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Seismic Design Considerations About Architectural Design Aspects and Irregularities

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ABSTRACT

Architectural design decisions play an important role on earthquake behavior of buildings. The earthquake response and dynamic behavior concepts are very unfamiliar for architects. On the other hand, Turkish Earthquake Code defines several irregularities and stated that they must be avoided to achieve a reliable earthquake performance. The earthquake resistant design (ERD) is started at the architectural design stage. This study is focused on plan geometries, architectural design and structural system configurations on earthquake response of structures. A general purpose finite element program was used to evaluate several irregularities and corresponding earthquake responses. First, vertical irregularity of soft story was considered for different structures having variable number of storys. In the second phase of the study, effect of heavy overhangs and overhang configuration was investigated. The projections in plan and projection ratios were compared from torsional response point of view. In the last phase, shear wall placement effects on torsional irregularity response was analyzed with 4 different configurations referring to a failure of a school in recent Van Earthquake in Turkey. The plan configuration of the basic structure was symmetrical and rectangle. The columns were intently chosen as square and dimensions were changed according to the number of storys. Beneficial observations and conclusions were drawn for architects as well as the structural engineers who are designing structures in earthquake regions.

Keywords: Earthquake, irregularity, architectural design, torsion, earthquake code.

1. INTRODUCTION

In Turkish Earthquake Code (TEC-2007), the definition of irregular buildings and conditions of irregular buildings were defined in section “Analysis requirements for earthquake resistant buildings”. At the beginning of the section it is highlighted that, because of their unfavorable seismic behavior, design and construction of irregular

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buildings should be avoided. The architectural irregularities were classified under two main headings as; irregularities in plan and irregularities in elevation. In this study irregularity conditions in TEC-2007 are investigated and architectural or geometrical configuration effect on the irregularities were studied with the help of the finite element method.

2. STRUCTURAL IRREGULARITIES

The first type of structural irregularity is the "Torsional Irregularity-A1". For a structural model, in order to determine the degree of torsional irregularity, a factor of "torsional irregularity factor η_{bi}" is defined. Under two orthogonal directions, the earthquake analysis is performed and the drift of the columns or shearwalls were determined for every floor level. The maximum and minimum drift values within the story is determined and the average of this values (Eq. 1) is named as average storey drift (Fig.1).

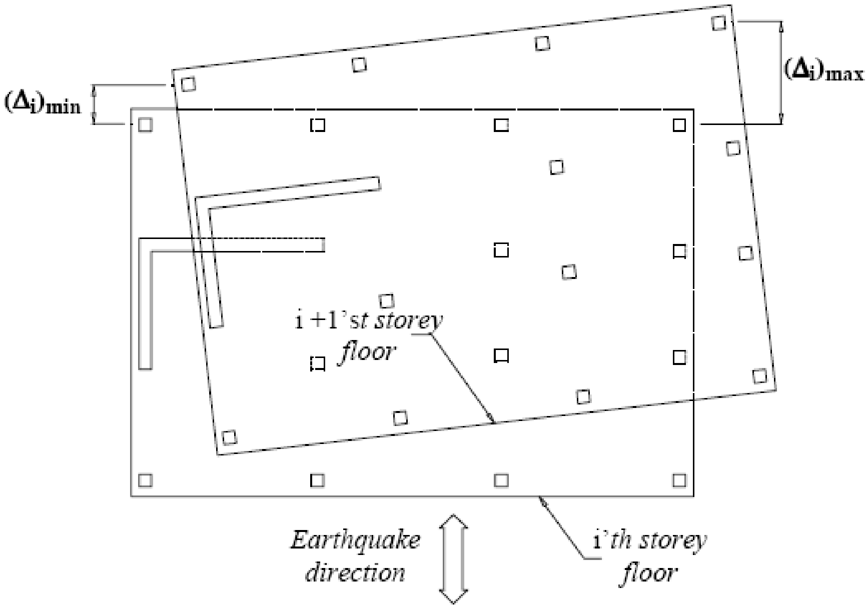


Fig. 1 Determination of maximum and minimum storey drift (TEC-2007)

$$(\Delta_i)_{average}=0.5*[(\Delta_i)_{max}+(\Delta_i)_{min}] \quad (1)$$

Torsional Irregularity Factor η_{bi}, is defined as; for any of the two orthogonal earthquake directions, the ratio of the maximum storey drift at any storey to the average storey drift at the same storey in the same direction (Eq. 2).

$$\eta_{bi} =[(\Delta_i)_{max}/(\Delta_i)_{average}] \quad (2)$$

If the torsional irregularity factor, η_{bi}, is greater than 1.2, then it is concluded that torsional irregularity was exist in that structure. At any i'th storey such that the condition $1.2 < \eta_{bi} \leq 2.0$ is satisfied, 5% additional eccentricity applied to this floor shall be amplified by multiplying with coefficient D_i given by Eq. 3 for both earthquake directions.

$$D_i = [\eta_{bi} / 1.2]^2 \tag{3}$$

If the η_{bi} value is greater than 2, than the structural system must be changed and reanalyzed. TEC-2007 allows architectures or civil engineers to design torsionally irregular structures for a definite degree. But in this case the, it states that the additional 5% eccentricity is amplified and the degree of internal forces in columns and beams are increased.

The second type of irregularity is the "Floor discontinuities –A2". *In any flor, the case where the total area of the openings including those of stairs and elevator shafts exceeds 1/3 of the gross floor area*, then A2 type irregularity is said to exist.

The third type of irregularity is the "Projections in plan-A3". For the *cases where projections beyond the re-entrant corners in both of the two principal directions in plan exceed the total plan dimensions of the building in the respective directions by more than 20%*, then A3 type irregularity it is said to exist (Fig. 2).

