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Seismic behavior analysis of multi-story reinforced concrete buildings having torsional irregularity

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ABSTRACT

Earthquakes are one of the most important and hazardous natural disasters in the world and in our country. They also have lots of characteristics from the point of effects caused by them. For this reason it requires special engineering approach to analyze those effects and to design earthquake resistant structures. Almost all of the life losses caused by the earthquakes are related with improperly designed buildings safety of which are not ensured against severe earthquakes. Structural damages and collapses cause very important economical losses. So, understanding of the characteristics of an earthquake and correct determination of the behavior of buildings under earthquake excitation turn out to be the most important requirement to build earthquake resistant buildings. When we take into consideration the destructive effects of severe earthquakes that happened especially in recent years (Kocaeli 1999, Düzce 1999) one can easily see the importance of knowing the behavior of buildings under earthquake loads. In this study torsional effects that occur during earthquake excitations are analyzed in multi-story reinforced concrete buildings. In that manner the behavior of reinforced concrete structures under earthquake loads are examined and by the way the behaviors of structures having torsional irregularities are enlightened and clarified. Moreover the effects of rigidity, ultimate capacity and ductility on the behavior of structures under ground motion are summarized. Torsional irregularity is a key irregularity in determination of the method to be used in earthquake analysis. Definition of the torsional irregularity of a multi-story reinforced concrete building is explained in accordance with Turkish Earthquake Code and the related principles of computations that have to be followed according to the code are given. Multi-story reinforced concrete buildings are classified according to their plan geometry and the effects of plan geometry on the torsional irregularity are explained. While in certain structures torsional irregularity may happen in very high levels in some structures it may happen so small that can be safely omitted. For that reason buildings forming torsional irregularity are classified and their characteristics and torsional irregularity parameters are given. Shear walls without causing any torsional irregularity on buildings having different plan geometries are shown.

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1. Introduction

In this study, the torsional irregularity, which is one of the most important irregularities in seismic behavior, is examined. Among all irregularities, the torsional irregularity is taken into consideration at most in modern earthquake codes. In 39 of those earthquake codes, there are rules and regulations regarding to this irregularity. Some of regulations are;

- In 11 codes, the torsional irregularity is not allowed in any way. In 6 of them it is stated that seismic joints should be used.

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- In 3 codes, the application of additional eccentricity is stipulated.
- In 13 codes, it is stated that dynamic analysis and calculation should be applied.
- In 10 codes, it is stated that additional eccentricities should be increased providing that some certain conditions are fulfilled and in extreme cases it is stated that dynamic analysis and calculation should be utilized.

Generally the way of solution is; to increase the eccentricities then to repeat the lateral load analysis when parameters related with torsional irregularity exceed certain values and if there exists further increase of those parameters dynamic analysis should be applied. The same solution is also adopted in Turkish Earthquake Code, which came into operation on January 1st 1998 (Özmen, 2001).

2. Method of Analysis

In seismic analysis of the sample structure examined in this study; equivalent earthquake force method and mode superposition method are used. In both methods the floor masses are applied to the shifted story mass centers. Structure is analyzed under the assumption of the rigid diaphragm behavior of floor slabs. The spectrum diagram, which will be used in seismic analysis of the system, soil characteristics and earthquake zone parameters, are taken from Turkish Earthquake Code. In structural analysis, SAP2000 Structural Analysis Program is used. The torsional coefficients which are defined by Turkish Earthquake Code are calculated according to the equivalent earthquake force method then using the results obtained from that analysis additional eccentricities are given to the story mass centers and seismic analysis is repeated. As a result, the seismic analysis of the building is performed by; a) Equivalent earthquake force method at shifted mass center, b) Equivalent earthquake force method at shifted mass center with given additional eccentricity, c) Mode superposition method at shifted mass center.

