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Comparative investigation of the costs and performances of torsional irregularity structures under seismic loading according to TEC

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Abstract. The poor seismic performance of reinforced concrete buildings during the latest earthquakes has become a serious issue in the building industry in Turkey. This case, designing new buildings without structural irregularities against earthquake loads reveals to be quite significant. This study mainly is focused on the effects of different torsional irregularities on construction costs and earthquakes performance of reinforced concrete buildings. In that respect, structural torsional irregularities are investigated based on the Turkish Earthquake Code. The study consists of major eight main parametric models. In this models consist of totally 49 models together with the variations in the number of storey. With this purpose, the earthquake performances and construction costs (especially steel quantities) of reinforced concrete buildings which having different structural torsional irregularities were obtained with the help of Sta4-CAD program. Each model has been analyzed by both the methods of equivalent earthquake loading and dynamic analysis. The obtained results reveal that the model-1 which has lower torsional irregularity coefficient shows the best earthquake performance owing to its regular plan geometry. Also, economical comparisons on costs of the torsional irregularity are performed, and results-recommendations are given.

Keywords: construction cost; torsional irregularity; earthquake performance

1. Introduction

Turkey which situated in an active earthquake zone is frequently exposed to destructive earthquakes. In Turkey, the studies conducted in order to determine the causes of damage of the buildings after recent earthquakes show that increases remarkably of damage level of building irregularities (Scawthorn and Johnson 2000, Adalier and Aydingun 2001, Sezen *et al*. 2003, Spence *et al*. 2003, Doğangün 2004, Kaplan *et al*. 2004, Arslan and Korkmaz 2007, Celep *et al*. 2011, Di Sarno *et al*. 2013).

There are strong relationship between the architectural design of buildings and the earthquake safety. Well arranged architectural designs are necessary certainly for withstanding devastating earthquake loads (Kirac *et al*. 2011, Inan and Korkmaz 2011, Inan *et al*. 2012, Inan *et al*. 2014). Because, the dimensions of height and plan of a building, the type and distribution of partition shear walls and columns, the selection of the structural system, distribution of mass and rigidities

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of a building affect significantly the earthquake safety. The best possible structural system which providing security measures against an earthquake is important not only for civil engineers but also in architects. But, architects are generally interested in the functional use and the aesthetics of structures. On the other hand, mistakes in the architectural design phase cannot be remedied by calculations performed subsequently by the structural engineer. For these reasons, architects are advised to in the design continuity, regular and symmetric structures (Dowrick 1987, Çatal and Ertutar 1990, Tezcan 1998). In other words, when the reinforced concrete buildings collapsed or damaged are examined, it is seen that the causes of collapse or damage are directly or indirectly related to the structural irregularities in the architectural design.

Studies aiming to prevent structural torsional irregularities of reinforced concrete structures in during earthquakes are made by some researchers (Moehle and Alarcon 1986, Özmen and Gulay 2002, Özmen 2004, Soyluk and Yavuz 2009, Lee *et al*. 2011). There are clear warnings and discouraging rules against these irregularities in the Turkey Earthquake Code (TEC) due to the adverse effects in the response of buildings to earthquakes. In other words, in the TEC are suggested that design and construction of buildings that have any of the defined irregularities should be avoided (TEC 2007).

In this study, effect to construction cost of structural torsional irregularities is comparatively examined with help of Sta4-CAD program (Sta4-CAD 2010) which uses the matrix displacement method. This examination is done with frameworks which have different torsional coefficient according to proposed design spectrum for Z2 soil class given in the TEC. Thus, researchers and practitioners by examination of the findings obtained from the structural analyses are aimed to give of the results related to the buildings seismic performance and costs of the torsional irregularity.

Here, it should be specified that reinforced-concrete analysis, static, earthquake and wind of reinforced concrete buildings with STA4 packet program as based on the standards and regulations can be done and also rough construction quantities can be calculated.

2. Torsional irregularity

There are diverse types of irregularities that should be avoided absolutely during the architectural design stage. Irregularities can be exist in the configuration of the building, differences between the story heights, in the distribution of masses and rigidities, in creating short columns, and in placement of the columns and shear walls. In this paper, only the torsional irregularities are taken into account and structural analyses are carried out according to the TEC.

