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Performance Analysis of Steel Structures with A3 Irregularities

Ercan Işık[1] · Mesut Özdemir[2] · İbrahim Baran Karaşin[1]

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Abstract
Determination of the behaviour of structures during earthquakes is a very important engineering concern. Irregularities in the structure may lead to more damage imposed on it by weakening its defence mechanism during an earthquake. Some of these irregularities may be indentations or protrusions in the plan. Such irregular buildings may be encountered in practice because of various reasons. This study examined the state of irregularity by the A3 plan in the Turkish Building Earthquake Regulation of 2016. Four different A3-type irregularity cases were considered. The building with no irregularities in its plan was taken as the reference building. The five steel structures were compared by obtaining pushover curves for both the X and Y directions. Additionally, as a rapid assessment method, the Canada Seismic Screening Method was used in the study. Both in the rapid assessment method and from the pushover curves, it was determined that buildings without irregularities are safer. The study also allows a comparison among the earthquake performances of the structures using the rapid assessment method. It may be stated that there was an agreement between the two methods. This shows that the rapid assessment method may be used for steel structures. The importance of constructing structures that do not include irregularities is emphasized with the study. If one has to construct such structures, the defence mechanism of the structure should be strengthened by taking various measures.

Keywords Steel · Building · Regular/irregular · Plan · Pushover · A3

1 Introduction

Studying the durability of structures against earthquakes, determining the parameters that affect earthquake safety analysing them have gained even more importance with the influence of destructive earthquakes experienced in recent years. With these reasons, determining the earthquake behaviours of structures and their safety has been included among the current concerns of earthquake engineering. Considering the earthquakes experienced, heavy damages and collapses in structures show that these structures do not have sufficient safety. This is why it is important to know the factors that will affect the durability of structures against earthquakes while examining their behaviours under an earthquake. The factors are also considered in structural design. As the defencelessness of structures increase, the damage created by an earthquake will also increase. The magnitude of the earthquake, cases where structures failed to meet adequate levels of safety and conditions that are set forth in regulations, that is, structural characteristics, will affect the damage that may occur in the case of an earthquake directly. In the case that structural design is planned to be simple and regular, it will be easier to assess the behaviours of structures during an earthquake and conduct an analysis accordingly.

The basic rule of the design under an earthquake effect is that the load-bearing system is as plain and simple as possible to ensure that the earthquake behaviour of the building is predictable, because there are uncertainties in earthquake ground motion, structural modelling and structural element behaviour, as well as the approximations in analysis and design methods (TBDY 2016). The probability of damage to the buildings that are not taken care of during design and construction varies depending on the extent of the earthquake (Celep and Kumbasar 2004). There are some irregularities in the buildings especially due to various reasons during the design. The resulting

✉ Ercan Işık
eisik@beu.edu.tr

[1] Civil Engineering Department, Bitlis Eren University, 13100 Bitlis, Turkey

[2] Vocational School of Technical Sciences, Bitlis Eren University, 13100 Bitlis, Turkey

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structural irregularities affect the seismic performance of buildings (İnel et al. 2007; Jereen et al. 2017; De Stefano et al. 2014). Knowing the parameters which can negatively affect the earthquake performance of structures and taking special measures against them in an earthquake-resistant structure design will positively affect the defensive mechanism of the structures (Işık et al. 2016). Structural damage evaluation is an important aspect in the assessment of the inelastic response of structures subjected to large alternate actions. The nature and amount of structural damage depends on the nature of the loads acting on the structures and the quality of the materials that compose the structural and non-structural elements, on the type and configuration of structural systems (Hadzima-Nyarko et al. 2011). The factors that would reduce buildings' performances are available in quick building evaluations. Short column, irregularity in plan/torsion, soft/weak storey, vertical irregularity, year of construction, current situation and visual quality, building regulation/pounding, heavy overhangs and hill-slope effects are some of these negative parameters (DRBB 2013; NRCC 1993; Kaminosono 1992; Okada 1999; Gülay et al. 2010; Işık 2016; Bayraktar et al. 2013; İnel 2016; Işık and Kutanis 2015; Srikanth et al. 2014; Alam et al. 2012; Sucuoğlu 2007; Eleftheriadou and Karabinis 2012; Hadzima-Nyarko et al. 2014; Mirshafiei et al. 2017; Zülfikar et al. 2017; Hadzima-Nyarko et al. 2016).

One of these irregularities is protrusion irregularities in the plans of structures. There are many studies on concrete structures with irregularities of this type (Öncü et al. 2009; Ulucan and Alyamaç 2008; Gök 2013; Şahbaz 2005; Bosco et al. 2013; De Stefano and Pintucchi 2008; Herrera and Soberon 2008; Cancellara and De Angelis 2017; Jereen and Issac 2017; Pavese et al. 2017). However, studies on steel structures with plans that have protrusions are very limited (Han et al. 2017; Homaioon Ebrahimi et al. 2017; Homaei et al. 2017).

Pushover analysis is widely used for determining performance of structures in a possible earthquake. Pushover analysis captures the nonlinear behaviour of the building effectively and hence, it can trace the behaviour of the structure progressively up to failure. Pushover analysis can provide the most effective measurement of global behaviour of structures in terms of base shear capacity and displacement ductility of the structure (Biradar and Prasad 2017).

This study considered a steel structure with a plan that has protrusions. Calculations were made, first of all, in the case that the structure had a proper plan. Four different building plans were taken into consideration for the case of existence of protrusions in the plan. Calculations were made for the five different plans and pushover curves were obtained for each plan in both directions. The results were compared and suggestions were made for the case of the protrusion in the plan. The aim of the study is to demonstrate the effects of creating protrusion in the plan due to various reasons on the earthquake performance of a steel structure.

