Vertical Structural Irregularities in Earthquake Codes within the Scope of Architectural Design

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ABSTRACT

In this study vertical structural irregularities which are often inevitable due to building requirements and architectural imperatives, and having a major impact on building costs are investigated. First of all, in the light of the comprehensive literature review, a wide classification of structural irregularities in the vertical plane resulting from the decisions taken in the architectural design phase has been made. Within the scope of structural irregularity definitions in vertical plane; earthquake codes of the countries having different seismic experience; Turkey, China, Iran, New Zealand, Mexico, India regulations; Eurocode-8 and ASCE/SEI 7/10 standards used by European countries with active fault lines have been examined in detail. Presence and the limits for each structural irregularity were compared in tables. In addition to this, the visual expression techniques of vertical structural irregularity definitions in the aforementioned regulations were examined to draw attention to the necessity of these in terms of understanding the regulations by architects. A detailed evaluation, which is enriched with visuals on vertical structural irregularities, has been carried out in order to create consciousness in architects and architecture students who are the target audience of the study. In order to prevent the seismic codes which contains a lot of formulas and calculations as a result of their nature, to be seen as information that should be memorized, common design decisions that may cause structural irregularities, and the measures that may be taken against these irregularities are presented. Each title is supported by simple but descriptive drawings because of the better understanding of the visual forms in human perception.

Keywords: Architectural design, Earthquake code, Earthquake resistant design, Vertical structural irregularity.

1. INTRODUCTION

The first written theory book in history, "The Ten Books on Architecture" by Vitruvius, states the three main components for a successful architecture as "durability, utility, and beauty". When these three fundamental principles are compared, an architectural structure first needs to be durable and has to endure all static and dynamic loads which are applied during its entire lifetime, so that other two fundamental components can also be long-lasting. The most unpredictable dynamic load a structure can be exposed to is an earthquake, which is one of the most destructive of natural disasters. The most important role in preventing an inevitable earthquake from turning into a tragedy belongs to the structural system which will ensure the durability of the structure from the design stage until the end of its expected lifetime.

The cornerstone of the ability to cope with natural disasters, which is the most important indicator of a civilized country, is a rational structural system that is presented in accordance with architectural design. It is expected that architects have sufficient understanding how earthquake affects the structure, because the structural system design not only contributes to the form and aesthetics of the structure, but it also determines the distribution of earthquake loads throughout the building; and it even affects the relative magnitude of the seismic forces. The most important point for a good seismic performance is being "regular" in the design of load-bearing system, in other words, exhibiting optimum or ideal behavior against seismic forces (Harmankaya and Soyluk, 2012).

The structural irregularities that affect the behavior of the structure under static and dynamic loads or its resistance to these loads vary widely with the design. In the literature, the most indisputable source in the definition of these irregularities in accordance with geometric decisions and corresponding dynamic calculations is the earthquake codes (De Stefano and Pintucchi, 2008). These codes developed by each country with their own experience are the legal documents that determine the minimum conditions for the production of seismically safe and functional buildings. The purpose of earthquake codes is to prevent the exposure of the structures to adverse conditions under the dynamic loading described according to the area in which they are located. However, there is a widespread belief that earthquake resistant building production is related to engineering calculations (Özmen,2008) and earthquake codes contain a technical language and mostly address the areas of civil engineers (Özmen and Ünay, 2007). However, the investigations made after the major earthquakes in the last 20 years show that this widespread belief is incorrect and when the building damage is examined, many buildings are observed to become unusable due to the decision taken during the architectural design process (Özmen, 2008; Öztürk, 2011). The documented result brings about the necessity that the earthquake codes should be a directing technical specification for the architects as the structure is formed at the architectural design stage and the preliminary design parameters are chosen by the architects.