3. Sample Structure

Because of the fact that the most serious torsional irregularities are seen on buildings having irregularity about the rigidity distribution, the sample structure is chosen geometrically regular. In this building the torsional irregularity is obtained by especially the assembly of shear walls closed to end edges i.e. the irregularity is obtained due to non-uniform rigidity distribution of vertical elements within the structure. What is aimed by choosing this sample is to emphasize that rather than the geometric characteristic of the building the load carrying system can also cause serious torsional effects. Consisting of 1 basement story, 1 ground story and 13 normal stories the building is a 15-story reinforced concrete structure. It has 28.50x19.00=541.50 m^2 living area which is rectangular in plan. At normal stories on 3 sides, projections having 1.5 m and 2 m span lengths are formed. Structural system of the building is formed with rectangular columns, polygon shaped shear walls and beams. The structural system is totally symmetrical in *y* direction but not in *x* direction. Total height of the building is 53.50m. Structural system is modeled as high ductility moment resisting frame system. Building is in the 2nd degree earthquake zone and Z2 local site class is assumed. Material types used in the project are C25 and S420. Floor plans a longitudinal section of the building are given in Figs. 1 and 2.

4. Classification of Buildings Having Torsional Irregularity

Buildings having torsional irregularity can be divided into 4 classes.

1. Buildings having geometrical irregularity.
2. Buildings having irregularity about rigidity distribution.
3. Buildings having irregularity about both geometry and rigidity distribution.
4. Buildings having hidden torsional irregularity.

5. Typical Buildings That Are Not Expected to Have Torsional Irregularity

A part of the results obtained from the studies done on buildings in this group are of expected type. However it is interesting to obtain some unexpected results. Some of the results are summarized below.

1. In general buildings that are symmetrical about both geometry and rigidity distribution have no torsional irregularity.
2. Buildings having shear walls especially on edges behave more regular about torsional irregularity.
3. In some buildings which are symmetrical about both geometry and rigidity distribution the torsional irregularity coefficients may approach to a limit value of 1.20.
4. It is concluded that for the torsional irregularity point of view the rigidity distribution is a more important factor than geometry.

6. Geometrically Irregular Buildings

Following results are obtained at the end of analyses performed on buildings belonging to this group.

1. Torsional irregularities of buildings having only geometric irregularity are not at very high levels. Even for buildings, which are unfavorable about torsion, torsional irregularity coefficients are at about 1.4.
2. In that type of buildings, small increases on sectional dimensions of elements along weak axes result in considerable decrease in torsional irregularity.
3. In unsymmetrical buildings, torsional irregularity coefficients stay at acceptable levels if there is no big irregularity about rigidity.

7. Irregular Buildings About Rigidity Distribution

At the end of analyses performed on buildings having rigidity irregularity following results are obtained.

1. In buildings having rigidity irregularity, the torsional can be at very high levels.

2. Even for buildings, which are unfavorable about torsion, the torsional irregularity coefficients stay below 2, which is the limiting value for the application of equivalent earthquake force given in Turkish Earthquake Code. So it can be clearly understood that it is nearly impossible to reach that value in structural applications.
3. Torsional irregularity can mostly be removed in this kind of buildings with arrangements done on load carrying elements along the weak axes of the structure.
4. The most effective way of decreasing the torsional irregularity is to locate the shear walls along the weak axes.
5. Increasing beam and/or column cross sectional areas can also be helpful for decreasing torsional irregularity in weak axes.
6. Even at the buildings having high amount of torsional irregularity, modeling difficulties may not be seen. It is brought forward that precautions in codes torsional irregularities need some change