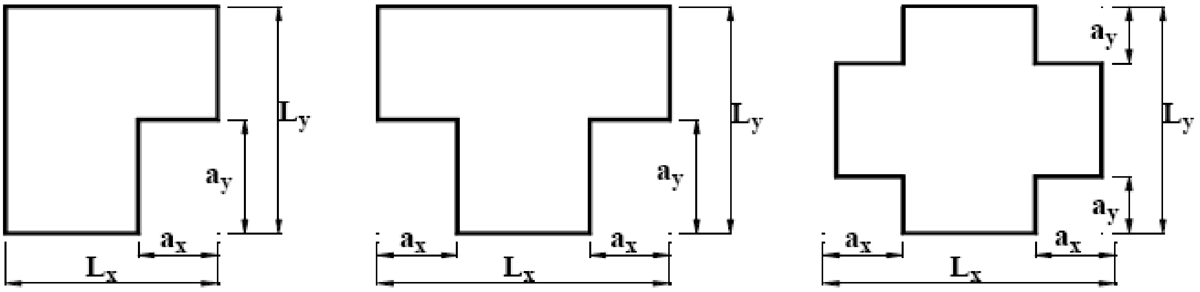


Fig. 2 A3 type irregularity (TEC-2007)

Irregularities in elevation is dived to 3 types. First one is "Interstorey strength irregularity or weak storey-B1". Effective shear area of any storey is the summation of shear areas of columns, shearwalls and 15% of area of nonstructural infills. The Strength Irregularity Factor (η_{ci}) is defined as the ratio of the *effective shear area* of any storey to the *effective shear area* of the storey immediately above. The limit value of B1 type irregularity is $\eta_{ci} < 0.8$.

B2 type irregularity is also called as "Soft Storey". In order to determine condition of soft storey, Stiffness Irrregularity Factor (η_{ki}) is defined. The ratio of average storey drift at any storey to the average storey drift at the storey immediately above is called as stiffness irregularity factor (Eq. 4). If this factor is greater than 1.5 than there exist soft storey irregularity.

$$\eta_{ki} = [(\Delta_i)_{average} / (\Delta_{i+1})_{average}] \tag{4}$$

3. EVALUATION OF ARCHITECTURAL DESIGN AND CORRESPONDING IRREGULARITY

In order to evaluate the architectural design decisions and earthquake response of the structure on the basis of structural irregularities, a reference model building was designed. Initially the model building didn’t contain any irregularity type and purposely it designed to have symmetry both on the X and Y directions. The reference model structure which is named as “regular structure”, has 5 bays in the X and Y directions with 5 m bay length. The total plan dimensions are 25mx25xm. The columns are chosen as square and a uniform grid system is obtained. The beams are rectangular with 250mm width and 500mm height. The dimensions of the columns are kept constant throughout the building but the dimensions are changed according to the number of stories of the model. In Fig. 3, the general layout of the model is shown.

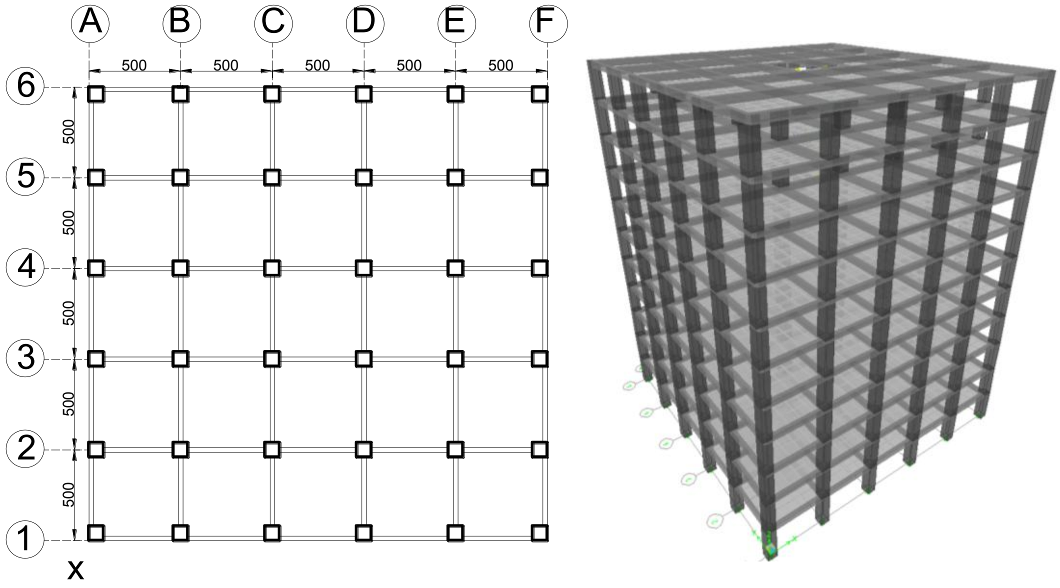


Fig. 3 Layout of the reference model and 3D model

The three dimensional model of the structure is created with the help of the general purpose ETABS finite element program. The columns and beams are modeled with frame elements, slabs are modeled with shell elements and due to in-plane rigidity, diaphragms are assigned to the storeys. The foundation of the structure is not considered and fix supports are assigned. The concrete strength of 15MPa is selected for material quality and corresponding modulus of elasticity is assigned to RC members. This class of concrete is average concrete quality for residential houses in the Turkish building stock. The mode-superposition method is applied for earthquake analyzes. The seismic zone of 1 (region of high seismicity) is assumed and corresponding effective ground acceleration coefficient (A_o) is set to 0.4. The building importance factor of 1 (residential structures) and local site class of Z3 with spectrum characteristics periods of (T_a=0.15 sec and T_b=0.6 sec) are assumed. The earthquake analyses are carried out in the two orthogonal directions and initially 5% additional eccentricity is assigned.

Seismic design acceleration spectra for Z3 soil type is presented in Fig. 4.

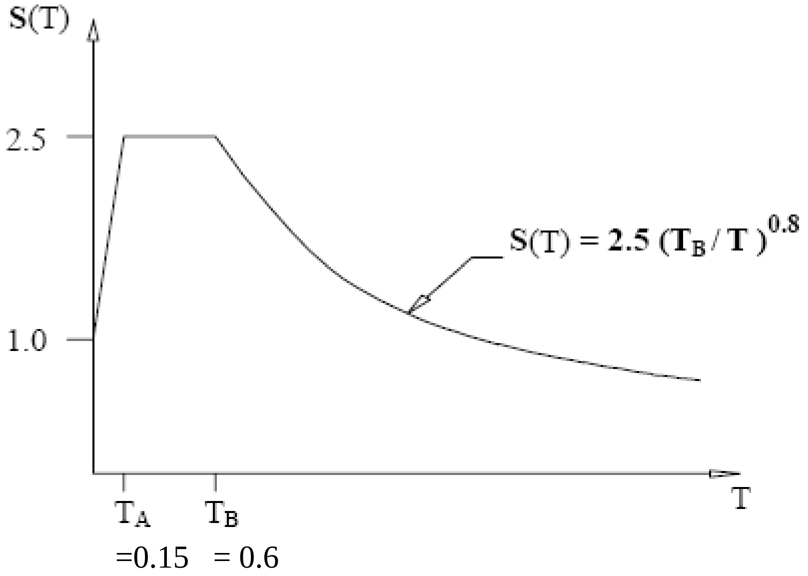


Fig. 4 Seismic design acceleration spectra for Z3 soil type (TEC-2007)

