Turkish J. Eng. Env. Sci.
27 (2003) , 11 – 19.

A Comparative Study of Torsionally Unbalanced Multi-Storey Structures under Seismic Loading

F. Gülten GÜLAY, Gökhan ÇALIM
İstanbul Technical University, Civil Engineering Department,
80626 Maslak, İstanbul-TURKEY
e-mail: gulayg@itu.edu.tr

Received 28.06.2001

Abstract

After a short review of the torsional irregularity requirements of the new Turkish Earthquake Code (TEC'97), a parametric study is carried out on various ten-storey shear-wall frames with rather high torsional irregularities. The internal member forces are computed and compared in the solutions with 5% accidental eccentricity and with increased eccentricities, under seismic loading, according to TEC'97. Torsional amplification factors are introduced and calculated along the height of the buildings. The numerical solutions of the investigated buildings show that the maximum increase in the bending moments at the most critical beams and columns is about 10%. The torsional irregularity coefficients of the sample structures evaluated according to Uniform Building Code'97 and TEC'97 are also compared in the study, the computations of which are based on absolute and relative displacements, respectively. The UBC'97 coefficients are rather high with respect to the TEC'97 values.

Key words: Torsional irregularity, Seismic design, Seismic Codes, Asymmetric buildings, Irregular structures

Introduction

Most recent earthquakes have shown that the irregular distribution of mass, stiffness and strengths may cause serious damage in structural systems. However an accurate evaluation of the seismic behaviour of irregular buildings is quite difficult and a complicated problem. Due to the variety of parameters and the choice of possible models for torsionally unbalanced systems, there is as yet no common agreement nor any accurate procedure advised by researchers on common practice in order to evaluate the torsional effects.

Numerous studies have been published on the assessment of code provisions and the seismic behaviour of torsionally irregular structures during recent years, such as, Zhu and Tso (1992), Calderoni *et al.* (1995), Chandler *et al.* (1996), Chandler and Duan (1996), Özmen *et al.* (1998), Tso and Smith (1999) and Tezcan and Alhan (2001).

The research work into contemporary seismic codes of various countries (Earthquake Resistant Regulations: A World List, 1996) shows that plan, or torsional irregularity is the most widely considered type of structural irregularity because of both its seismic damage potential and its complex nature. The investigations into the seismic codes of 40 different countries show that some dissipative or preventive measures are required for this type of irregularity such as:

- The presence of torsional irregularity is not allowed in 11 out of the 40 earthquake codes investigated. If it is unavoidable, then structural dilatations are required or suggested in six of these.

- 3-D analysis based on an increased eccentricity value is required in four of these codes.
- 3-D dynamic analysis is required in 13 of the seismic codes as a preventive measure.
- In 10 of the seismic provisions an increase in accidental eccentricity or dynamic analysis is advised depending upon the level of torsional irregularity.

Despite some preventive measures and provisions required in the seismic codes, torsional irregularity in buildings is sometimes inevitable for architectural reasons; therefore its effect must be carefully taken into consideration in design work.

The general procedure for the design of torsionally unbalanced systems is as follows: the structure is first analysed with accidental eccentricity, and then the torsional irregularity parameters are computed at each storey level. If the torsional irregularity exceeds an allowable limit, the lateral load analysis is repeated with increased eccentricity, or else the geometrical configuration must be modified to reduce the existing eccentricity. Recent seismic codes UBC'97 (Uniform Building Code, 1997) and the new Turkish Earthquake Code TEC'97 (Turkish Earthquake Code, 1997) have adapted almost the same procedure except for slight modifications.

The main objectives of this paper are:

1. To evaluate and compare the variation of the value of torsional irregularity coefficient η_b computed according to TEC'97 and UBC'97 over the height of torsionally unbalanced sample buildings.
2. To observe the level of change of internal forces computed with increased eccentricity compared to the 5% accidental eccentricity for the code-designed sample buildings, in order to assess the Turkish code requirements for torsional irregularity (Çalım, 1999).