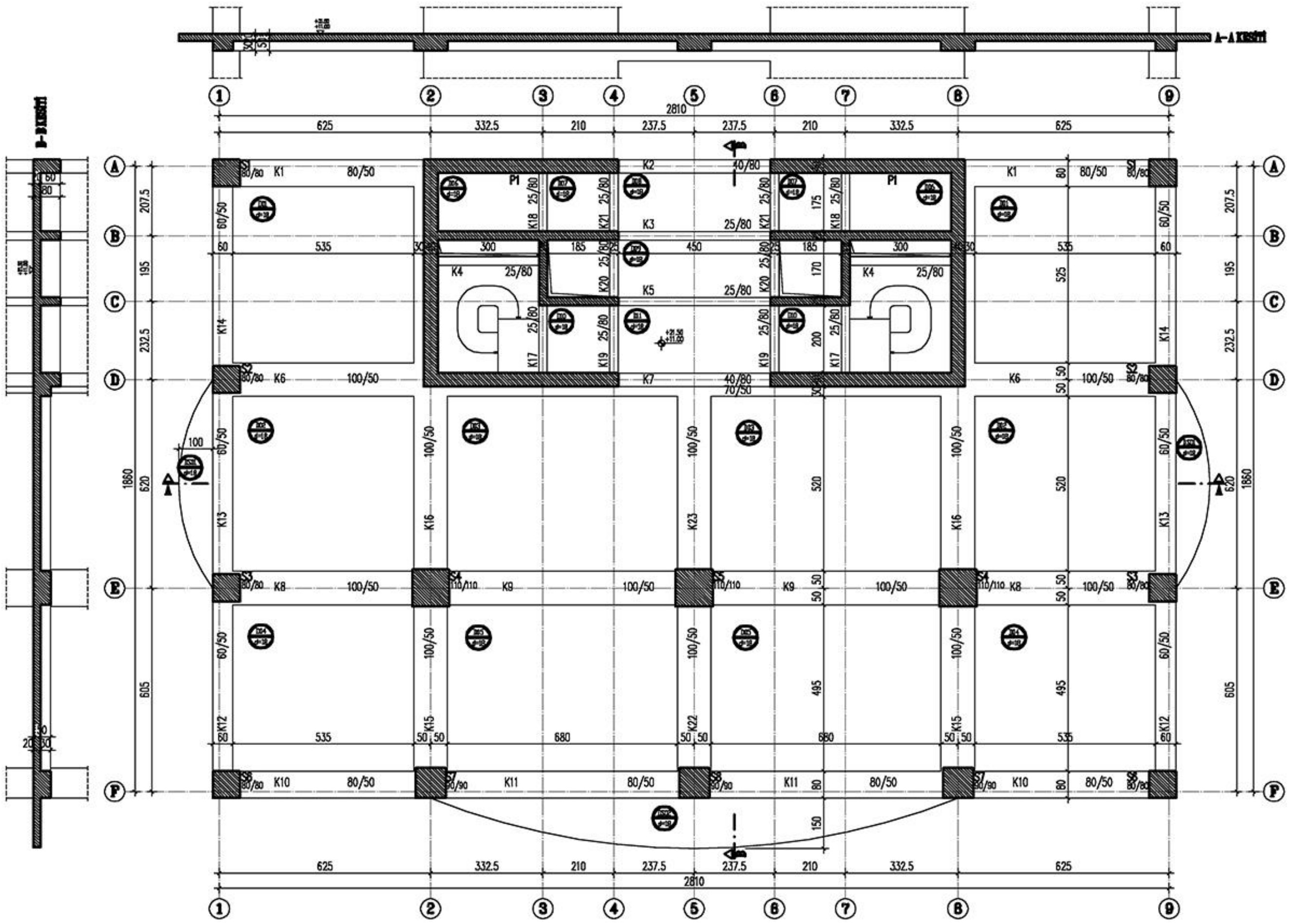

Fig. 1. Normal story formwork plan of the sample structure.

8. Irregularities in Geometry and Rigidity

The results obtained from studies done investigations on buildings in these groups are parallel to behavior occurred in "buildings having rigidity irregularity". The results are summarized below.
1. Torsional irregularity can be at high levels.
2. The torsional irregularity coefficients stay below the limiting value of 2.00 even at the buildings, which are unfavorable about torsion.
3. The torsional irregularity can mostly be removed with arrangements done on structural elements along weak axes of structure.
4. The most effective solution for decreasing the torsional irregularity is to locate the shear walls along the weak axes.
5. Even at the buildings having high amount of torsional irregularities, modeling difficulties may not be seen.

The behavior type of this type of building is parallel with irregular buildings only in aspect of rigidity distribution. Hence, it can be concluded torsional irregularity depends on almost only unbalanced rigidity distribution in the plan.