3.1 Evaluation of interstorey strength irregularity (soft storey)

Soft storey mechanism and corresponding failure type is the most frequent failure mode of RC structures in Turkey. It consists of a localization of buildings seismic deformations and formation of plastic hinges in the columns of the ground storey. The formation of hinges at the ground storey columns may cause the entire building to collapse. Soft storey mechanism can be formed if infills are omitted in the first storey. A large number of residential and commercial buildings built in Turkey had soft stories at the first-floor level on the two sides of main streets, because the first stories have been often used as stores and commercial areas. These areas are generally enclosed with glass windows instead of brick infill walls so as to be used as showrooms. Heavy masonry infills start immediately above the soft storey (Dogangun 2004). In Fig. 5, several soft storey failures in Turkey are illustrated.

Source: (http://world-housing.net)   Source: (Arslan 2007)

Fig. 5 Soft storey failures

In order to evaluate soft storey irregularity, the number of storeys, the height of the ground storey are chosen as parameters. The brick infills are assumed to be exist in the upper stories and there is no partition wall in the ground storey. The partition walls are assumed to be brick infill type and they are modelled with shell elements within the frame. The window openings at the exterior partition walls are also considered. The infills are assumed to carry only compressional forces and has no tensional strength. The contact condition between partition walls (shell elements) and column or beams (fram elements) are such that at the compression strut ends, the contact length is equal to 1/3 times the length of the corresponding column or beam. At the tension interfaces, there is no force transfer between frame elements and shell elements. The general view of the generated model is given Fig. 6.

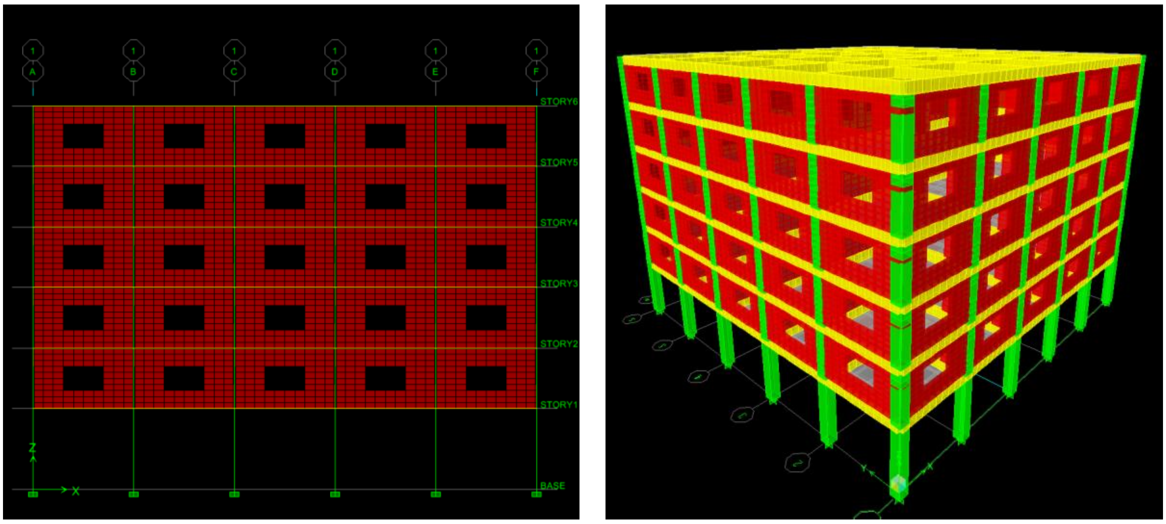


Fig. 6 ETABS model of the soft storey analyze case

The number of storeys are varied between 2 and 13 (maximum). The height of the ground storey is also a parameter and it is in between 3m and 8m. The geometry of the columns are assumed to be rectangle and dimensions are changed according to the number of storeys. In Fig. 7, the dimension of the columns with respect to total number of storeys are given.

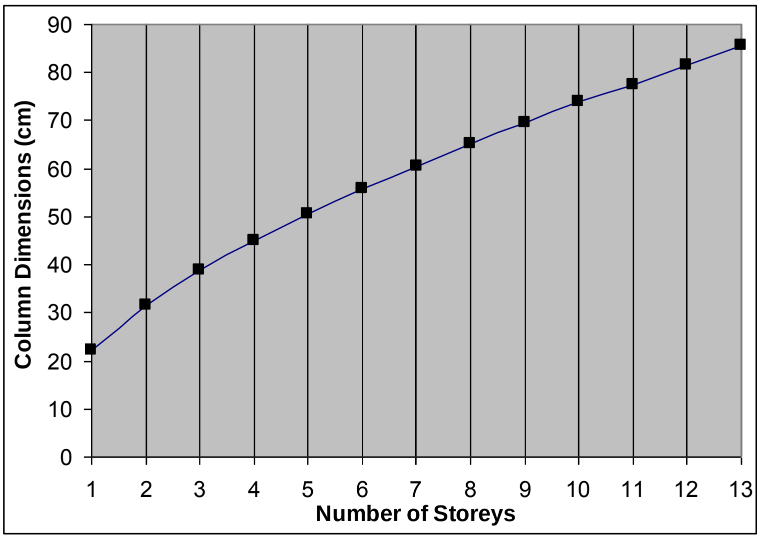
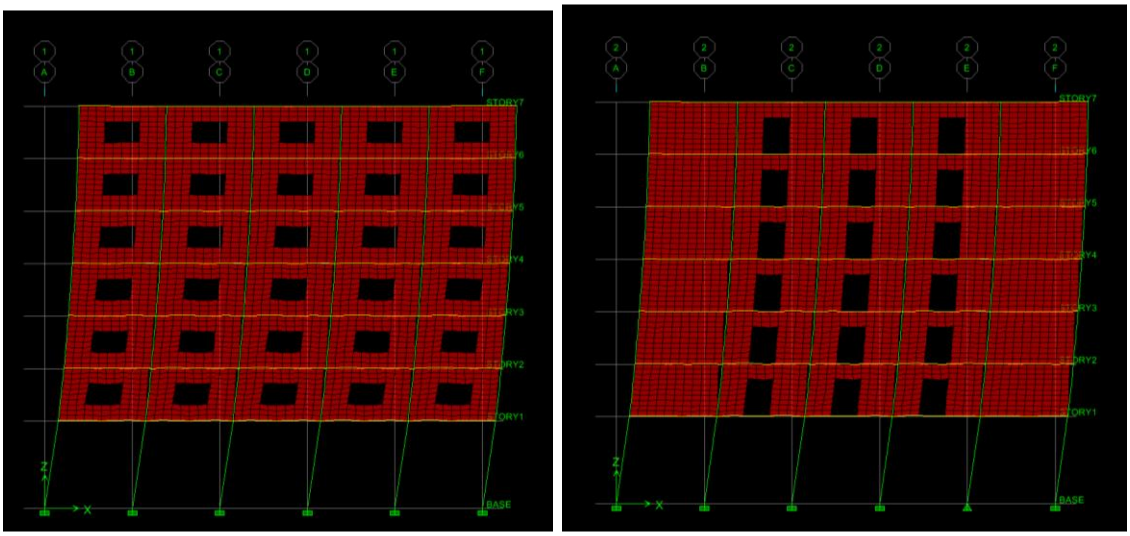