The study firstly provided information on the case of indentations and protrusions that may be encountered in structures. Provisions in regulations about the types of structures in which this may happen were presented. Information was provided about pushover analysis, which is used to describe the effects of an earthquake, and a pushover curve for an example structure was described. Detailed information was provided about the steel model which was selected for the calculations of the designed buildings due to its significance in design and assessment of material models. The Canada Seismic Screening Method was used in the study as a rapid assessment method. The five steel structures were compared by obtaining pushover curves for both the X and Y directions. The Canada Seismic Screening Method was applied on these buildings and it was aimed to calculate the effects of having indentations–protrusions in their plan in the fast assessment method. The study also allows a comparison between the rapid assessment method and the earthquake performances of the structures. The study aims to reveal the importance of building regular structures in terms of both assessment methods. It aims to explain extent to which the case of A3 irregularity, which will negatively affect the structure's defence mechanism, would influence earthquake safety. The study emphasizes the importance of building structures that do not have irregularities.

2 Classification of Irregularities and A3-Projections in Plan

In terms of earthquake behaviours, horizontal and vertical discontinuities and dramatic variations in rigidity and mass in structures are among factors that weaken structural defence mechanisms. Structures with these characteristics are accepted as irregular structures.

Irregularities in a structure can weaken the defensive mechanism of the structure during an earthquake, causing the structure to be damaged more. It is therefore necessary to avoid irregularities as much as possible during the design phase of a structure. However, irregular constructions processes can occur due to a number of reasons such as negative geometric conditions of the land to be used for construction, wishes of the owner of the building, architectural reasons and straying off the project during construction. In this respect, there is great importance in design, analysis and manufacturing based on the regulations that demonstrate basic elements in irregular structure design, and precautions increasing the defence mechanisms of such structures due to earthquakes in reducing possible loss of life and property.

The irregularities in a structure can be classified under two main categories as irregularities in the plan and vertical irregularities. The states of irregularity in the plan are divided into four (EC 8, 2005; TBDY 2016; TEC 2007; Celep and Kumbasar 2004). These are:

- Irregularity of structural system
- Irregularity in plan
- Discontinuity of floor system
- Irregularity in torsion.

This study considered the irregularity of indentation and protrusion in the plan. Due to various reasons, structures can be constructed in different geometries instead of simple geometries such as a square or a rectangle. It is recommended based on earthquake-resistant building design principles that large indentations or protrusions should be avoided as much as possible in the adjacent case building floor plans. The reason is that, if these sections are not separated from each other by joints, irregularities are defined in the earthquake regulations which have the aim of preventing excessive forces to build up in the sections where the geometry change occurs (Doğangün 2013). The case of the presence of indentation and protrusion in a plan is expressed as the A3 irregularity state in the Turkish Building Earthquake Regulation. A3-Projections in a plan: The cases where dimensions of projections in two perpendicular directions in plan exceed the total plan dimensions of that storey of the building in the respective directions by more than 20% (TBDY 2016; Herrera and Soberon 2008). A3-type irregularities are shown in Fig. 1.

Additionally, as different parts of the structure have an ability to move independently due to the effects of blocking in such structures, some sections experience straining. The different behaviours of the four different cases of irregularity are shown in Fig. 2.

3 Pushover Analysis

Pushover analysis is a common approach for determining seismic demand in building designs and evaluations (Hsiao et al. 2015; Estêvão and Oliveira 2015). A pushover curve is calculated from the static multiplier, obtained by application of the theorem of virtual work, considering kinematic varied configurations of the mechanism under study, in large displacements. Along with this incremental kinematic analysis, the contribution of links considered until reaching the ultimate equilibrium condition. The displacement capacity for each contribution is a threshold considered as a performance level of the system (Casapulla and Argiento 2016; Jalayer et al. 2015). Pushover analysis is frequently

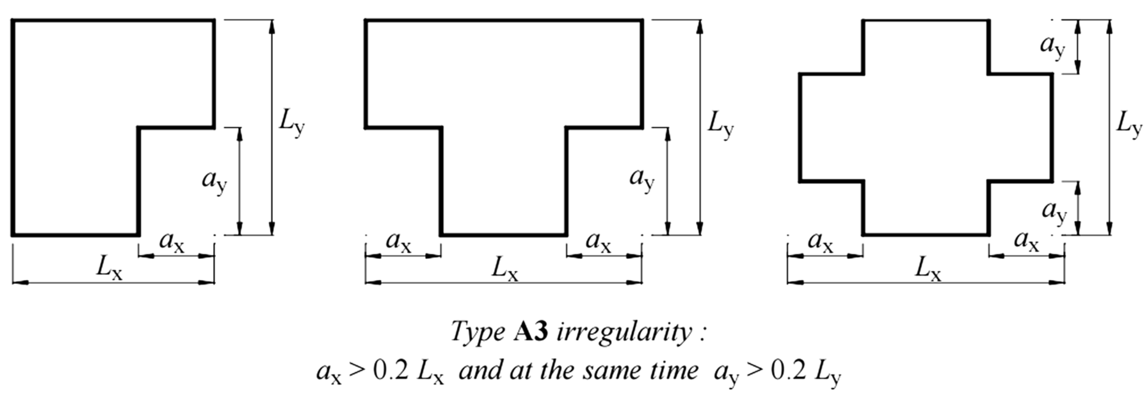


Fig. 1 Types of A3 irregularity

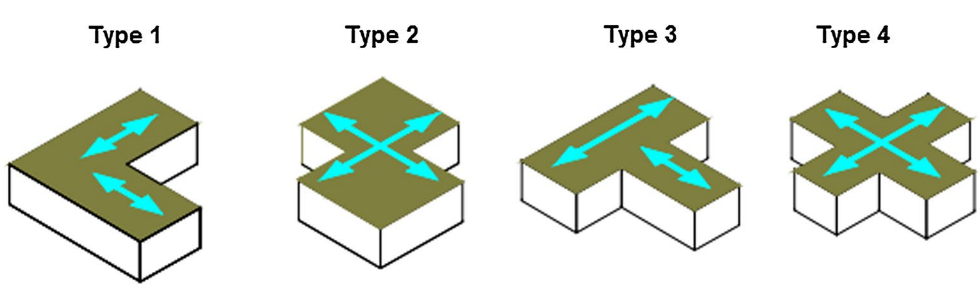


Fig. 2 Behaviours of the irregular structures

utilized to predict nonlinear behaviour of structural systems (Gholipour and Alinia 2016).