In the TEC defined an torsional irregularity coefficient "η_{bi}" for torsional irregularity. Here, η_{bi} can be express for any of the two orthogonal earthquake directions as the ratio of the maximum storey drift at any storey to the average storey drift at the same storey in the same direction (Fig. 1). Accordingly, in case of $\eta_{bi}=((\Delta_i)_{max}/(\Delta_i)_{ave})>1.2$, torsional irregularity is said to be exist. In this instance, the displacement computations on both earthquake directions are considered the ±5% additional eccentricity (Fig. 2). The additional eccentricity ±5% to be applied to the structure is increased by multiplying it by $D=(\eta_{bi}/1,2)^2$ factor.

where $(\Delta_i)_{max}$ is maximum reduced storey drift of i^{th} storey of building, $(\Delta_i)_{ave}$ is average reduced storey drift of i^{th} storey of building, D_i is amplification factor to be applied in Equivalent Earthquake Loading (EEL) Method to ±%5 additional eccentricity at i^{th} storey of a torsionally

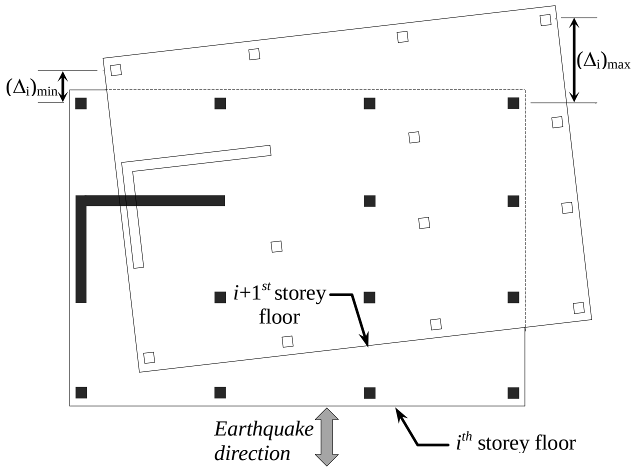

Fig. 1 Structural torsional irregularity defined in the TEC (TEC 2007)

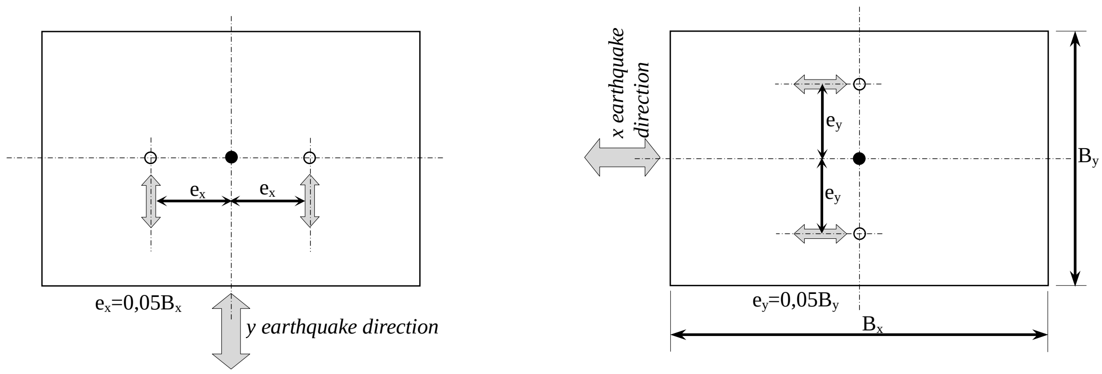

Fig. 2 Application of the shifted mass centres (additional eccentricity) of earthquake forces (TEC 2007)

irregular building.

In case of $\eta_{bi}>2$ according to the TEC, the EEL method instead of the dynamic methods (mode superposition or time history analysis methods) is suggested to implement.

In some cases, the TEC uses of dynamic analysis instead of the EEL method. For structures that torsional irregularity exists, there are some restrictions against the utilization of the EEL method. In this study, buildings with the different η_{bi} value have been analyzed by using both the dynamic analysis and the EEL methods, for 1, 2, 3, 4, 5, 6 and 7 stories. Analyses have been made with the aid of Sta4-Cad package program using a three-dimensional mathematical model.

3. Numerical example

In this study is aimed the evaluation of effect of the torsional irregularities defined in the TEC in determining cost and earthquake behavior of reinforced concrete buildings with the same rigidity distribution and same floor gross area. In other words, in this paper, the effect to rough

Table 1 Project parameters of considered the models

Earthquake zone	1
Effective ground acceleration coefficient (A_0)	0,4
Building importance factor (I)	1
The structural behaviour factor (R)	4
Story height (m)	3
Live load factor	0,3
Soil class	Z2
Bedding values of Z2 soil (kN/m^3)	50000
Allowable bearing value of Z2 soil (kN /m^2)	300
Z2 soil class spectrum characteristic periods (s)	T_A=0,15 / T_B=0,40
Concrete class (C)	C25
Concrete young's modulus (N/mm^2)	30000
Concrete compressive strength, f_c (N/mm^2)	25
Tensile strength of concrete, f_t (N/mm^2)	1,8
Steel class (S)	S420
Steel young's modulus (N/mm^2)	200000
Initial uniaxial yield stress of steel, f_y (N/mm^2)	300
Slab thickness (m)	0,15
The cross-sectional dimensions of beam (cm)	25×50
The cross-sectional dimensions of column (cm)	40x×40

construction cost and earthquake behavior of reinforced concrete buildings of different torsional irregularities coefficient is examined. For this purpose, dimensions of the beams and columns in all models to not be affecting from other parameters have been kept same.