Fig. 7 Dimension of the columns with respect to total number of storeys

After performing the dynamic analyses in the two orthogonal directions, the stiffness irregularity factor (η_{ki}) is determined for each case. The deflected shape of the model structure is depicted in Fig. 8.



a) Axis 1-1 b) Axis 2-2

Fig. 8 Deflected shape of the structure for earthquake direction of X

In Fig. 9, the calculated stiffness irregularity factors are presented with respect to the number of storeys and ground storey height.

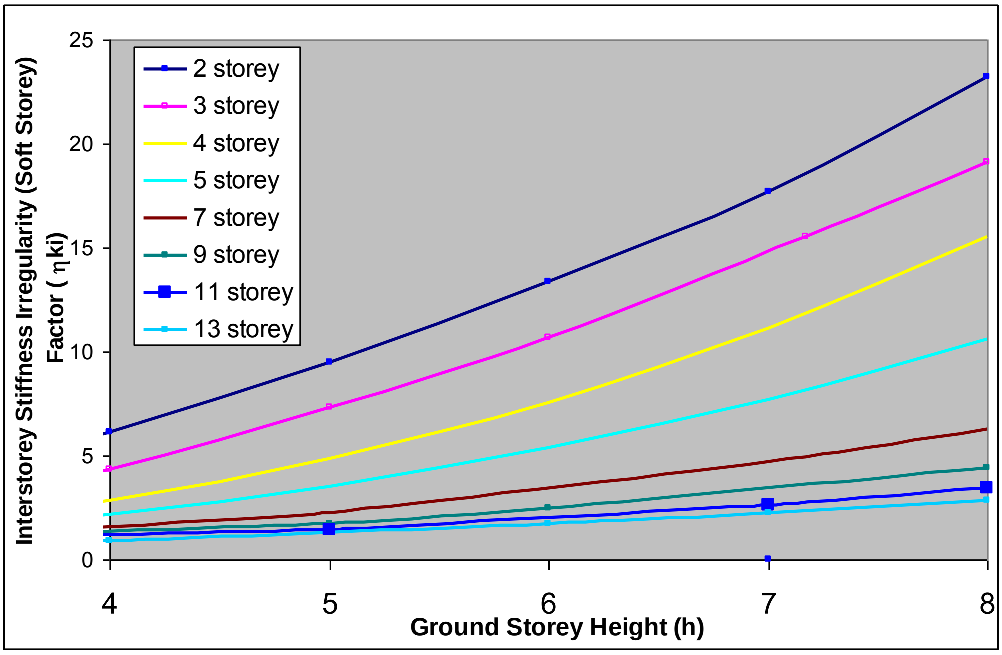
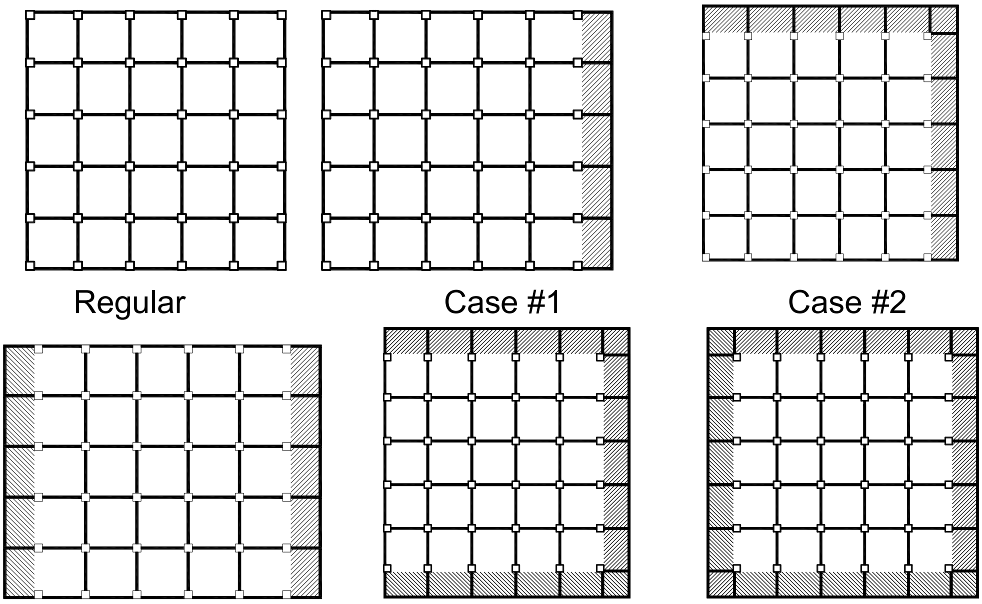


Fig. 9 Calculated stiffness irregularity factors

As opposite of the expectations, the soft storey irregularity factor is higher for structures having less storeys. The worst case is obtained for structure with 2 storeys. As the number of storeys increases, the η_{ki} values are in decreasing trend. The reason of this result may be explained with the change in the dimensions of the columns. The dimensions and strength of the infill are constant for all cases. On the other hand, the dimensions of the columns are small for structures with less number of storeys. It is known that, brick infill walls increases the stiffness of the frames and contribute to the rigidity. This contribution is higher for structures with small columns but limited for structures with stiffer columns and higher number of storeys. For low-rise buildings, nonstructural infill walls compromise a significant portion of the total strength. The height of the ground storey has also considerable effect on the earthquake response and soft storey behavior.