Pushover analysis is a static-nonlinear analysis method where a structure is subjected to gravity loading and a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behaviour until an ultimate condition is reached. Lateral load may represent the range of base shear induced by earthquake loading and its configuration may be proportional to the distribution of mass along building height, mode shapes or other practical effects (Computers and Structures 2011).

A capacity curve obtained from pushover analysis represents the relationship between the base shear force and the displacement of the roof. The base shear is normalized by building seismic weight while the roof level displacement is normalized by building height to represent the shear strength coefficient and roof displacement drift, respectively. A typical example of an idealised capacity curve is shown in Fig. 3 (İnel and Meral 2016).

In the presented method, the pushover curve is represented by two straight segments. In the method, the yield point is determined first, the base shear force at the yield point (VT_{yield}) is taken approximately as the design base shear force, the top point displacement design is considered as the principal roof displacement. The base shear force (VT_{target}) is determined using the dynamic characteristics of the moment of dislocation when the apex of the endpoint of the drawn equivalent pushover curve is determined as the target displacement.

4 Material Model and Description of the Structure

Mathematical models are used for describing the stress–strain relationship for any material. A material model has a very important role in seismic analyses of structures (Işık and Özdemir 2017). The calculations in this study were made using the Menegetto–Pinto steel model (stl_mp) (Menegotto and Pinto 1973).

This model proposed by Menegotto and Pinto is widely used to simulate the cyclic response of steel structures and steel bars of reinforced concrete structures (Bosco et al. 2014). This is a uniaxial steel model initially programmed by Yassin (1994) based on a simple, yet efficient, stress–strain relationship proposed by Menegotto and Pinto (1973), coupled with the isotropic hardening rules proposed by Filippou et al. (1983). The current implementation follows the one carried out by Monti et al. (1996). An additional memory rule proposed by Fragiadakis et al. (2008) is also introduced, as higher numerical stability/accuracy under transient seismic loads should be confined to the modelling of reinforced concrete structures, particularly those subjected to complex loading histories, where significant load reversals might occur. As discussed by Prota et al. (2009), with accurate calibration, this model, initially developed with ribbed reinforcement bars in mind, can also be employed for modelling of smooth rebar's, that are often found in existing structures. The stress–strain relationship for this steel model is given in Fig. 4.

Ten model-calibration parameters must be defined in order to fully describe the mechanical characteristics of the material (Table 1).

Structural steel is used for a variety of types of structures ranging from residential buildings to industrial plants, from mill buildings to cranes and from transmission towers to silos (Ballio and Mazzolani 1983). I300 profile was selected for all columns and beams used in the steel frame building designed and investigated in this study. The cross-sectional

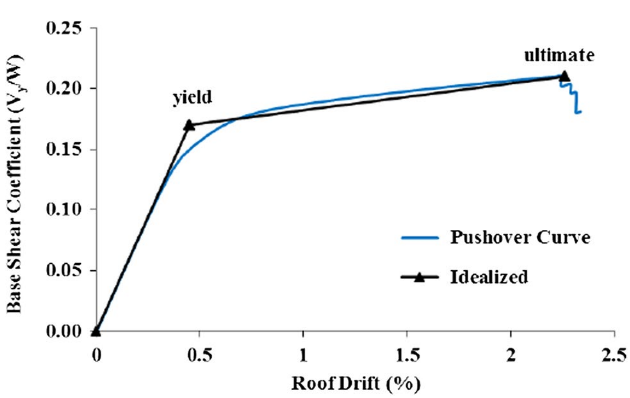


Fig. 3 Typical pushover and idealised capacity curves (İnel et al. 2016)

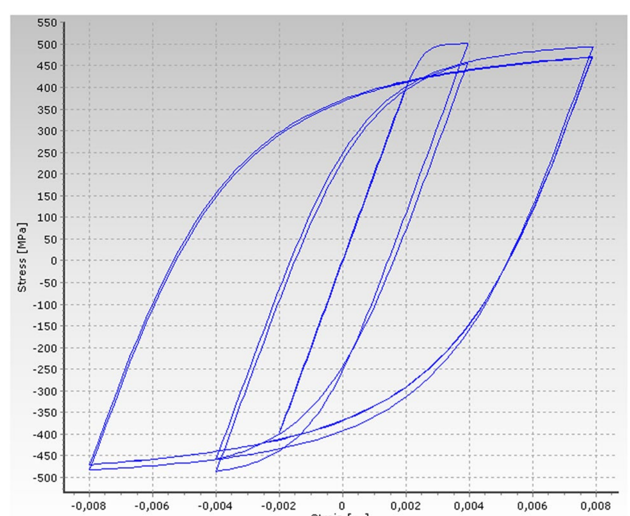
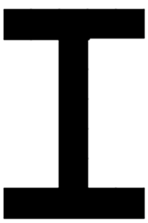


Fig. 4 Stress-strain relationship for the Menegetto-Pinto steel model (Antoniou and Pinho 2003)

Table 1 Modal-calibration parameters for the Menegetto-Pinto steel model

Material properties	Typical values	Default values
Modulus of elasticity (Es)	2.00E+08–2.1E+08 (kPa)	2.00E+08
Yield strength (fy)	230,000–650,000 (kPa)	500,000 (kPa)
Strain hardening parameter (U)	0.005–0.015 (–)	0.005 (–)
Fracture/Buckling strain		0.1 (–)
Specific weight—(Gama)	78 (kN/m3)	78 (kN/m3)
Transition curve initial shape parameter (Ro)	20 (–)	20 (–)
Transition curve shape calibration coefficient (A1)	18.5 (–)	18.5 (–)
Transition curve shape calibration coefficient (A2)	0.05–0.15 (–)	0.15 (–)
Isotropic hardening calibration coefficient (A3)	0.01–0.025 (–)	0 (–)
Isotropic hardening calibration coefficient (A4)	2–7 (–)	1 (–)



Upper and lower flange width	200 mm
Upper and lower flange thickness	15mm
Body height	300mm
Body thickness	15mm

Fig. 5 Dimensions and cross section of structural elements

representation and the dimensions of the selected profile are shown in Fig. 5.