With this purpose, analyses were made comparatively for different torsional irregularity coefficient (η_{bi}) in considered each model. The models considering for numerical application are shown in Fig. 3. All models seen in this figure are designed to as have the same storey gross area (400 m^2), but torsional irregularity coefficient are considered as different of each model. The numbers of storey have been selected to be 1, 2, 3, 4, 5, 6 and 7. According to the building code requirements for reinforced concrete (TS500 2000), all models are designed with C25 concrete class and S420 steel class. In all model, dimensions of the beams and columns have been kept constant. Each model is assumed to be in the 1st degree earthquake zone in Turkey, so effective ground acceleration coefficient is taken 0,4. The other parameters considered in the structural analyses are summarized in Table 1. Also, the properties of Z2 soil type defined in the TEC given in Table 2. As seen from Table 2, TEC gives information about soil types depending on the topmost layer thickness of soil (h_1).

All models considered in this study are analyzed with “Sta4-Cad” which is 3D structural analysis software in the design and detailing covering all stages related with reinforced concrete structures. The necessary controls in the analyses are made in accordance with the current TEC and TS500. Here, cost variations (especially steel quantities) with torsional irregularity coefficient of the models are investigated according to different storey numbers of these models.

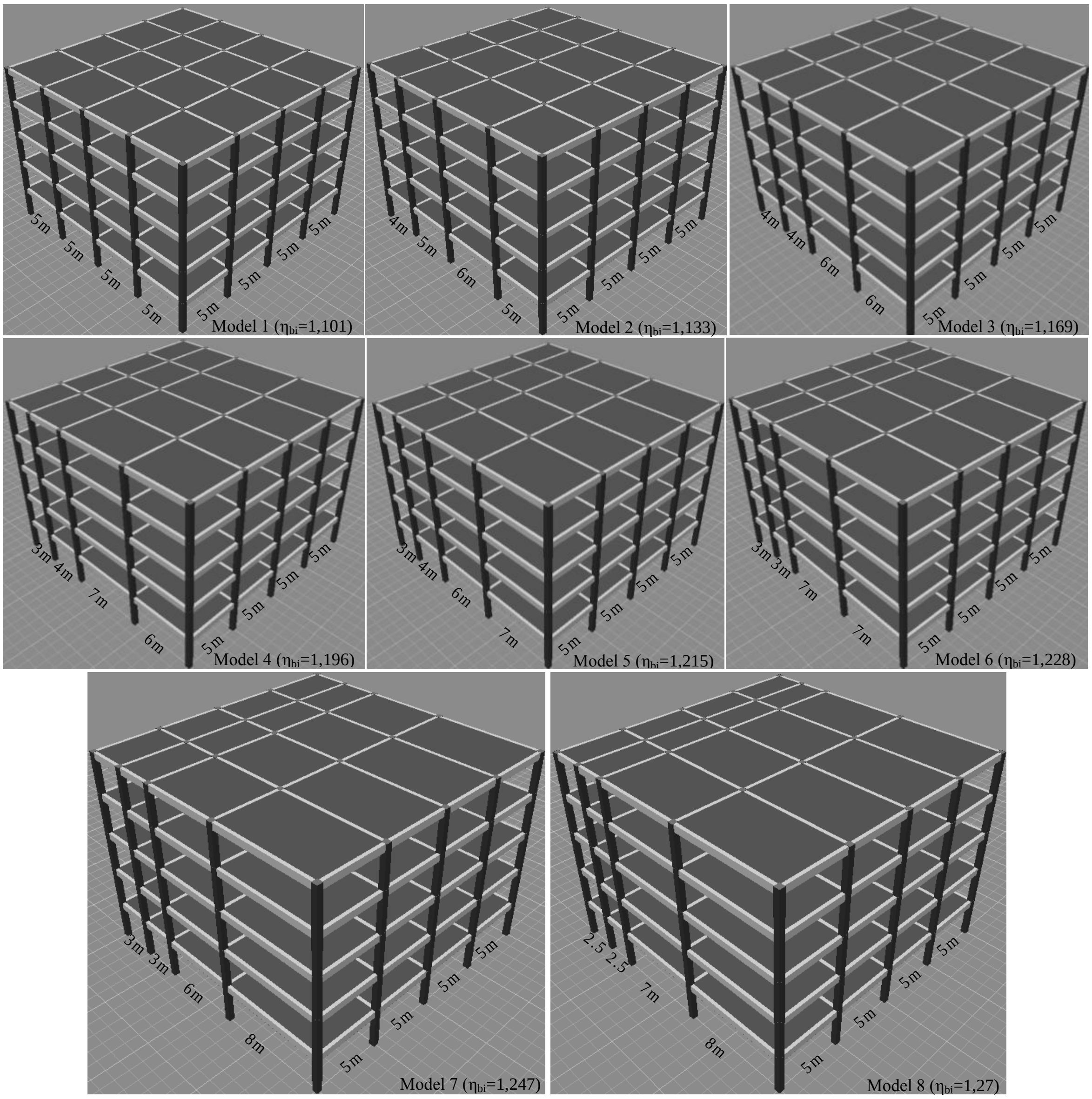

Fig. 3 Views of as five storey of the models considered in this study

Table 2 The Z2 soil type properties defined in TEC

Soil type	The soil topmost layer thickness (h1)	Description of soil types
Z2	h_1>15m	Soft volcanic rocks such as tuff and agglomerate, weathered cemented sedimentary rocks with planes of discontinuity V_s≈700-1000 m/s; Dense sand, gravel V_s≈400-700 m/s; Very stiff clay, silty clay V_s≈300-700 m/s
	h_1≤15	Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity V_s≈400-700 m/s; Medium dense sand and gravel V_s≈200-400 m/s; Stiff clay and silty clay V_s≈200-300 m/s

The performed analyses, the minimum torsional irregularity coefficient (η_{bi}) is obtained from model 1 (reference model) as 1,101. Therefore, for being $\eta_{bi} < 1,2$, there isn't torsional irregularity in this model. Conversely, the maximum torsional irregularity coefficient (η_{bi}) is obtained from model 8 as 1,27.

4. Findings and discussions

The aim of this study was to investigate the effect on the earthquake behavior and the rough construction quantities (especially steel quantities) of buildings which have different torsional irregularity coefficient. The considered all models were designed as frame systems. Here, the torsional irregularities were generated with respect to only one axis (x).