3.2 Evaluation of torsional irregularity

Open or closed cantilever projections is a form of irregular mass distribution commonly encountered in the Turkish urban pattern to enlarge the plan dimensions and create space for balconies (Ozmen 2007). The aim of the cantilever projections is to maximize the gross floor area of the building due to the intention of the most effective utilization of land. The cantilever projection length in Turkey is generally in between 1.5m-2m, and in some cases 3m. In order to investigate the cantilever projection on the earthquake response of the structures, 4 different cantilever configurations were attached to the reference model (regular case). In the first configuration there is one cantilever (case #1), in the second and third cases there are two cantilevers (case #2 and #3), in the fourth case there are three cantilevers (case #4) and in the last case there are four cantilevers (case #5). The schematic illustration of the cases is given in Fig. 10.



Regular Case #1 Case #2

Case #3 Case #4 Case #5

Fig. 10 Analyses cases of cantilever projection cases

The number of storey is 9 for all cases. The length of the cantilevers are 2m. The models are analyzed and maximum and minimum storey drifts are determined. Torsional irregularity factors (η_{bi}) are calculated according to the Eq. 2 and graphically tabulated in Fig. 11.

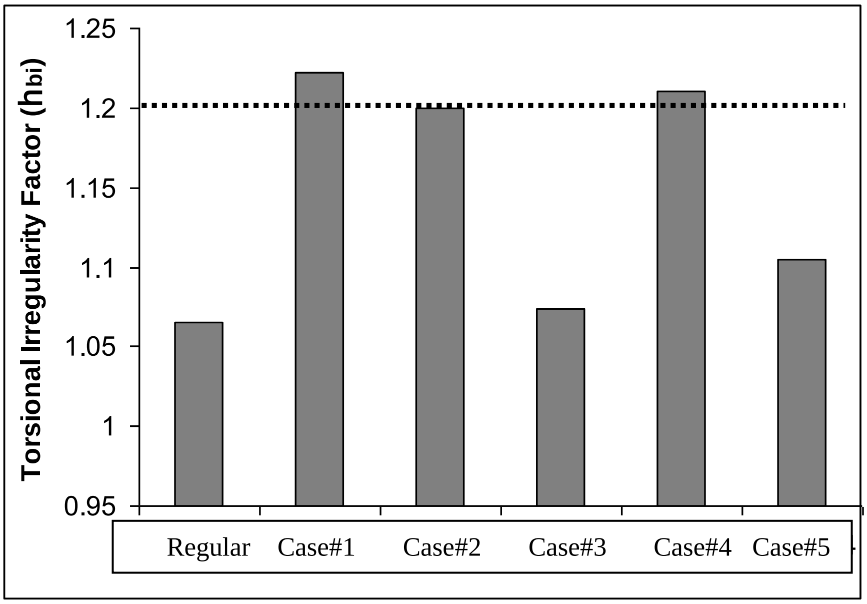


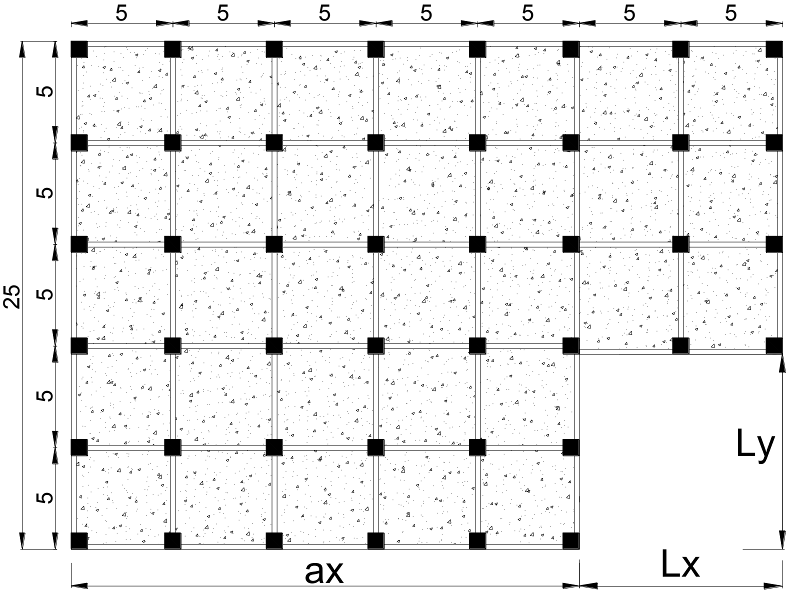
Fig. 11 Torsional irregularity factors for different cantilever projection configurations

The torsional irregularity factor of the regular case is quite close to 1. On the other hand, addition of one cantilever disturbs the torsional stability and η_{bi} value exceeded the limit value of 1.2. Also η_{bi} constant is exceeded the limit value for case #4, which has 3 projections. The torsional irregularity factor for case #2 is just below the code limit. Case #3, which has 2 projections on the opposite faces produced η_{bi} value very close to the regular case. Although case #2 and case #3 has two cantilevers, configuration of the cantilevers change the behavior. The η_{bi} value of case #5 is also below the code limit. If the cantilever projection is symmetrically designed on the plan area, it doesn't create torsional irregularity. On the other hand, for one and three sided cantilevers, the torsional movements may create additional stress on the columns during the earthquake, which are under great stresses.