The Code Provisions for Torsional Irregularity

The new Turkish Earthquake Code, TEC'97, which was put into effect in 1998, imposes some limits on the use of various structural irregularities in buildings, such as an increase in design forces or a requirement for dynamic analysis. Under the code provisions, torsional irregularity is taken into account in design work as follows:

The torsional irregularity coefficient η_b, defined as the ratio of the maximum relative storey drift to the average relative storey drift, is computed at each storey level. The 5% accidental eccentricity (ε_a) is included in the drift computations. If the value of η_{bj} is between 1.2 and 2, then the eccentricity is increased by a factor as in the following formula:

$$\varepsilon_{ij} = \varepsilon_a(\eta_{bj}/1.2)^2 \tag{1}$$

where ε_{ij} represents the amplified or increased eccentricity for the jth storey, which is to be considered in the analysis procedure, and ε_a represents the accidental eccentricity that equals 0.05.

If the value of $\eta_{bj} \leq 2$, then the equivalent static loading method for the earthquake analysis can be utilised for buildings up to 60 m in height on the condition that there is no B2 type irregularity. On the other hand, if the value of η_{bj} exceeds 2 at any storey, then a complete 3-D dynamic analysis or change of configuration is essential. In addition, if a dynamic approach is utilised then the base shear computed according to the modal analysis may not be less than the value obtained with the equivalent static analysis; otherwise it is increased by a factor.

The provisions for torsional irregularities according to UBC'97 are quite similar, except that the computation of the torsional irregularity coefficient η_b is based on *absolute* storey displacements instead of relative displacements as in TEC'97. In order to evaluate the effect of this slight difference on the computations, η_b values were computed according to TEC'97 and UBC'97 and compared for torsionally unbalanced sample buildings.

Computation Procedure

The parametric investigation is performed on R/C shear-wall frames with rather high torsional irregularity levels. The buildings considered are first pre-designed according to Turkish provisions. Torsional irregularity coefficient η_{bj} at each jth storey of the structures is computed in line with UBC'97 and TEC'97, and then the curves for η_{bj} versus storey numbers are evaluated over the heights of the structures for comparison purposes, in the first part of the study.

Then a series of analyses are performed on four sample structures utilising TEC'97 in order to observe and detect the level of the increase in the internal forces with the increased eccentricity ε_i given in the formula (1). The comparison and evaluation procedure is based on the numerical approach given in the recent study by Özmen *et al.* (1999).

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

1. The initial structure named SS1 is analysed with 5% accidental eccentricity for the seismic loads of TEC'97, and the computed internal forces in the structural members are called F_a.
2. The values of torsional irregularity coefficient η_{bj} are computed at each j^{th} storey of the building considered. If $\eta_{bj} > 1.2$ then the increased eccentricity ε_{ij} is computed.
3. The seismic analysis of the building is repeated with the increased eccentricity ε_{ij} and the computed internal forces are called F_i.
4. The ratio of F_i/F_a for any beam or column member is called the torsional amplification factor (TAF). In order to observe the change in TAF values over the height of the structure, the curves for the TAF values of critical members versus storey numbers are evaluated.
5. The weighted averages of TAF values for the most critical members of the buildings are also computed by taking the corresponding internal force F_a due to the accidental eccentricity as the weight factors and tabulated. The representative columns and the beams at the flexible and stiff sides are called c_f, b_f and c_s, b_s, respectively.
6. The above procedure is repeated for the other sample structures.

Numerical Investigations

The numerical study is carried out on four different ten-storey shear-wall framed buildings derived from the initial structure, SS1 (Çalım, 1999). The typical floor dimensions of the SS1 building are given in Figure 1. All beam dimensions are assumed to be 25 cm × 50 cm. The cross-sectional dimensions of the vertical structural members are tabulated in Table 1.