All geometric conditions of the A3 irregularity in the Turkish Building Earthquake Regulation as of 2016 were taken into consideration. Calculations were made initially for the steel structure with no irregularity. At the same time, it was chosen as the reference building to be able to make comparisons with buildings that have irregularities. The geometric representations of the selected buildings are shown in Fig. 6.

The blueprint of the building which has no irregularity is given in Fig. 7. The structure was chosen have 7 spans in the X direction and 5 spans in the Y direction. The supporting systems were chosen as a total of 4 floors made up of a ground floor and 3 normal floors, and the heights of all floors were taken as 3 m.

The blueprints of the buildings with A3 irregularities are given in Fig. 8.

The 3-D models of the buildings are given in Fig. 9.

5 Analysis Results

A comparison of the pushover curves in the X direction for the steel frame buildings of types of is shown in Fig. 10.

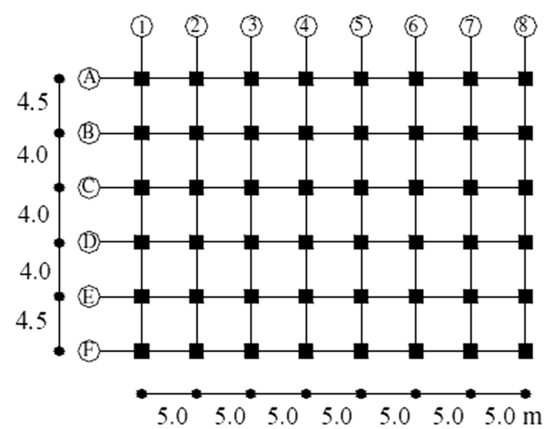


Fig. 7 The blueprint of reference building

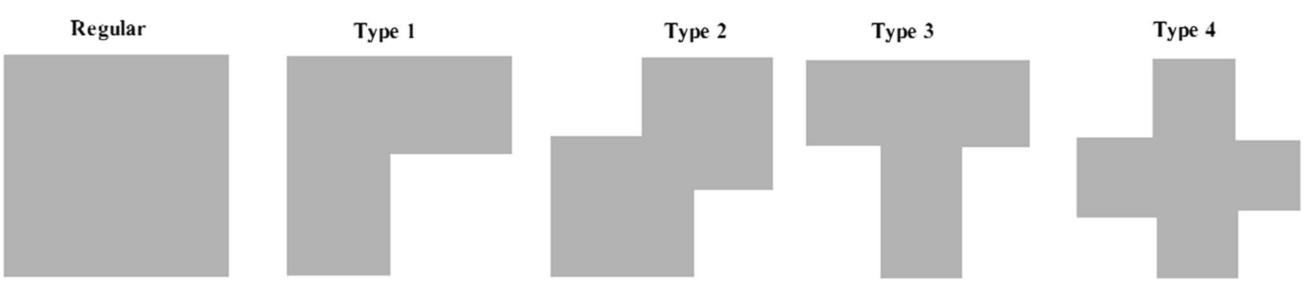


Fig. 6 Geometric representations of selected buildings

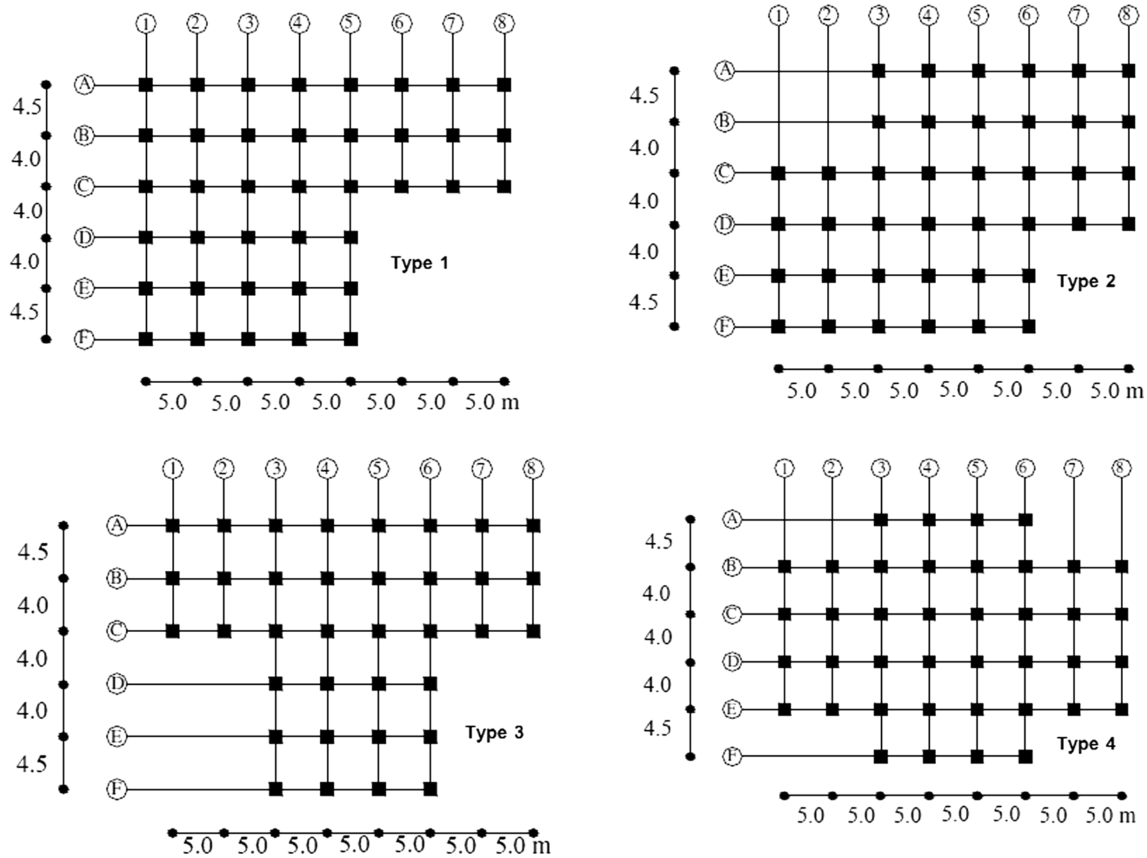


Fig. 8 The blueprints of A3 irregularity buildings

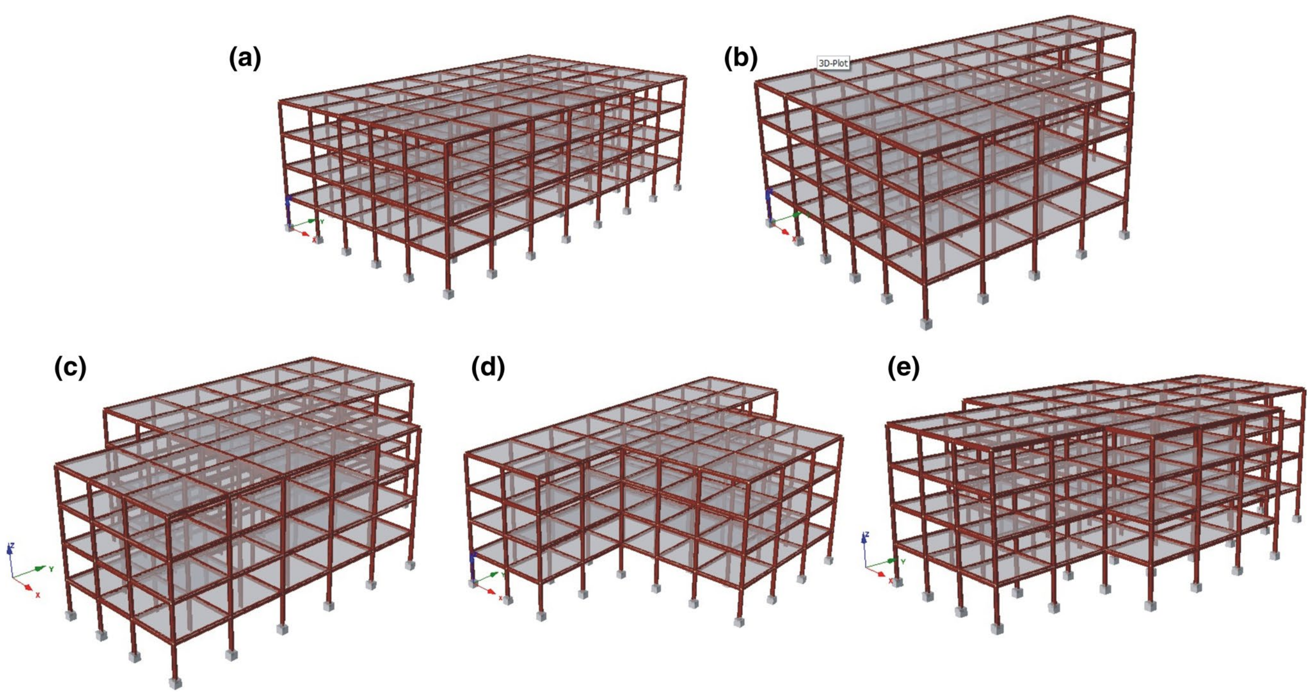


Fig. 9 3-D model of buildings **a** reference, **b** type 1, **c** type 2, **d** type 3, **e** type 4