9. Hidden Torsional Irregularities

Following results are obtained at the end of analyses performed on building belonging to this group.
1. Torsional irregularity can also occur in the buildings having regular geometrical shape and regular rigidity.
2. The reason for torsional irregularity in this type of buildings is lack of rigidity on the edge axes.
3. Rigidity of edge axes must be increased in order to remove torsional irregularities.
4. In certain cases, torsional irregularity can be lowered or totally removed as a result of decrease in shear wall rigidity at the central zone (Özmen, 2001).

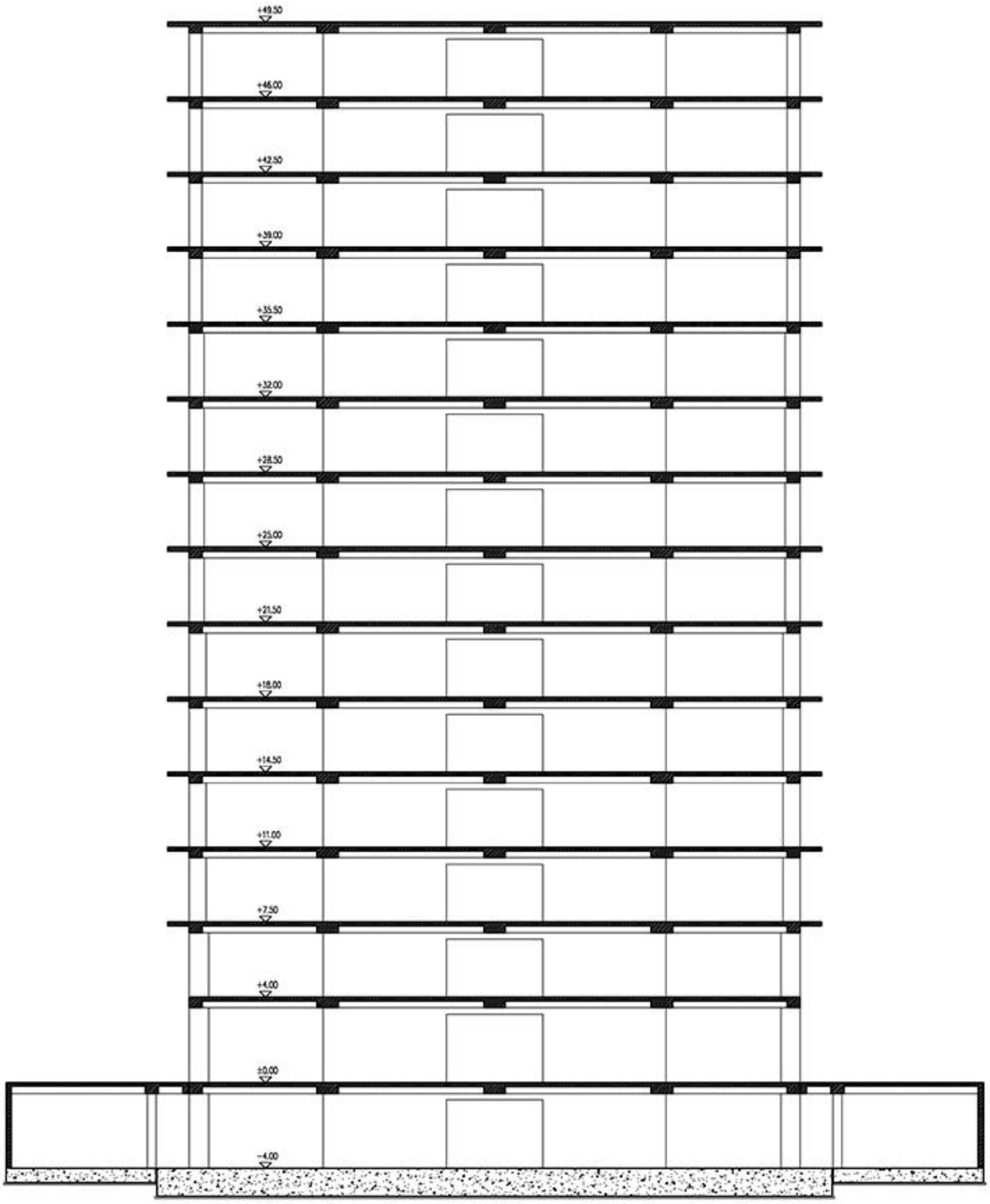

Fig. 2. Longitudinal section of the sample structure along *x* direction.