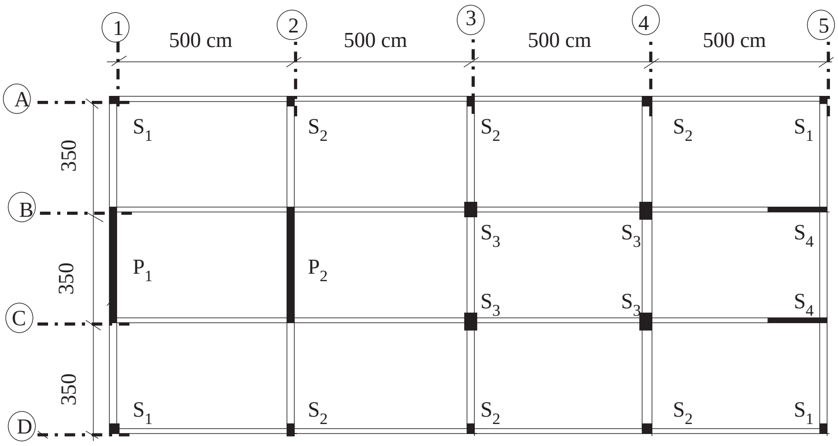

Figure 1. Floor Plan of Sample Structure SS1.

Table 1. Dimensions of vertical members of sample structures in cm.

Storey	S_1	S_2	S_3	S_4	P_1
10-9	30 × 30	30 × 30	30 × 30	150 × 25	25 × 375
8-7	30 × 30	30 × 40	40 × 40	150 × 25	25 × 375
6-5	30 × 40	30 × 45	45 × 45	150 × 25	25 × 375
4-3	30 × 45	30 × 55	45 × 60	150 × 25	25 × 375
2-1	30 × 55	30 × 70	45 × 70	150 × 25	25 × 375

The sample structure SS2 is obtained by adding a 5 m span lengthwise to SS1. The sample structure SS3 is obtained by adding another 5 m span lengthwise to SS2. The sample structure SS4 is produced by shifting the location of the shear-wall: P_1 from the 1^{st} to the 2^{nd} axes and the shear-wall: P_2 from the 2^{nd} to the 3^{rd} axes, respectively. The dimensions of the structural members of the investigated buildings are assumed to be unchanged.

The total height of the buildings is 31 m. The storey height is 4 m at the first level and 3 m at the others. The structures are assumed to be located in the second-degree earthquake region, and the coefficient of effective ground acceleration is thus $A_0 = 0.30$. The coefficient of building importance is taken as I = 1, since the sample structures are considered to be residential buildings. The local soil profile is Z2, and the characteristic spectrum periods T_A and T_B are thus taken as 0.15 s and 0.40 s, respectively. The structural behaviour constant is considered to be R = 7, as suggested by the code (Turkish Earthquake Code, 1997).

The equivalent static earthquake loading approach is utilised for the seismic analysis of the systems. Since the systems are all symmetrical about the X-axis, the lateral load analyses have been carried out only in the Y direction. The mass centres of the sample structures are assumed to be at the geometrical centres of the floor plans.

The SAP90 Structural Analysis Package (Wilson and Habibullah, 1992) is utilised for 3-D analyses. The 3-D computer models for the sample structures utilised in the computations are shown in Figures 2 and 3.

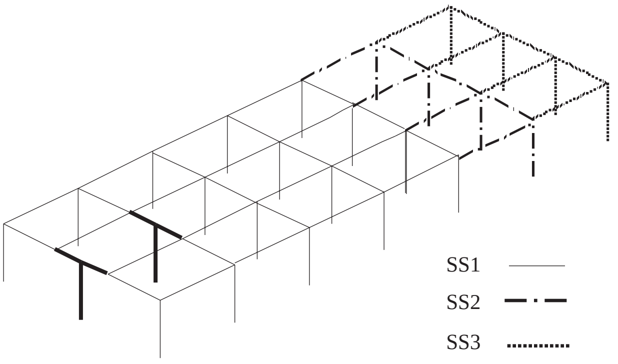

Figure 2. SAP90 Model for SS1, SS2 and SS3 Structures.

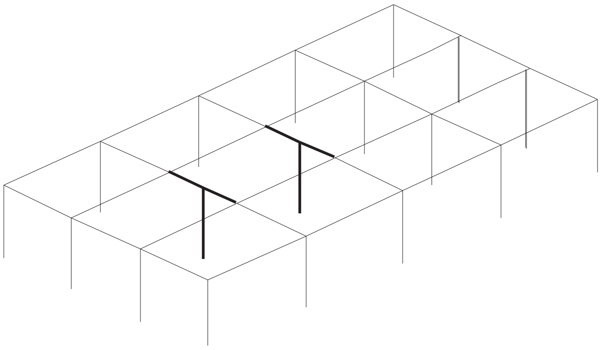

Figure 3. SAP90 Model of SS4 Structure.