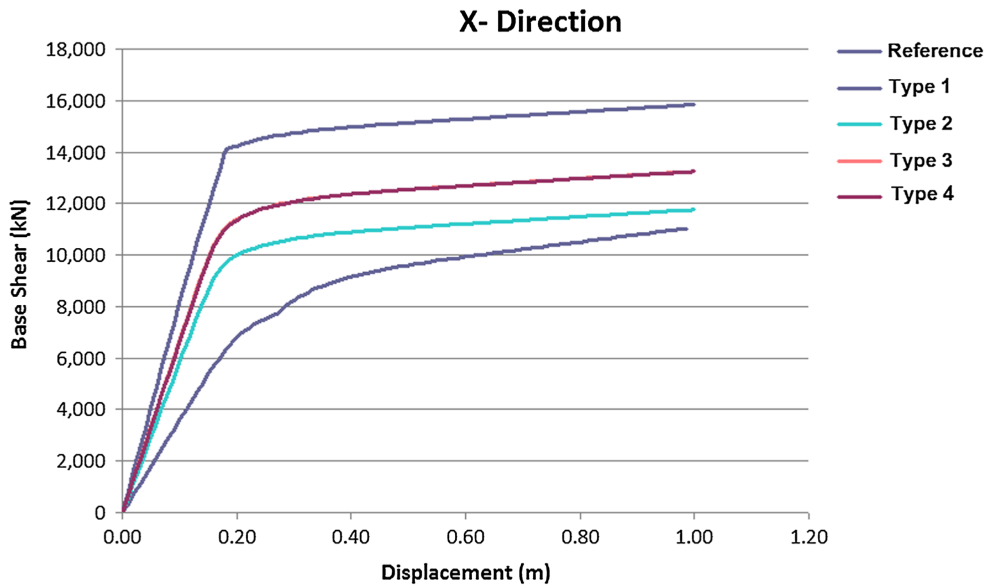


Fig. 10 Comparison of pushover curves for X direction for different steel models

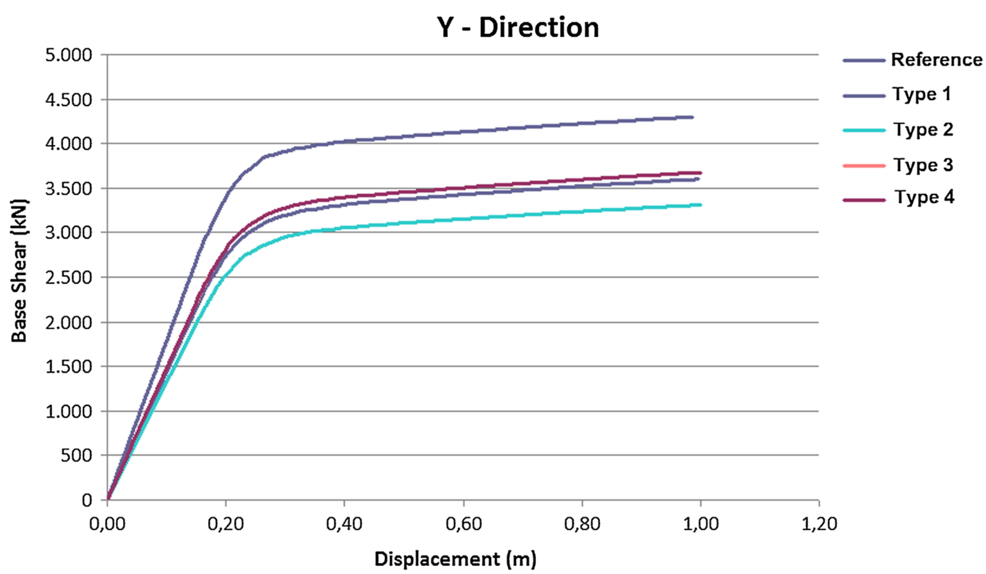


Fig. 11 Comparison of pushover curves for X direction for different steel models

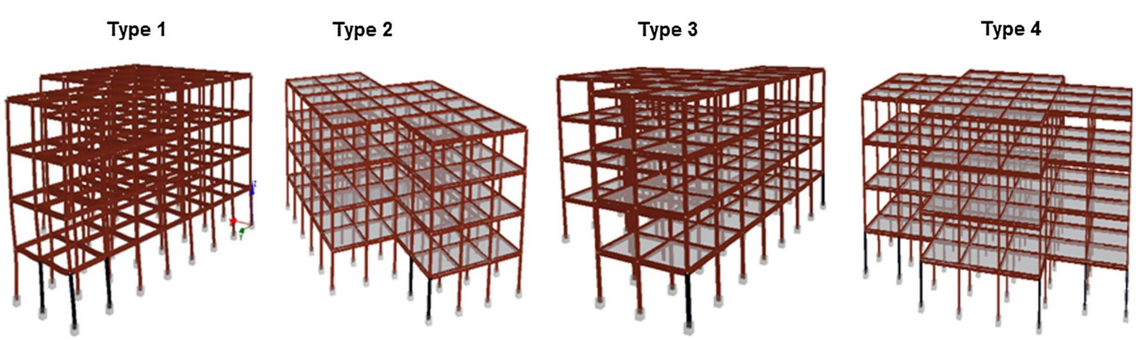


Fig. 12 Initial states of damage in the buildings with irregularities in X direction

A comparison of the pushover curves in the Y direction for the steel frame buildings of different types is shown in Fig. 11.

Figure 12 shows the initial damage conditions in X directions for each case of irregularity discussed in the study.

Figure 13 shows the initial damage conditions in Y direction for each case of irregularity discussed in the study.

In the study, calculations were also made according to the Canadian Seismic Screening method for the irregularity condition in the undertaken plan. The proposed method in line with the principles published by the National Research Council of Canada is considered to be the first step of a multistage review and includes the numerical preliminary assessment of the earthquake risk in each building in the building group being examined. After numerical evaluation, a more extensive study must be made based on the order of priority (NRCC 1993; Foo and Davenport 2003; Çelik et al. 2007; Işık 2015).

In this method, each parameter was named with a letter. Each parameter was calculated by using the coefficient given in the Canada Seismic Screening Method. In the first step, the structural index (SI) was calculated as;

$$SI = A * B * C * D * E * F \tag{1}$$

Then non-structural index (NSI) was calculated for each building as;

$$NSI = B * F * G * H \tag{2}$$

The seismic priority index was calculated as the sum of the structural index and non-structural indices as;

$$SPI = SI + NSI \tag{3}$$

The results were compared to limit values given in Table 2 for deciding on the priority of the building.

Since horizontal irregularity was examined in the study, all values related to the structure were taken as the same but this irregularity value was changed. The A value was assumed 5, because the building was considered to be built in a high-risk zone. For the coefficient B, which describes the properties of soil on in which the building is constructed, the soil type was assumed to be rock, so the B value was taken as 1. The ductile was considered the load-bearing system and the C value was taken as 1. For the parameter D, the flooring was regarded as diaphragm and this value was taken as 1. Considering 10–300 people as the number of people living in the building, the coefficient of F was added to the calculation as 1.5. The visual quality of the construction was considered as well and the G value was accepted as 1. The parameter H is used to take non-structural factors into account and it was taken as 1. All these parameters were taken as the same for both the reference building and all the types that contain irregularities in the plan considered in the study. However, the coefficient E containing the irregularities in the structure was taken as 1 for the reference building, whereas it was taken as 1.5 for the other types. When the parameter E was calculated for all the examined structures, only the irregularity considered in the design was taken into account and other irregularities were assumed to be non-existent. The results of the Canadian seismic survey method for the 5 different structures are shown in Table 3.

Table 2 Priority levels for buildings in the Canada Seismic Screening Method (Çelik et al. 2007)

Score type	Limit values	Evaluation
SI or NSI	1.0–2.0	Sufficient seismic safety
SPI	< 10	Low priority buildings
SPI	10–20	Middle priority buildings
SPI	> 20	High priority buildings
SPI	> 30	Very hazardous buildings

Table 4 shows the comparison of the maximum base shear forces obtained from the pushover curves calculated for the X and Y directions for all structures examined in the study.

