frames on the stiff and flexible sides.

· The torsional amplification factors (*TAF*) for the frames at the stiff side are greater than the ones at the flexible side. However, it must be pointed out that, the magnitudes of end moments at the flexible side are far greater than the ones at the stiff side. Hence, the factors at the flexible side are more important from the designer's point of view.

· The amplification factors of beams and columns are similar, especially for the axes at or near the extreme edges.

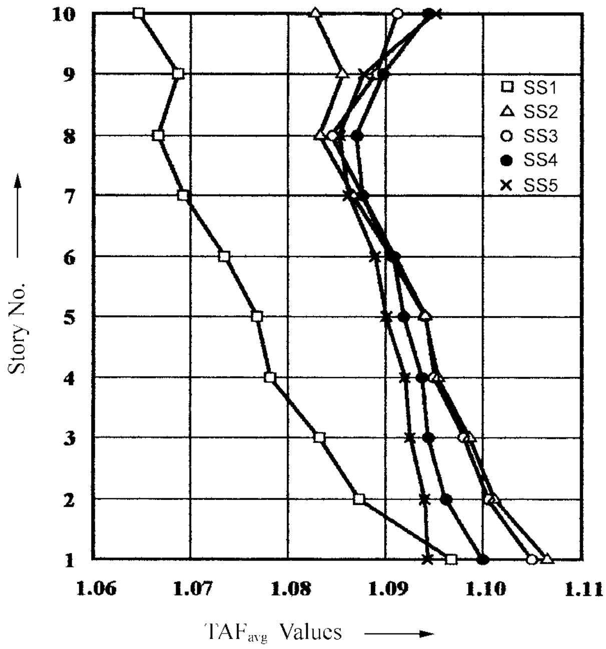

Fig. 5 Story-wise distribution of TAF_{avg} values

Closer inspection of *TAF* values throughout all the critical sections of the sample structures reveals that, rather high *TAF* values exist in especially higher story levels. However, they are not of much importance for design purpose, since the corresponding end moments are rather low.

In order to obtain an overall amplification factor for the systems, the weighted average of all *TAF* values are computed, by taking the corresponding end moments M_a due to the accidental eccentricity, as the weight factors (Özmen *et al.* 1999), using the following expression

$$TAF_{avg} = \frac{\sum M_a \frac{M_i}{M_a}}{\sum M_a} = \frac{\sum M_i}{\sum M_a} \tag{5}$$

The comparison of the TAF_{avg} values with the previously computed ones indicates that the values for the maximum beam and column end moments and the average amplification factors obtained by frame-wise summation of the considered structures are nearly identical.

The change of TAF_{avg} values versus the number of stories, computed by Formula (5), is shown graphically, in Fig. 5. It is observed that the story-wise distribution of TAF_{avg} shows again quite a small variation, ranging between 1.064 and 1.106.

6. Conclusions

The effect of increased eccentricity, on a series of sample structures with rather high torsional irregularities, is investigated in the paper. The most significant results of the parametric investigation are as follows:

· Considering both torsional amplification factor (*TAF*) values for maximum moments and TAF_{avg} values, torsional amplification at flexible sides are found to be less than 13%.
· On the other hand, torsional amplifications at stiff sides are in the order of 22%. However, since the end moments at stiff sides are quite small in magnitude, this amplification does not play an important role in the design.
· The overall weighted averages of torsional amplifications are less than 10% for all the sample structures.
· The amplifications for maximum moments and weighted averages differ only slightly.
· The weighted average amplifications also differ slightly along the heights of the structures.

Earthquakes have repeatedly demonstrated that, complex and/or irregular structures have a rather small chance of survival compared with regular structures. It is also well known that, torsional irregularity is one of the major factors causing severe damage during earthquakes. In most of the recently developed earthquake codes, this potentially dangerous irregularity has been dealt with by simply increasing the accidental eccentricities by a certain amount.

In the present study, it has been demonstrated that, even for structures with rather high torsional irregularities, this procedure results in amplification of the order of 10% in the design bending moments which can be considered rather low as compared with the severe damage potential of these type of buildings.

Hence, it is concluded that, some other parameters should be defined and also more serious measures are to be established in the codes, to overcome the possibility of damage of this kind of irregular buildings.

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