3.3 Buildings with re-entrant corners and projections in plan

Due to the shape of the land, architectural necessitates, functional or user requirements, buildings may have projections in plan. In this case, the projections are named as wings and the sharp corners on the intersection of wings are called as re-entrant corners. During the past earthquakes, the buildings which have large projections with re-entrant corners such as with T, L, Y or U shaped plan geometry have sustained significant damage. The main reason of observed damage is that, projections or wings make different movements in different directions. This causes torsion and rotation of the building and consequently distorts the building form. The second important problem is the stress concentration at the notch points in the re-entrant corners. The third problem is about the analyze assumptions. Torsional forces are difficult to predict and analyze. The magnitude and distribution of forces depend on the length of the projections and their ratios. If several re-entrant corners are formed due to architectural necessities, the building must be divided to sub structures and earthquake separation joints must be provided. The mass center and center of rigidity must be coincide for each blocks.

In this study, the projection in plan and torsional response is analyzed. The ratio of the projection in the X and Y direction is a parameter. The reference model is same as the regular structure in the previous case. The projections are inserted in the building plan form at the right side (Fig. 12). The Lx and Ly dimensions are chosen as 5m (20%), 10m (40%) and 15m (60%). The model identifiers of the analyze cases are listed in Table 1. The number of storeys is selected as 10.



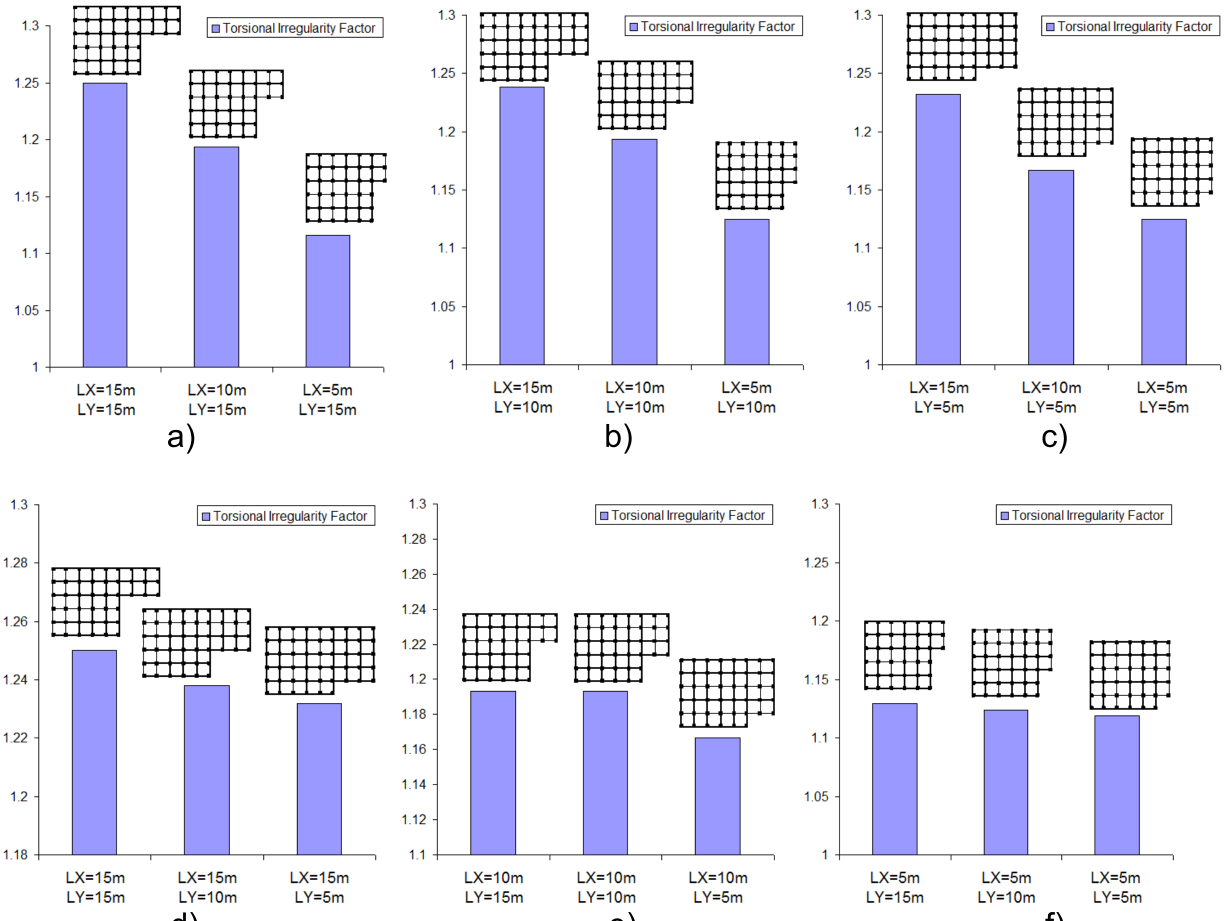
Dimensions are in m.

Fig. 12 Model structure for projections in plan cases

Table 1 Analyze cases for projections in plan cases

Lx / Ly	**5m-(20%)**	**10m-(40%)**	**15m-(60%)**
5m-(20%)	*Case (20%-20%)*	*Case (40%-20%)*	*Case (60%-20%)*
10m-(40%)	*Case (20%-40%)*	*Case (40%-40%)*	*Case (60%-40%)*
15m-(60%)	*Case (20%-60%)*	*Case (40%-60%)*	*Case (60%-60%)*

For two orthogonal earthquake directions dynamic analyses are carried out and torsional irregularity factors for every floor is determined. The maximum obtained value is tabulated in Fig. 13. The graph in Fig. 13-a is for cases, Ly=15m (60%) and Lx value is set as 15m (60%), 10m(40%) and 5m (20%). Similarly in Fig. 13-b, Ly=10m (40%) and Fig. 13-c, Ly=5m (20%). Keeping constant the projection length in the Y direction, the increase in the projection length in X direction, causes an increase in the torsional irregularity factor. For every Ly value (5m, 10m or 15 m), the cases with Lx value of 15 m (60%) causes torsional irregularity factor to exceed the limit value of 1.2. On the other hand, whatever the Ly projection length, the cases with a projection length of 5m in the X direction (20%) yield torsional irregularity factors close to the 1.1. the inferior result is obtained for the case of Lx=15m-Ly=15m.



a) b) c) d) e) f)

Fig. 13. The comparison of torsional irregularity factors

In Fig. 13-d-e-f, the projection length in X direction is determined as 15m, 10m and 5m respectively and effect of projection length in Y direction is evaluated.