In comparison to the regular structure, the maximum base shears forces decreased by 17% in the Y direction and

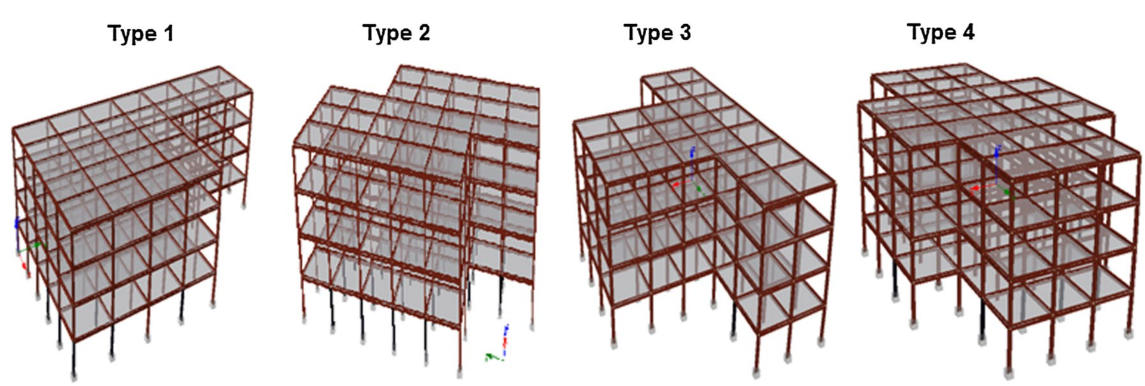


Fig. 13 Initial states of damage in the buildings with irregularities in Y direction

by 22% in the X direction. This appears to be a sufficient result to demonstrate the necessity of regular construction. The highest decrease in the X direction was found in Type 1, while the highest decrease in the Y direction was found in Type 2. As Type 3 and Type 4 had symmetry, the values for the X and Y directions were highly close to each other. Type 3 and Type 4 had the lowest amount of change in both perpendicular directions. It was found that Type 1 and Type 2 had lower levels of earthquake resistance in comparison to Type 3 and Type 4 (Fig. 14). This shows the importance of designing buildings symmetrically. Structural defence mechanisms of irregular buildings with symmetry are affected less. As the centre of rigidity will get further away from the centre of mass in irregular structures, the torque will create additional shear forces on vertical load-bearing structures. These will affect the earthquake resistance of the structure negatively. The torsional effect that will be created by these additional forces in irregularly constructed buildings should also not be ignored. Presence of indentations–protrusions in the plan will also lead to irregular upholstery. In systems with irregular upholstery, shear forces occur within the upholstery. The upholstery will be forced more due to these additional shear forces.

Considering the initial damage situations of the irregular steel structures in the study, it may be seen that all initial damages occurred on the areas in the plan that contained protrusions.

Table 3 Results of assessment using Canada Seismic Screening Method

Building name	A	B	C	D	E	F	G	H	SI	NSI	SPI	Risk status	Priority
Reference	5	1	1	1	1	1.5	1	1	7.5	1.50	9.000	Low	5
Type 1	5	1	1	1	1.5	1.5	1	1	11.25	1.50	12.750	Middle	4
Type 2	5	1	1	1	1.5	1.5	1	1	11.25	1.50	12.750	Middle	3
Type 3	5	1	1	1	1.5	1.5	1	1	11.25	1.50	12.750	Middle	2
Type 4	5	1	1	1	1.5	1.5	1	1	11.25	1.50	12.750	Middle	1

Table 4 Comparison of the base shear forces

Building name	X direction		Y direction	
	Base shear (kN)	Difference	Base shear (kN)	Difference
Reference	15,842.667	0	4293.179	0
Type 1	11,034.478	30%	3598.226	16%
Type 2	11,765.495	26%	3307.748	23%
Type 3	13,250.93	16%	3675.235	14%
Type 4	13,241.643	16%	3674.843	14%

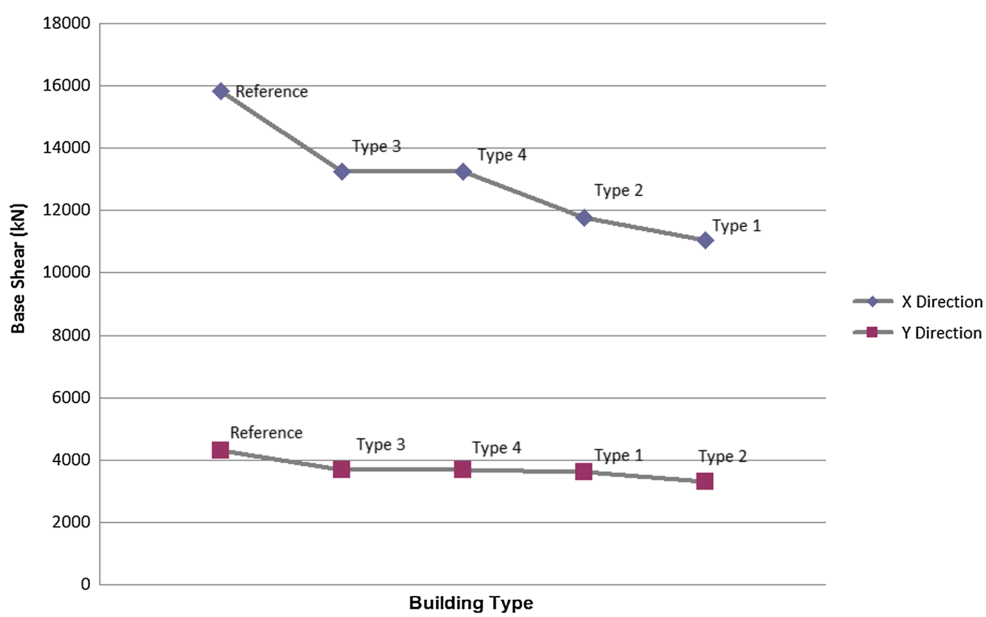


Fig. 14 Comparison of the maximum base shear forces of the buildings

In terms of the area they covered in the structural plan, Type 1, Type 2 and Type 3 were similar to each other. The greatest area was covered by Type 3 due to the empty spaces in the plan. In the light of this information, it may be stated that the area of the empty in the plan is not a highly effective parameter. All buildings examined in the study consisted of four storeys. Increasing the number of storeys will change the results.