From the structural analyses; inadequate of ductility area in the some columns of the ground floor of 6-storey model 4, 5, 6 and 7, and inadequate of ductility area in the some columns of the ground floor of 5-storey model 8 have been seen to be Fig. 4 and Fig. 5, respectively.

These results is reveals that according to other models is to unsafe while number of floors of these models increase. In other words, the structural safety and floor number decreases while torsional irregularity coefficient (η_{bi}) increase. In brief, the structural analyses demonstrate that models to lower torsional irregularity coefficients show the better seismic performance. This means that the model 1 (reference model) is very well behaved.

The torsional irregularity coefficients variations with all models which considered in this study are given in Fig. 6.

As seen from this figure, it is seen that the torsional irregularity coefficient values obtained from model 1 (reference model) are smaller than the ones obtained from other models. On the other hand, the largest torsional irregularity coefficient values are given model 8. As a result, model 8 shows the worst seismic performance among the models.

Distributions of the steel quantities obtained from structural analysis of the models which have different torsional irregularity coefficient are given in Fig. 7. As seen from this figure, the steel quantities obtained from the model-8 are the largest values. In other words, the steel quantities increase while torsional irregularity coefficient (η_{bi}) increases. This finding is reveals that the torsional irregularity in terms of cost in design of structures is important.

Here, it should be noted that according to torsional irregularity coefficient (η_{bi}) of total concrete quantities does not change.

Distributions of the displacement values obtained from the x and y direction of the models which have different torsional irregularity coefficient are given in Fig. 8 and Fig. 9, respectively. From these figures, displacement values of model-1 (reference model) in the x and y direction are generally lower than those of other models. On the other hand, x and y direction the largest displacement values occurs in model 8. These results show that the torsional irregularity in terms of displacement in design of reinforced concrete buildings is quite important.

Displacements obtained from performed structural analyses for the 4, 5 and 6 storey models are given in Fig.10, Fig.11 and Fig.12, respectively. As seen from these figures, the floor displacements of model 8 gave larger values than the considered other models. On the other hand, the floor displacements of model 1 gave smaller values than those of other models. In other words, the displacements at floor levels increase while torsional irregularity coefficient (η_{bi}) increase, too.