10. Analysis Results

As a result of analyses equivalent seismic load method and mode superposition method, torsional irregularity coefficient which are calculating according to relative and absolute story drifts are shown in Table 1 and Table 2.

Although it is geometrically symmetric, there occurs torsional irregularity in the building, because the rigidity distribution of the structural system is irregular. At the end of calculation, torsional irregularity coefficient for the building has been found as max η_b=1.529. It has been seen that the torsional irregularity is increases when the shear walls taking part on the sample building are located to outer axes. With the aid of this examination it can be concluded that torsional irregularity may be on very high levels on buildings, which are irregular from the viewpoint of rigidity distribution.

All these results clearly exposes the need of giving importance on the selection process of structural system. Structural systems begins to come out at the architectural plan phase. Often various architectural reasons do not allow modeling of the desired structural system.

However with some changes and additions that will not affect architectural made by the engineer on the forming phase of the structural system, torsional irregularity can be reduced to minimum levels. In the sample structure locating structural walls to symmetric axes where rigidity distribution is dense will be a precaution which will fairly decrease the degree of torsional irregularity.

On this kind of buildings, in order to reduce the degree of torsional irregularity, shear walls, even at a limited number and on a limited dimension have to be located to weak axes.

Table 1. Torsional irregularity coefficients calculated with equivalent seismic load method.

STORY	$X_{+0.05}$		$X_{-0.05}$		$Y_{+0.05}$	
	Relative η_{bi}	Absolute η_{bi}	Relative η_{bi}	Absolute η_{bi}	Relative η_{bi}	Absolute η_{bi}
1	1.385	1.385	1.529	1.529	1.170	1.170
2	1.362	1.370	1.499	1.509	1.159	1.162
3	1.326	1.351	1.460	1.489	1.146	1.155
4	1.311	1.339	1.443	1.474	1.138	1.150
5	1.297	1.328	1.427	1.462	1.131	1.145
6	1.286	1.319	1.416	1.452	1.125	1.140
7	1.276	1.312	1.405	1.444	1.120	1.137
8	1.276	1.306	1.404	1.438	1.116	1.133
9	1.267	1.301	1.395	1.433	1.111	1.130
10	1.260	1.297	1.387	1.428	1.106	1.127
11	1.251	1.293	1.377	1.423	1.100	1.124
12	1.248	1.289	1.375	1.419	1.096	1.122
13	1.234	1.285	1.359	1.415	1.090	1.119
14	1.219	1.281	1.343	1.411	1.084	1.116
15	1.196	1.277	1.317	1.406	1.078	1.114

Table 2. Torsional irregularity coefficients calculated with mode superposition method.

STORY	$X_{+0.05}$		$X_{-0.05}$		$Y_{+0.05}$	
	Relative η_{bi}	Absolute η_{bi}	Relative η_{bi}	Absolute η_{bi}	Relative η_{bi}	Absolute η_{bi}
1	1.411	1.411	1.491	1.491	1.223	1.223
2	1.385	1.394	1.465	1.474	1.222	1.222
3	1.346	1.374	1.427	1.455	1.218	1.220
4	1.327	1.359	1.407	1.440	1.223	1.217
5	1.308	1.347	1.388	1.427	1.225	1.219
6	1.294	1.336	1.372	1.416	1.226	1.220
7	1.282	1.327	1.359	1.407	1.223	1.221
8	1.279	1.320	1.356	1.400	1.219	1.220
9	1.269	1.314	1.345	1.393	1.211	1.219
10	1.261	1.309	1.338	1.388	1.201	1.217
11	1.251	1.304	1.329	1.383	1.189	1.214
12	1.247	1.299	1.327	1.378	1.177	1.211
13	1.231	1.295	1.312	1.374	1.163	1.207
14	1.213	1.290	1.294	1.370	1.150	1.203
15	1.185	1.285	1.266	1.365	1.138	1.199

As a result of analyses explained in the above paragraph and the result of researches made on this subject, it has been determined that only on the geometrically irregular buildings torsional irregularity is not on high-levels. Begin on very high-levels of torsional irregularity for buildings having H, L, T and Y shapes on the plans, is related with the rigidity distribution of the structural system. At the end of the little dimension increases on the structural elements on the weak axes of these kind of buildings, torsional irregularity can be removed on a large scale.