Each structure is first analysed under seismic loading with $\varepsilon_a = \pm 5\%$ accidental eccentricity, and the torsional irregularity coefficients η_{bj} according to TEC'97 and UBC'97 are computed. Since their values are all greater than 1.2, the increased eccentricities ε_{ij} at each storey of the buildings considered are also computed. Figure 4 shows the variation of the ε_{ij} values over the heights of the considered structures in accordance with the two codes, TEC'97 and UBC'97.

The internal forces, namely bending moments and shear forces, of the most critical beams and columns at the outermost axes, corresponding to $\varepsilon_a = \pm 0.05$ are called F_a. The structural analyses are then repeated with the increased eccentricity ε_{ij} values, computed according to TEC'97, at each j^{th} storey of the buildings considered. The member forces utilising the increased torsional effects are then called F_i.

The TAF values defined as F_i/F_a are evaluated for the critical structural members at each j^{th} storey of the investigated buildings. The TAF values versus the storey numbers for buildings SS1, SS2 and SS3 are shown in Figure 5. Here the notations c_f and b_f represent the column and the beam at the outermost flexible sides, respectively. Figures 6(a) and (b) illustrate the change of the TAF values of the beam and column members of building SS4 considering increased eccentricity (+) ε_{ij} and Figures 7(a) and (b) illustrate the TAF values of SS4 considering decreased eccentricity (−) ε_{ij} where b_s and c_s represent the column and the beam at the stiff sides, respectively.

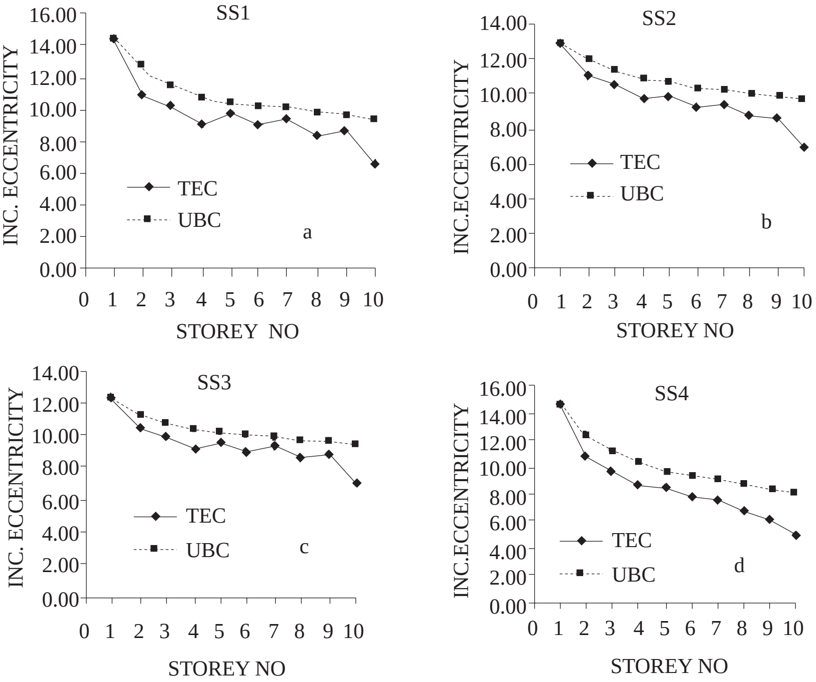

Figure 4. Increased eccentricity values ε_i for buildings SS1, SS2, SS3 and SS4.