The Canada Seismic Screening Method revealed that presence of indentations and protrusions in a plan increased the total score (SPI) of the structure by 40% and its structural index (SI) by 33%. In this method, the direction and amount of indentations and protrusions in the plan are not considered. The method considers the presence of these. This is in agreement with the general logic of fast assessment methods. As a result of this, this value was found to be the same for the four different cases of irregularity (Fig. 15).

6 Conclusions

This study, focused on irregularities in the plan of a structure among negative parameters that may damage it. Information was provided about the irregularities that may be found in a structure.

This study examined states of the irregularity based on A3 plan in the Turkish Building Earthquake Regulation. The cases of indentation and protrusion in the structure were examined separately by modifying the floor pattern plan of a selected steel structure. Pushover curves were obtained for the selected plans. The results were obtained, and recommendations were made.

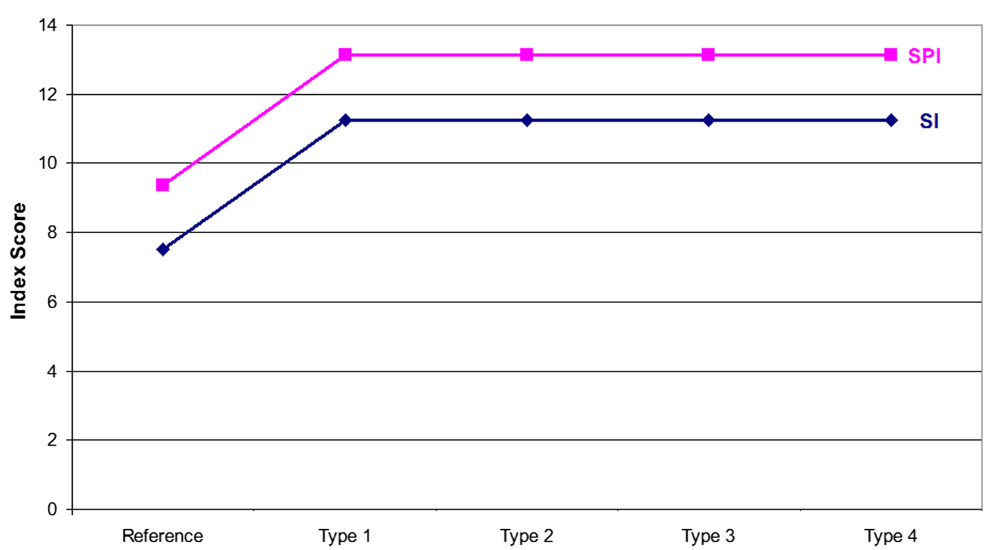
Since the Type 3 and Type 4 plan irregularity areas were very close to each other, the pushover curves were very close to each other in both directions. Irregularity in a construction plan reduces the performance of the construction in several ways. As the irregularities change in the X and Y directions, the base slicing forces also change.

According to the results obtained by applying the Canadian Seismic Scanning Method, which is a rapid evaluation method, the irregularity state in the plan is affected the defensive mechanism of the structure negatively. In this method, there is no value of where the irregularity state in the plan is. A single value is recommended for each irregularity in the plan. However, the static pushover curves show the importance of where the irregularity in the plan is.

As the vulnerability of structures increases under earthquake effects the amount of damage that can occur also increases. In this context, this emphasizes the importance of building design and regulation provisions. Structural systems that do not contain irregularities, designed in compliance with regulations and are effectively quality-controlled during the construction stage can display ductile behaviour even in a very severe earthquake, thereby achieving damage within acceptable boundaries. It is necessary to avoid negativity parameters that are found and will be found in both the design and construction stages. Each negativity will adversely affect the defence mechanism of the structure against earthquakes.

Presence of irregularities in structures is an unfavourable situation and it is recommended to avoid this situation as much as possible. In irregular buildings, which are expected to be encountered occasionally in practice, some precautions must be taken to reduce the negative effects of irregularity. Separating the structures which have defected geometry and which may be affected by torsion where irregularities are large with appropriate earthquake joints may compensate the geometric defects. Joints between blocks in new buildings should be constructed in accordance with the regulations. Irregularities on buildings may be taken into account in the

Fig. 15 Comparison of the final scores of the buildings



same way for concrete and steel structures without any discrimination. Since the damping ratio of steel structures is smaller than that of concrete structures, it will be appropriate to treat steel structure joints more tolerantly. By leaving the earthquake joints and dividing the structure into sections, one structure will be provided with the ability to behave as multiple independent structures. What is important here is that horizontal displacement levels, which are to be shown by structures that act independently should not cause any damage on the other sections that are considered to act independently. Therefore, it is important to leave earthquake joints as appropriate. Otherwise, although the irregularity in the plan is removed, the interactions of the separated structures due to horizontal displacements can increase the amount of damage. It should not be forgotten that building blocks separated by structural joints carry the risk of collision damage in an earthquake. The joints between building blocks should be arranged in such ways that, during an earthquake, the blocks can operate in all directions independently from each other. Therefore, the earthquake joints described in the regulations must strictly adhere to the rules.

Additionally, attention must be paid to eccentricity, which forms between the centre of mass and the centre of rigidity in structures that are irregular in their plans. An increase in the eccentricity between two centres will also increase the torsional moments due to an earthquake. This then causes the structure to experience more difficulty. It is important for earthquake-resistant construction design that structures are designed in their plan to be as simple and symmetrical as possible in order to minimize the effects of torsional loads on structures with irregularities in their plan.

A structure with a regular load-bearing system was selected in the study. It should be kept in mind that load-bearing system irregularity combined with irregularity in plans will decrease the durability of structures against earthquakes even more.

The study examined only the case of whether or not there are indentations and protrusions in the plan. Future studies will aim to reveal the extent to which the amounts of indentations and protrusions will affect structural performance. Moreover, the changes in the width and depth values of the structure on the plan should be additionally taken into account.

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