Obtaining max η_b=1.529 in the examined building and in the frame of made researches even on inconvenient buildings from the viewpoint of torsibility, η_b torsional irregularity coefficients remained under value 2.0 which has been determined as limiting value for applying equivalent load seismic method in Turkish Earthquake Code. On the application, meeting boundary value appears to be an impossible subject.

In the *y* direction, the building which is entirely symmetrical in the vertical direction, results in torsional irregularity coefficient η_b=1.170. Also with the dynamic analyze, it is resulted in η_b=1.226. The values nearly become with the boundary value, shown in Turkish Earthquake Code for the obtaining the irregularity of the buildings, show that the irregularity coefficient is not realistic. It can be evaluated that considering the earthquake effects of 5% additional eccentricities results in the torsional irregularity coefficient of the *y* direction becomes nearly to 1.20 where the building is entirely symmetrical in the vertical direction.

Additional eccentricities had been found 8.12% with the aid of calculated torsional irregularity and then the analysis reviewed with the new eccentricity. The analyze show that additional eccentricity make frame end forces 1.4% much bigger in columns and beams, 2-4% much bigger in shear walls than with the 5% eccentricity. Modeling difficulties hadn't been encountered after these analyze results. For this reason, reviewing the analysis with the additional eccentricity, which is located as a precaution for the torsional irregularity in Turkish Earthquake Code, cause suspicion whether it is necessary or not.

The comparison between the frame end forces calculated by Superposition of Modes Method under dynamic analyze and Equivalent Load Method has given following results.

- The modal analyze results are much more inconvenient in the beam far away from the zone where buildings rigidity dense. However equivalent seismic loads results are much more inconvenient in the beam in zone where rigidity is dense.
- The equivalent earthquake loads results in columns close to axis passing through buildings mass center are; frame end forces in earthquake direction much more inconvenient whereas in the column far away from these axes the frame end forces in modal analyze results is inconvenient.
- The equivalent earthquake loads results in structural walls near to the mass center are; frame end forces in earthquake direction much more inconvenient whereas in the shear walls far away from mass center the frame end forces in modal analyze results is inconvenient.

The important result is, frame end forces and modal analyze results occurred by the orthogonal to the earthquake direction are much bigger than the equivalent earthquake load results. This situation is explained as that the torsional irregularity resulting from earthquake loads identified more realistically by dynamic analyze. Although the major frame end forces are much bigger than the minor frame end forces, there hadn't been observed any effect for modeling.

The maximum irregularity coefficient is found η_b=1.529 when the absolute displacements are used. However the reason of the equality of this value and torsional irregularity coefficients which are calculated by the relative displacements is that the maximum value occurs in the basement floor. However, using the absolute or relative displacements in order to find out irregularity coefficient, does not affect the results. (2nd floor η_b=1.509; relative η_b=1.499).

11. Conclusions

Torsional irregularity can occur in the buildings that have regular geometrical shape and regular rigidity distribution. The reason of this irregularity which is called hidden torsional irregularity, is due to lack of rigidity along the extern axes. In certain cases, torsional irregularity can be lowered or totally removed as a result of decrease shear wall rigidity at central zone.

As a conclusion torsional irregularity is more related to the rigidity distribution than the geometrical plan of the building. For this reason, determination of the load carrying system of a structure is the most important issue at the planning stage of the project. It is essential that shear wall locations and cross-sectional areas must be properly selected, and the shear walls must be symmetrical in the plan in order to prevent torsional irregularity. Today, availability of the computer software makes the solutions more precise. The important issue at this subject is whether the load carrying system is appropriate to the behavior manner of the structure or not. However, it must not be forgotten that the behavior of the structure does not work always as expected. It should be known that planning and design stage is not composed only of structural analyze and sectional calculations.

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