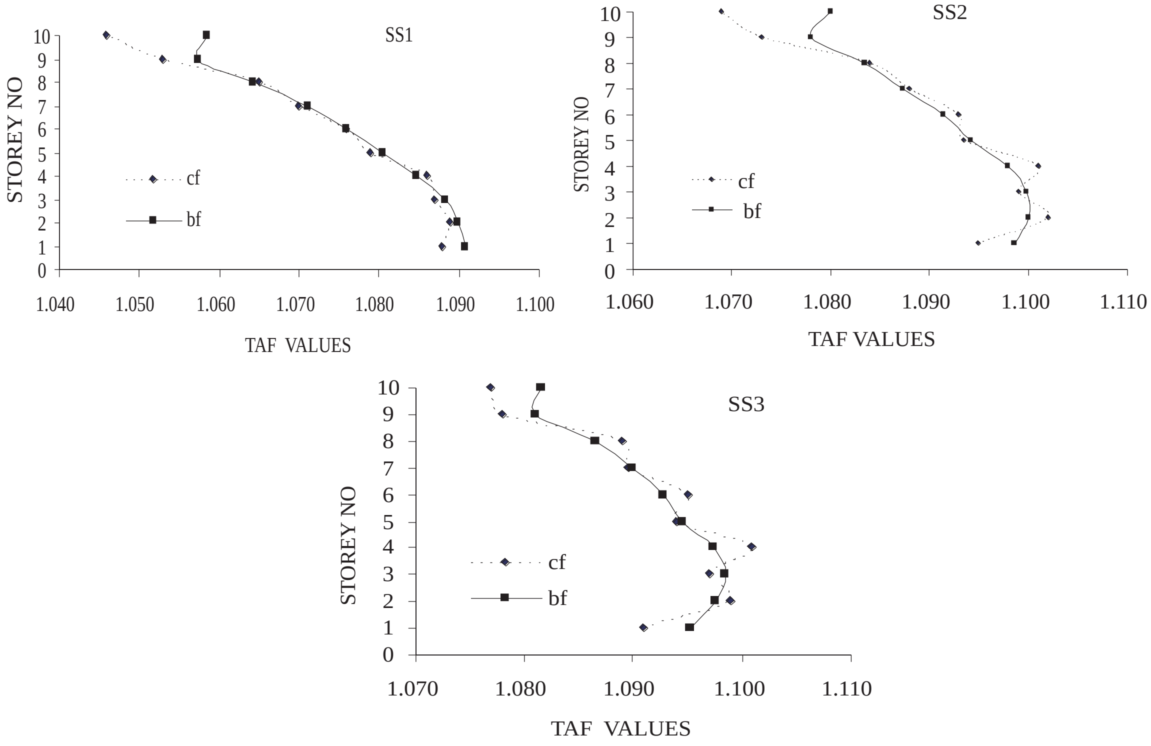

Figure 5. TAF values versus storey numbers of buildings SS1, SS2 and SS3.

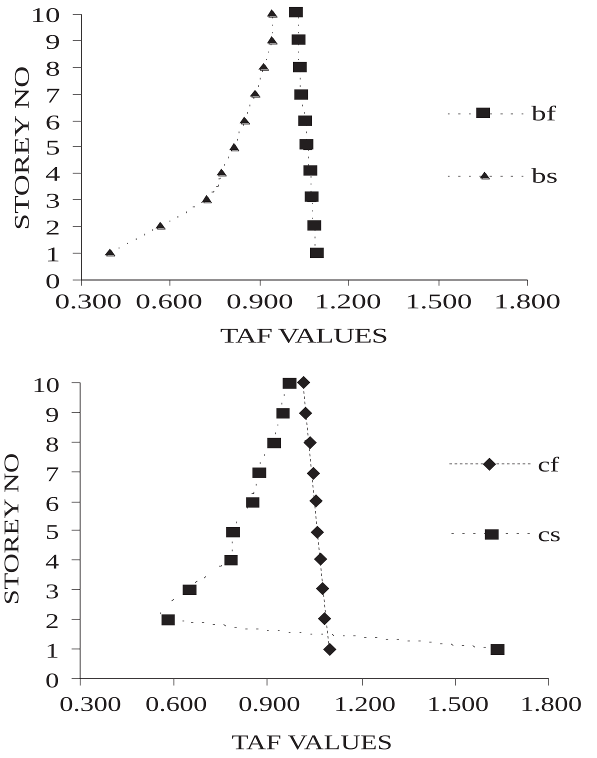

Figure 6. TAF values versus storey numbers of the beam and column members of building SS4 considering increased eccentricity (+) ε_i.