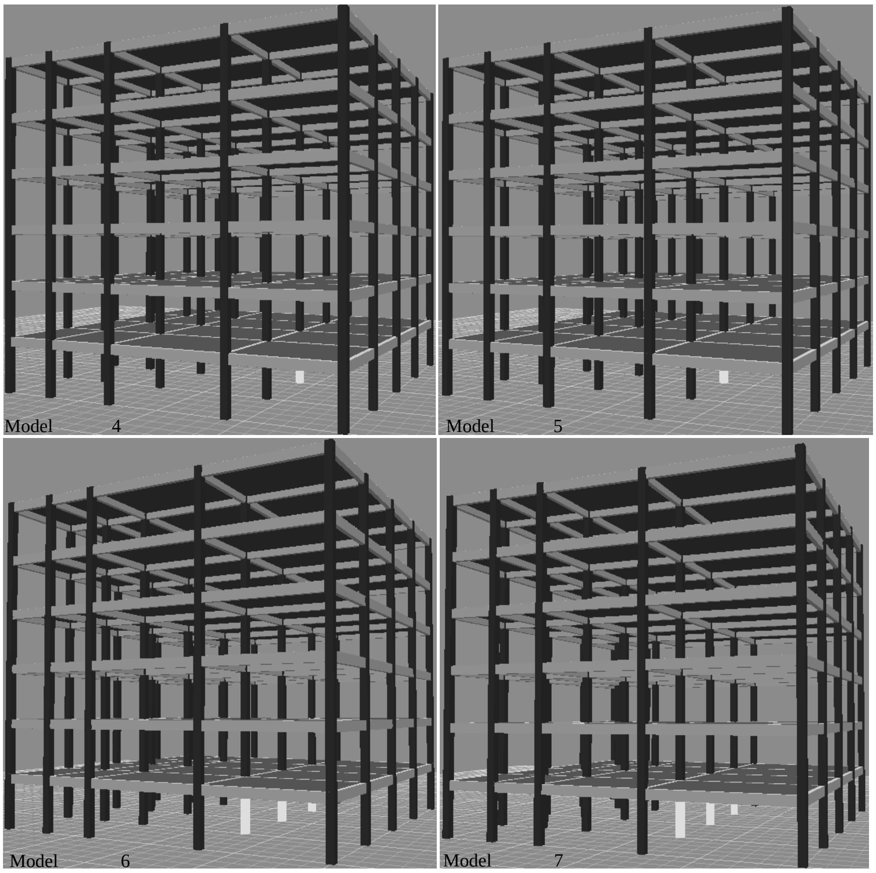

Fig. 4 View from the ground floor ductility area inadequate columns of 6-story model 4, 5, 6 and 7

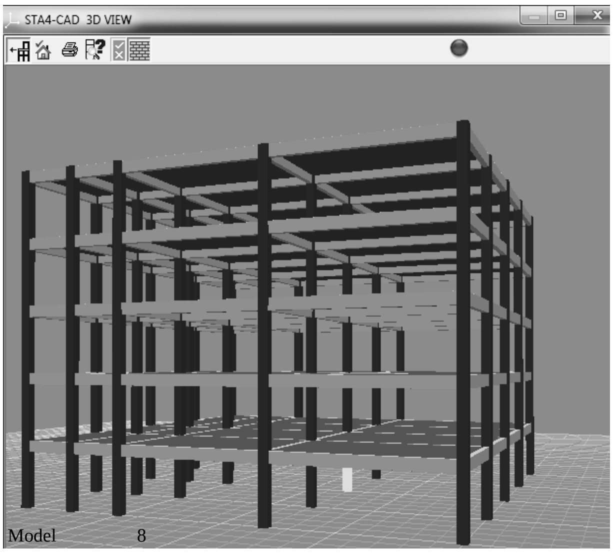

Fig. 5 View from the ground floor ductility area inadequate columns of 5-story model 8

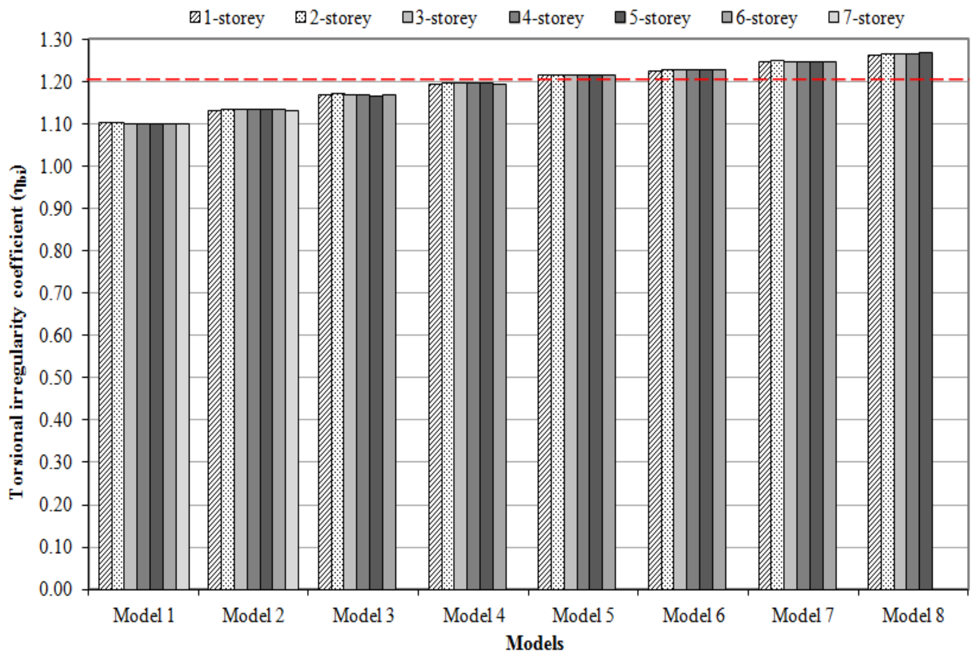

Fig. 6 Variations of torsional irregularity coefficients with the different models and number of storey