3.4 Shearwall configuration and torsional response

In the previous sections, plan geometry of the structure and torsional response is investigated. In some cases, although the structure is architecturally symmetric and regular in plan, the configuration of the structural elements or disposition of shearwalls or columns may create torsional rotation. A very good example of this type torsional failure was observed in Van Earthquake (2011) in Gedikbulak Village Primary School. The school building from the outside appearance, is symmetrical and seems to be regular. The school has only 3 storey and it has no cantilever projection, projection in plan, soft or weak storey formation, short column etc. Unfortunately, the structure collapsed during the earthquake which has maximum ground acceleration of 0.18g. this PGA value is below the maximum code design acceleration of 0.4g defined for the region. The plan and configuration of columns and shearwalls are presented in Fig. 14. The structure is modeled in ETABS package program and it is found that second mode is torsional. The torsional irregularity factor of the model is found to be 1.37, which is greater than the code limit of 1.2.

Source: (www.meb.gov.tr) Source: (http://fotogaleri.hurriyet.com.tr/)

Fig. 14 Failure of a symmetrical school building

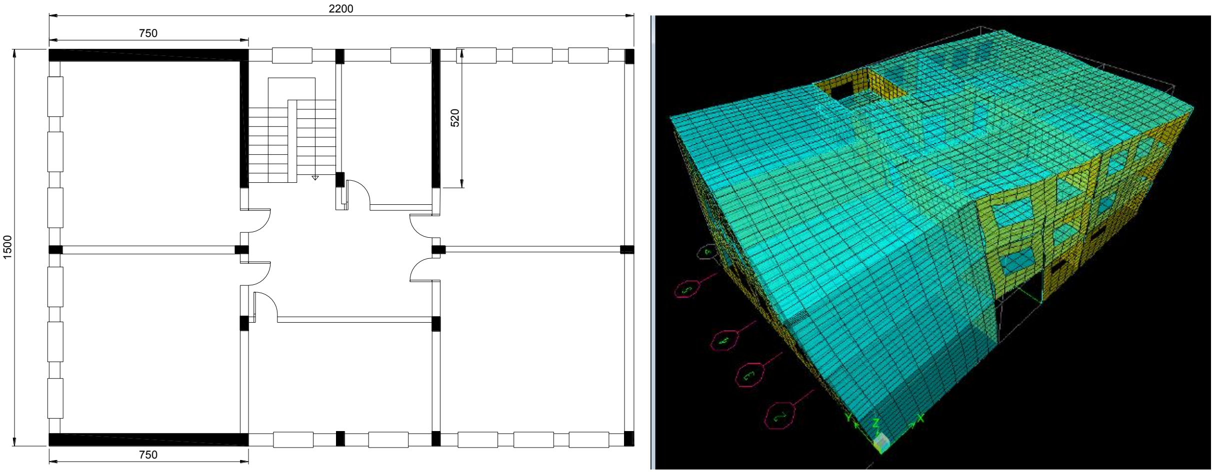


Fig. 15 Plan view and seismic response of the school building.

In order to represent structural configuration and torsional response, 4 models, including the reference regular case, is analyzed. For regular case there is no shear wall in the structure and symmetrical structural system is named as regular. In the second case, two shearwall are placed on the core of the structure, symmetrically. In the third case, shearwalls are shifted 5m (one bay) in the X direction and in the fourth case the shearwalls are shifted 10m. Both structural systems are symmetrical along the X direction, while, only first and second models are symmetrical in the Y direction. The number of streys are varied between 1 to13. The other details and modeling assumptions are similar to the previous cases. In Fig. 16, the plan view of the cases are given.

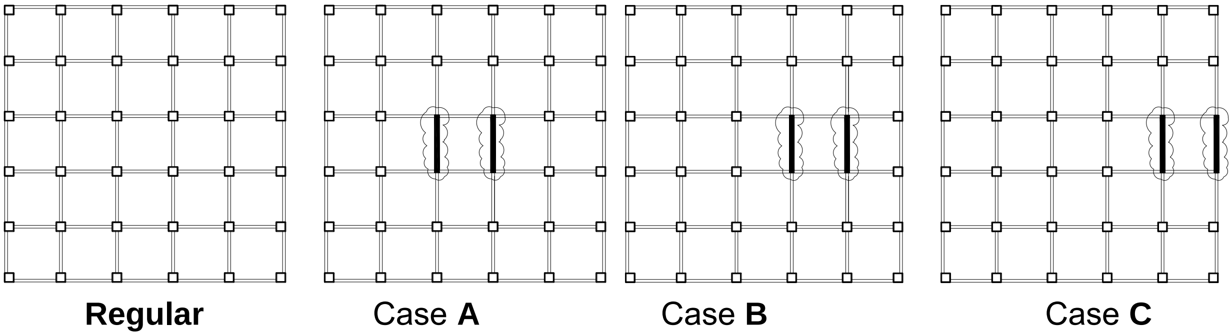


Fig. 16 Analyze case models for the effect of location of shear walls.

The models are analyzed under two orthogonal earthquake directions (dynamic analyze) and torsional irregularity factor are determined. The obtained maximum torsional irregularity factors are tabulated in Fig. 17 with respect to the number of storeys.