The weighted averages of TAF values are obtained and given in Table 2 by utilising the following expression:

$$TAF_{avg} = \frac{\sum M_a \frac{M_i}{M_a}}{\sum M_a} = \frac{\sum M_i}{\sum M_a} \qquad (2)$$

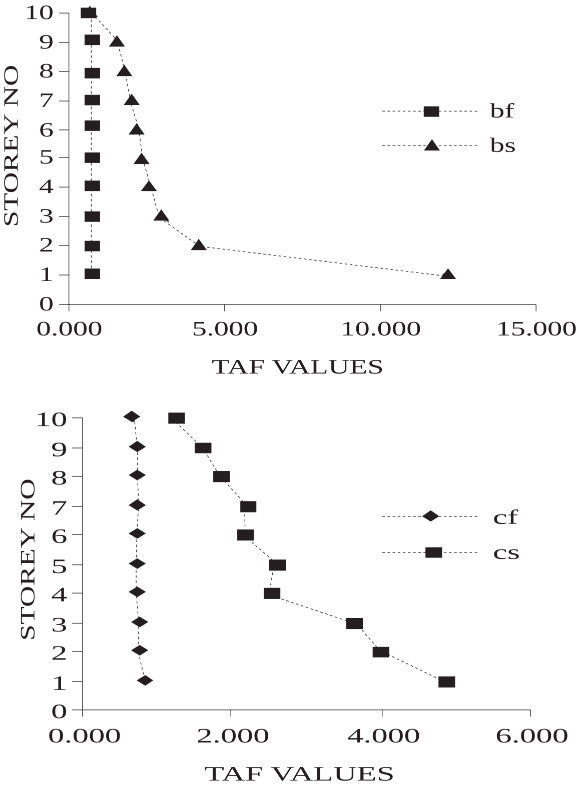

Figure 7. TAF values versus storey numbers of the beam and column members of the building SS4 considering decreased eccentricity (–) ε_i.

where M$_a$ and M$_i$ are the bending moments due to the accidental eccentricity and the increased eccentricity, respectively, for the outmost column and beam elements of buildings SS1 SS2, SS3 and SS4.

The bending moment values M$_a$ and M$_i$ obtained for the column and beam members (c$_f$, b$_f$ and c$_s$, b$_s$) for the most critical structure, SS4, are tabulated in Table 3.

Table 2. Weighted averages of TAF values for bending moments of the beams and columns at the flexible and stiff sides.

Structures	Eccentricity	c$_f$	b$_f$	c$_s$	b$_s$
SS1	(+) ε_i	1.076	1.078	-	-
SS2	(+) ε_i	1.095	1.095	-	-
SS3	(+) ε_i	1.094	1.094	-	-
SS4	(+) ε_i	1.059	1.061	0.851	0.781
SS4	(−) ε_i	0.886	0.891	1.121	1.098

Table 3. Bending moment values for the outmost column and beam memberends at the flexible and stiff sides of building SS4 (in KNm).

Storey		c_f		b_f		c_s		b_s	
		ε_a	ε_i	ε_a	ε_i	ε_a	ε_i	ε_a	ε_i
		M_a	M_i	M_a	M_i	M_a	M_i	M_a	M_i
1	1st end	-55.22	-60.68	62.43	68.24	12.35	25.44	6.49	-2.61
	2nd end	46.27	51.02	-62.43	-68.24	-19.85	-27.04	-6.49	2.61
2	1st end	-83.88	-90.98	87.91	95.31	-31.32	-21.3	20.83	11.82
	2nd end	78.18	84.96	-87.91	-95.31	16.15	6.23	-20.83	-11.82
3	1st end	-91.59	-98.74	97.08	104.55	-22.62	-15.61	28.07	20.24
	2nd end	89.23	96.35	-97.08	-104.55	17.96	10.55	-28.07	-20.24
4	1st end	-89.49	-95.71	102.02	109.12	-34.69	-27.47	29.26	22.68
	2nd end	87.93	94.2	-102.02	-109.12	32.76	25.09	-29.26	-22.68
5	1st end	-94.1	-100.37	103.06	109.51	-22.64	-18.05	26.3	21.46
	2nd end	93.59	99.66	-103.06	-109.51	22.5	17.56	-26.3	-21.46
6	1st end	-85.79	-90.43	101.09	106.59	-28.62	-24.46	25.67	21.83
	2nd end	85.55	90.34	-101.09	-106.59	28.12	23.76	-25.67	-21.83
7	1st end	-81.72	-85.53	97.23	101.69	-20.72	-18.1	24.83	22.06
	2nd end	81.89	85.86	-97.23	-101.69	20.47	17.7	-24.83	-22.06
8	1st end	-68.04	-70.39	85.68	88.77	-24.11	-22.2	19.66	18.03
	2nd end	69.9	72.48	-85.68	-88.77	24.7	22.62	-19.66	-18.03
9	1st end	-60.00	-61.71	75.27	77.36	-12.24	-11.6	13.1	12.36
	2nd end	61.71	63.31	-75.27	-77.36	12.62	11.92	-13.1	-12.36
10	1st end	-49.65	-50.36	44.72	45.95	-14.96	-14.49	7.77	7.34
	2nd end	55.72	56.59	-44.72	-45.95	15.29	14.79	-7.77	-7.34