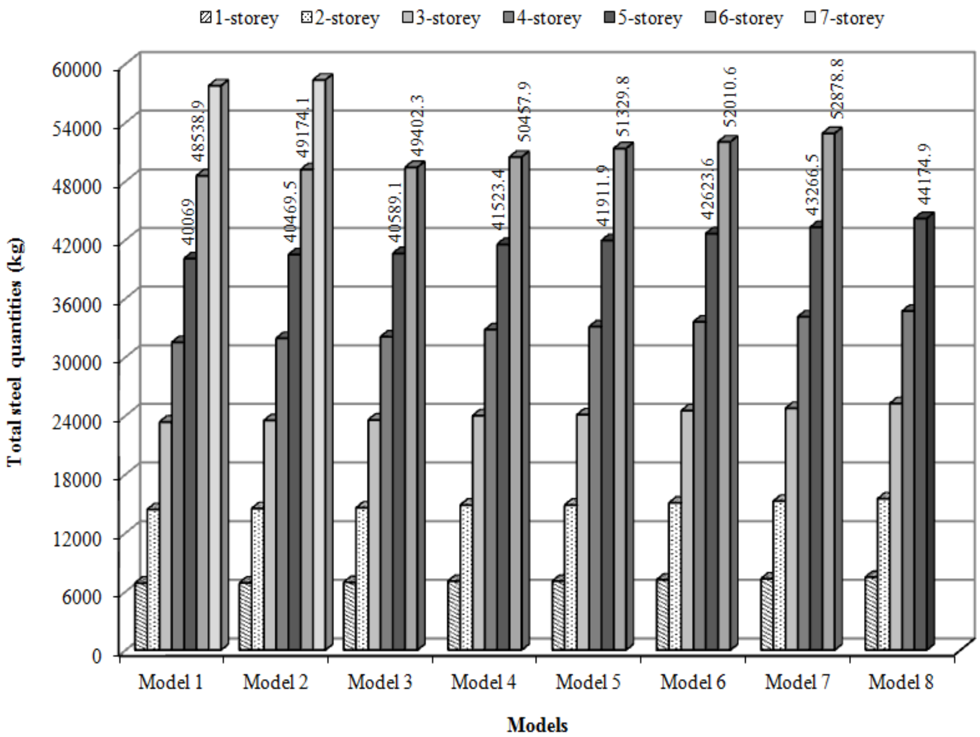

Fig. 7 Distributions of the steel quantities of frames considered in this study

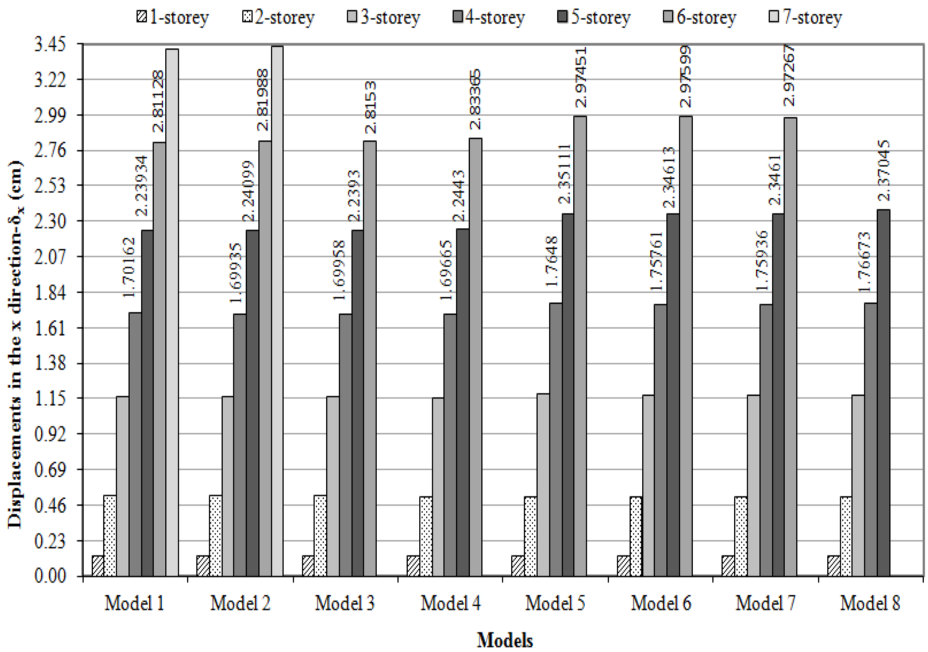

Fig. 8 Variations of displacements in the x direction with the different models and number of storey