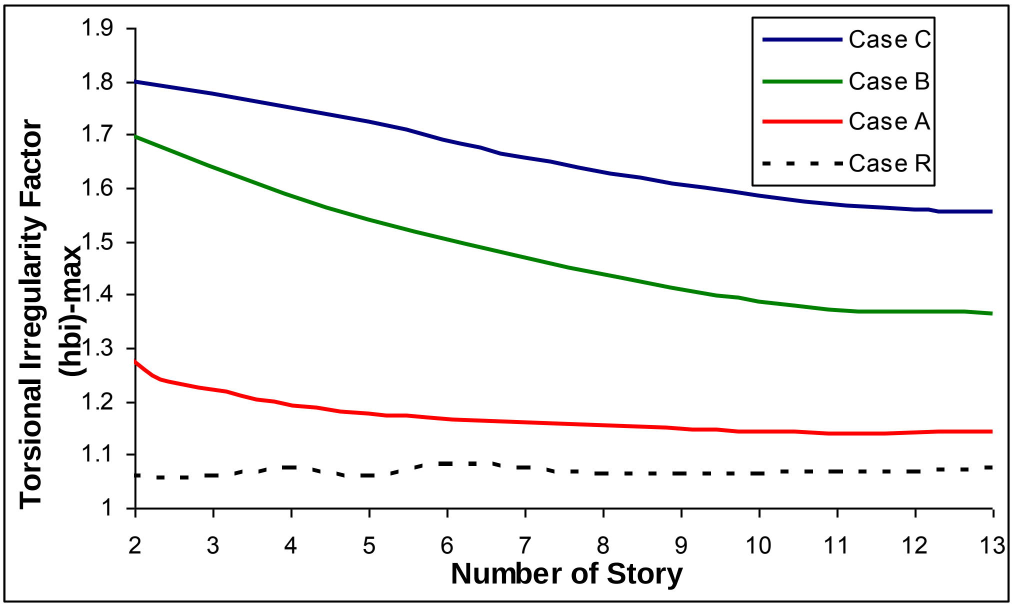
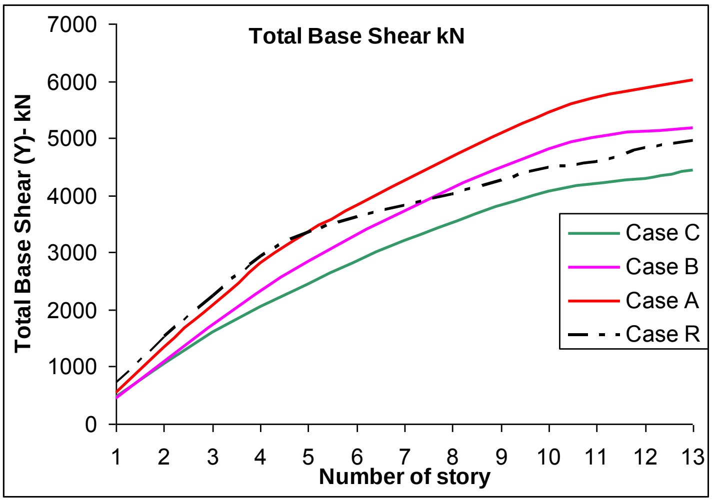


Fig. 17 Maximum torsional irregularity factors with respect to the number of storeys

Although the structural plan has symmetry in the X and Y directions, the unsymmetrical placement of the shearwalls resulted in a torsional movement in the structure. For case B and Case C, for all number of storeys, the η_{bi} value is above the code limit of 1.2. it is interesting that, η_{bi} values are higher for structures with 2-4 storeys and has decreasing trend as the number of storeys increases.

Total base shear for earthquake loadings and total base torsional moment values are presented in Fig. 18 in comparison with regular case R. Although the base shear of Case A is highest among the other cases, maximum torsional base moment is obtained in Case B and Case C.



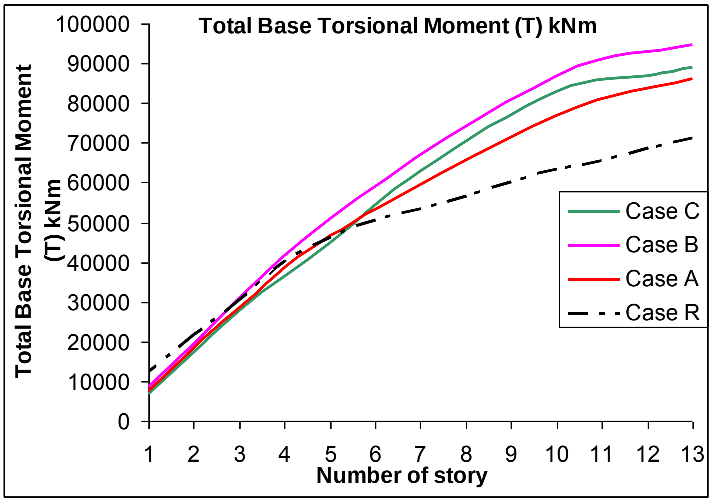


Fig. 18 Total base shear and base torsion graphs

4. CONCLUSIONS

In this study, architectural configuration and corresponding earthquake behavior is evaluated on the basis of structural irregularities. In the first case of the study, soft story response and stiffness irregularity factors are evaluated. According to the analysis results it can be concluded that; the height of the ground story has important influence on the soft story deformations. As the height of the ground story increased, stiffness irregularity factors are also increases. The number of storey has opposite effect on the risk of soft story mechanism. If someone compares the low-rise and high-rise structures, as the number of storeys increases, the calculated stiffness irregularity factor has decreasing trend. That means, structures with lower stories are more risky than the structure with more storeys. The reason of this fact that, the stiffness of the infill masonry walls are more dominant in low-rise structures with smaller column dimensions.

In the second phase of the study, cantilever projections and torsional response is evaluated. Five different cantilever projection configuration cases are analyzed and compared to the reference model structure. The torsional irregularity factor is found to be maximum for the case with one cantilever. The second highest value is found for the case with 3 cantilevers. This is followed by case with two cantilever ad adjacent sides. The closest value for torsional irregularity factor is found in case with two cantilevers at the opposite sides.

In the third phase of the study, projection in plan with re-entrant corners are evaluated. Projections are attached at the one side of the building. Th Lx and Ly values are changed and totally 9 different cases are obtained. Taking the Ly projection length constant, as the projection length in the x direction increases, the torsional irregularity factor is also increasing. If Lx length is equal to 15m (60%), whatever the Ly value is, torsional irregularity factor is higher than the code limit.

In the last phase of the study, importance of structural configuration is evaluated on the basis of torsional irregularity. For this purpose a geometrically symmetrical building is modeled with 4 different structural system configuration. Although reference model was regular, the unsymmetrical placement of shearwalls disturb the torsional response of the structure and cause to overload the structural members which are under considerable stresses.

There is a strong relationship between the architectural design of a building and its earthquake safety. After the recent earthquakes in Turkey, several buildings are heavily damaged or collapsed because of the geometrical form of the structure or the architectural design decisions. The formation of soft story, collapses due to torsional movement or heavy damage due to unsymmetrical and irregular arrangements are the most encountered reasons of failure. In this study the importance of geometrical form or architectural configuration is highlighted in the case of earthquake. The courses related with earthquake and dynamic behavior has less or no participation in the context of the architectural education. On the other hand, as the designer of the buildings, architect determinate the general form of the building and also earthquake response of the structure.

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