The first natural periods T_1 in seconds and the total equivalent earthquake load or the base shear V_t in KN computed in accordance with TEC'97 for the sample structures are shown in Table 4.

Table 4. Total base shear V_t and the first natural periods T_1 of the sample structures.

Structure	SS1	SS2	SS3	SS4
T_1 (s)	0.921	0.956	0.953	0.834
V_t (KN)	1420.23	1636.99	1895.35	1529.60

Conclusions

In conclusion, designers realise that it is a challenging matter to make a rigorous and accurate analysis of torsionally unbalanced structures under seismic loading, due to the complexity of the problem and the variability of the parameters. It is also a well-known fact that torsional effects are important and may cause severe structural damage as experienced in recent earthquakes, so this must be avoided during the planning procedure as much as possible.

The following results are obtained based on the limited number of solutions:

- All four of the investigated buildings are torsionally irregular structural systems. The torsional irregularity coefficient η_b exceeds the limit value 1.2 in all storeys of the buildings, and their values are higher at the lower storeys, as expected. Thus, in accordance with the code requirements, the structural analysis must be carried out with different increased eccentricity ε_{ij}values at each storey.
- The values of η_b coefficients computed according to UBC'97, based on absolute displacements, are rather higher than those obtained under TEC'97 and are smoother in character along the height of the structure. The average of the percentage increases of the four sample

buildings (SS1, SS2, SS3, SS4) is 8.01% , where the difference at the top storeys of buildings SS1 and SS4 raises to 26% (Table 5).

- On the other hand, the difference is more evident between the increased eccentricities ε_i, computed according to UBC'97 and TEC'97, respectively. The increased eccentricities ε_i computed according to UBC'97 at the top storeys of buildings SS1 and SS4 are about 60% higher than those computed according to TEC'97 (Figure 4). The average of the increase of the four sample buildings is 17.1%, (Table 5).

Table 5. Average percentage increase in the η_b and ε_i values computed according to UBC'97 and TEC'97.

Structure	SS1	SS2	SS3	SS4	Avg
η_b	10.21	5.92	4.97	10.94	8.01
ε_i	22.00	12.45	10.35	23.60	17.10

- Thus, computing with UBC'97 will naturally give larger design values than TEC'97 in terms of the torsional irregularities. In order to evaluate the effect of this difference on TAF values, a parallel study was carried out on similar structures by designing according to UBC'97, (Özmen and Gülay, 2002).
- The upper limit for the $\eta_{bj} = 2.0$ as defined in TEC'97 may be exceeded at lower storeys of some buildings, as in SS4 ($\eta_{b1} = 2.044$). In that case 3-D dynamic analysis is required according to TEC'97, which is in reality an indication of a requirement to change the dimensions of structural members.
- The investigations made in the sample structures with different configurations showed that in all cases the amount of increase in the internal forces of the most critical beam and column members is within the range of maximum 10% in comparison with those computed with 5% accidental eccentricity.
- The increase in internal forces mostly occurs at the lower storeys of the structures and gradually decreases towards the upper storeys.
- The range of the weighted average of TAF values change about 1.059-1.095 for the computed beam and column members (Table 2). On the other hand, the increases in the internal forces of the shear-wall members are disorderly distributed and sometimes give conflicting results.
- When the structural systems are computed with decreased eccentricity, that is with (−) ε_i, the internal forces of the structural members at the stiff side of the structures may increase up to a maximum of 38% compared to those computed with $\varepsilon_a = -0.05$ accidental eccentricity. The weighted average values are about 1.10-1.12 for the computed beam (b_s) and column (c_s) members (Table 2). However, this increase may not be considered important because the design forces are rather low for those structural members.
- For engineering applications, it may be more practical to consider the additional torsional effects (for $\eta_{bj} < 2.0$) simply by increasing the design forces by a reasonable amount, instead of performing many long and complicated calculations, presented here. A practical approach to the additional torsional effects in the structural member forces is suggested in the recent study by Özmen (2001).