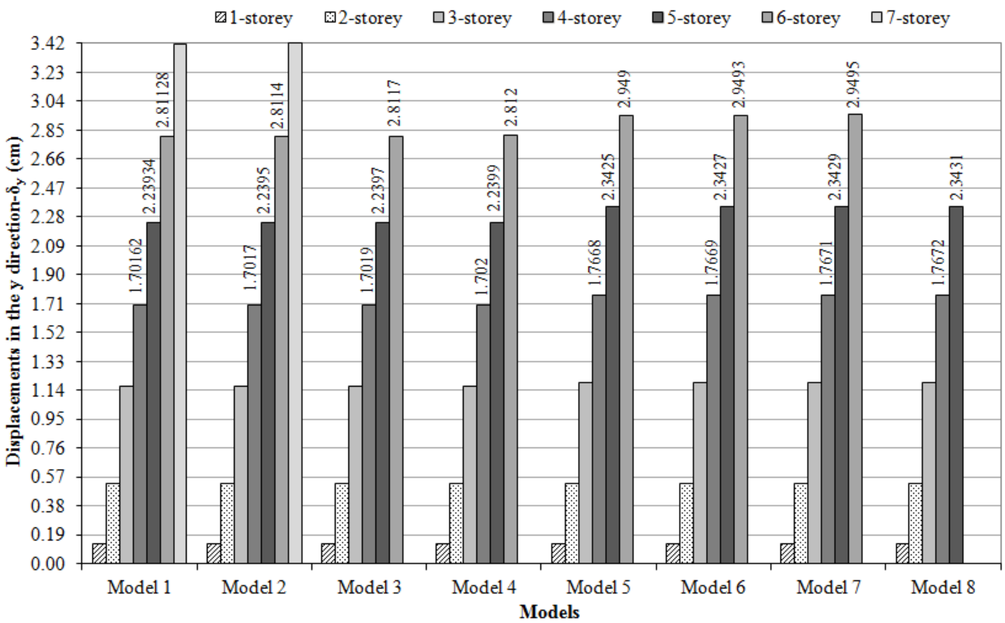

Fig. 9 Variations of displacements in the y direction with the different models and number of storey