Finally, based on the limited parametric studies performed, it can also be concluded that if torsional irregularity is unavoidable some additional and more rational measures must also be considered to ensure the inherent safety of the structure, in addition to the code requirements of rigorous 3-D torsional analysis of the structure.

Acknowledgements

The authors express their gratitude to Prof. Dr. Günay Özmen for his valuable discussions throughout the study.

References

Calderoni, B. Mazzolani, F.M. and Ghersi, A. 'A New Approach to the Problem of In-plan Irregularity in Seismic Design of Buildings' 10^{th} European Conference on Earthquake Engineering, 843-848, Duma (ed.) Rotterdam, ISBN90 54 10528 3, 1995.

Chandler, A.M., Duan, X.N. and Rutenberg, A. 'Seismic Torsional Response: Assumptions, Controversies and Research Progress' European Earthquake Engineering, X, 1, 37-51,1996.

Chandler, A.M. and Duan, X.N., 'Assessment of Some Factors Affecting the Performance of Asymmetric Code-Designed Buildings' Proceedings of European Workshop on the Behaviour of Asymmetric and Setback Structures, Capri, 58-77, 1996.

Çalım, G. 'Investigation of Torsional Irregularity in Multi-Storey Frames with Shear-walls' (in Turkish). Graduate Thesis for the completion of Master's Degree, I.T.U, 1999.

Earthquake Resistant Regulations: A World List, International Association for Earthquake Engineering, Tokyo, 1996.

Özmen, G. Orakdöğen, E., Pala and S., Gülay G., 'Çok Katlı Yapıların Deprem Hesabında Burulma Düzensizliğinin İrdelenmesi' Prof. Kazım Çeçen Anma Kitabı, Gedenkschrift, Renk Ajans, İstanbul, 231-237, 1998.

Özmen, G., Pala, S., Gülay, G. and Orakdöğen, E. 'Effect of Structural Irregularities to Earthquake Analysis of Multi-Storey Structures' (in Turkish). Technical Report of Turkish Earthquake Foundation, TDV/TR 017-28, 1999.

Özmen, G. and Gülay, F.G. 'An Investigation of Torsionally Irregular Multi-Storey Buildings under Earthquake Loading' Structural Engineering and Mechanics, An International Journal, 14/2, 237-243, 2002.

Özmen, G. 'Torsional Irregularity in Multi-Storey Structures' (in Turkish). Technical Report of Turkish Earthquake Foundation, TDV/TR 036-61 2001.

Tezcan, S. and Alhan, C. 'Parametric Analysis of Irregular Structures under Seismic Loading According to the New Turkish Earthquake Code' Engineering Structures 23, 600-609, 2001.

Tso, W.K. and Smith, R.S.H., Re-Evaluation of Seismic Torsional Provisions' Asymmetric and Irregular Structures, European Association of Earthquake Engineering Task Group 8, İstanbul, 1, 27-43, 1999.

Turkish Earthquake Code for Buildings in Hazardous Areas (ABYYHY'97) (in Turkish). Ministry of Public Works and Settlement Ankara, 1997.

Uniform Building Code (UBC) Volume 2, Structural Engineering Design Provisions, International Conference of Building Officials, USA, 1997.

Wilson, E.L. and Habibullah A. SAP90 Structural Analysis Program and User's Manual, Computers and Structures, Inc., California, 1992.

Zhu, T.J. and Tso, W.K., 'Design of Torsionally Unbalanced Structural Systems Based on Code Provisions II: Strength Distribution', Earthquake Engineering and Structural Dynamics, 21, 629-644, 1992.