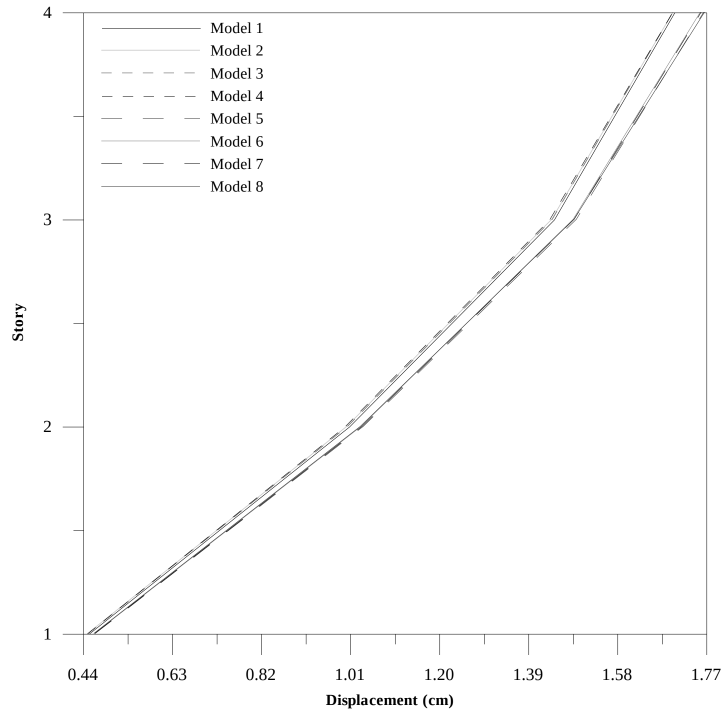

Fig. 10 Displacement obtained for the 4-story models

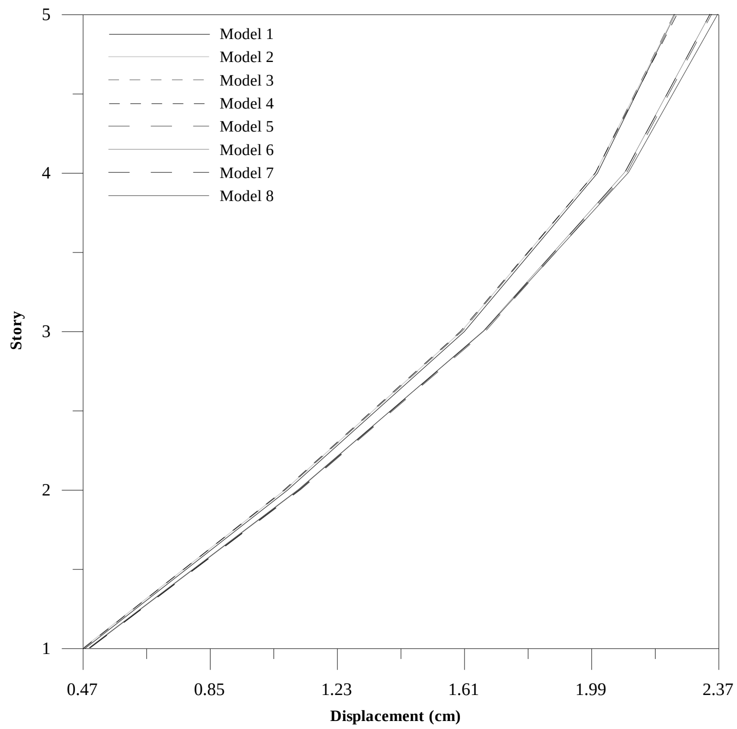

Fig. 11 Displacement obtained for the 5-story models

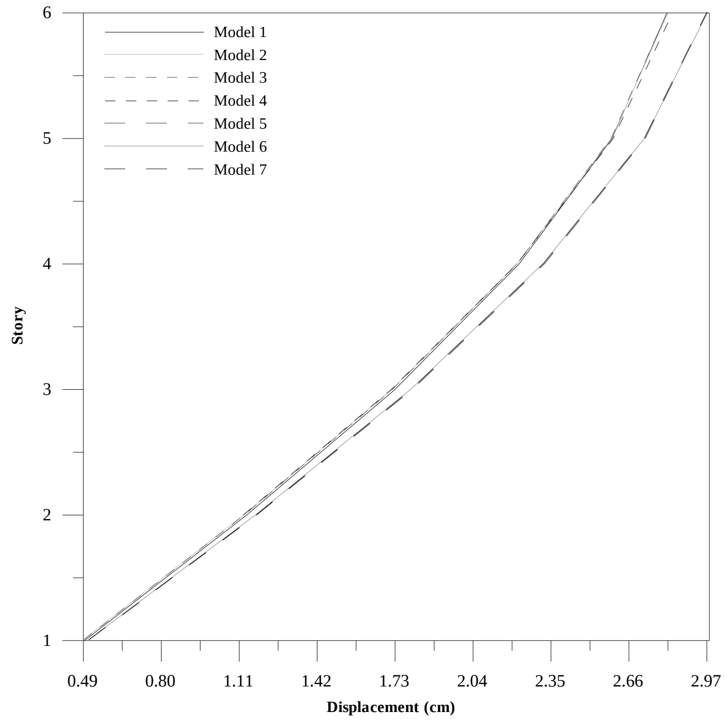

Fig. 12 Displacement obtained for the 6-story models

5. Conclusions

The purpose of this study is to examine the effects on construction costs and earthquakes performance of reinforced concrete buildings of different torsional irregularities and to compare the obtained results with each other and with reference model (model 1). These comparisons are made to different torsional irregularity coefficient, displacements and steel quantities for the models considered in this study. The main conclusions and recommendations drawn from this study are given below:

- The performed structural analyses are shown that total steel quantities increase while torsional irregularity coefficient ($\eta_{bi)}$ increases. With this aspect, model 1 (reference model) which have small torsional irregularity coefficient (η_{bi}) is seen to be more economical according to considered other models in this study.
- These results show that the design of buildings is quite important of torsional irregularity in terms of cost.
- Obtained results show that the structural safety and floor number decreases while torsional irregularity coefficient (η_{bi}) increases.
- The floor displacement values in the x and y directions of model-1 (reference model) are generally lower than those of other models. This finding is reveals that the storey displacement values increase while torsional irregularity coefficient (η_{bi}) increases. This situation, according to the other models of the reference model (model 1) is to be one of the most important advantages.

- From the findings of this study, in countries which situated in an active earthquake zone such as Turkey reveals to be quite important in terms of cost of the taking into account of structural torsional irregularity in the design of reinforced concrete buildings which was built.
- From the obtained results, it is advised the regular buildings for the design of earthquakes resistance.
- Construction costs and storey displacements in all the models increase by torsional irregularity coefficient (η_{bi}). On the other hand, earthquakes performance and floor number decrease while torsional irregularity coefficient (η_{bi}) increases.

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