The term "regularity" guided by earthquake codes aims to find appropriate solutions to the seismic behavior of buildings rather than symmetrical and repetitive solutions limited by strict rules (Mezzi et al., 2004). There is a strong relationship between the architectural design of a building and its structural behavior during the earthquake. However, in some cases, structural irregularities are inevitable due to architectural difficulties, functional requirements or design authenticities. Although codes, in line with their own philosophy, recommend the construction of regular buildings, they also avoid introducing a prohibitive provision for irregular buildings. The greatest reasoning for this is to leave architects as free and creative as possible in their design originality. However, it should be kept in mind that the laws of nature and physics demolish the designs that ignore the loads that the structures will be exposed (Tezcan, 1998). At this point, the codes impose penalties for buildings with structural irregularities that are classified as horizontal and vertical. This execution is mostly to refine the calculation method and therefore to increase the cross-sectional effects on the structural elements. As a result of these regulations; irregular building designs that are kept on the safe side by increasing size and reinforcement, adding new structural elements, increasing the material strength are allowed. However, interventions to prevent the negative effects of the earthquake increase the building costs, which is an important parameter in evaluating the function and performance of a building (Tuna, 2000; Dražić and Vatin, 2016). The product of architecture differs from other sectors in terms of being large scale and having large budgets. The most efficient use of the budget in construction projects is very important for many people or organizations that are the component of the sector (İlerisoy and Tuna, 2018), and structural irregularities should be avoided for the projects implemented in earthquake regions in order to reduce the costs.

Vertical structural irregularities, which are often inevitable due to the use of buildings and architectural necessities that have a great impact on building costs, are the subject of this study. The aim of this study is to provide a consciousness on how the design decisions in the vertical plane are addressed in the current earthquake codes and to create a guiding source for the discipline of architecture. In this direction, in order to reinterpret the knowledge of the architecture against the earthquake which is an unchanging fact and to have the equipment that the architects can use effectively in this regard, the earthquake regulations are handled with an architectural perspective.

2. METHOD

Architectural design is not just an arrangement where the search for aesthetics and functionality are fulfilled only in the plan arrangement. On the contrary, a structure creates its first effect on people by means of its design along its vertical direction. In parallel with the first visual effect, the design decisions taken along the height of the buildings have an important effect in earthquake performance. Therefore, structural irregularities in the vertical plane of architectural design are examined in detail. Vertical structural irregularities, which make buildings vulnerable to horizontal forces and cause additional increases in cost, are defined according to static and dynamic calculation methods in seismic codes; however, most designs are formed with architecturally constructed configurations. For this reason, the structural irregularities caused by the decisions in the vertical plane must be taken into consideration in the preliminary planning stage of the architectural design. In this respect in the light of the comprehensive literature research, a broad classification of irregularities formed as the results of architectural design decisions on the vertical plane has been made. Firstly, vertical structural irregularity limits which are changed according to different earthquake codes are investigated. The current earthquake code data of the countries included in the International Association for Earthquake Engineering (IAEE, 2018) were used. Regarding the regulations reviewed; the earthquake codes of the countries written in their own languages (Spain, Ecuador, Russia, Colombia, Thailand, the Republic of Dominican, Colombia) and earthquake codes of the countries that cannot be reached within the academic internet network (Croatia, Pakistan, Singapore, Armenia, Ukraine, Canada and Montenegro) are excluded from the scope of this study. Earthquake codes of countries such as Nepal, Argentina, Romania, Ghana, Uganda, Switzerland, Egypt, Taiwan, Nicaragua and Japan were also excluded from the study because of the lack of explanations under the heading of structural irregularities. As a result, Eurocode-8 (CEN, 2004)and ASCE/SEI 7-10 (ASCE, 2016)standards used by the European countries located on active fault lines and the codes of countries with different seismic experiences which are Turkey (AFAD, 2018), China (MOHURD, 2010), Iran (BHRC, 2007), New Zealand (NZSEE, 2014), Mexico (FDGM, 1995), India (BIS, 2002) earthquake codes were examined in detail (Figure1).

In the light of the classification made, the conditions and limits of existence for each structural irregularity in the mentioned codes have been made into tables and compared. In this study, which deals with 8 earthquake regulations in total, the intersection points and differences of the decisions formed with different seismic experiences have been revealed.

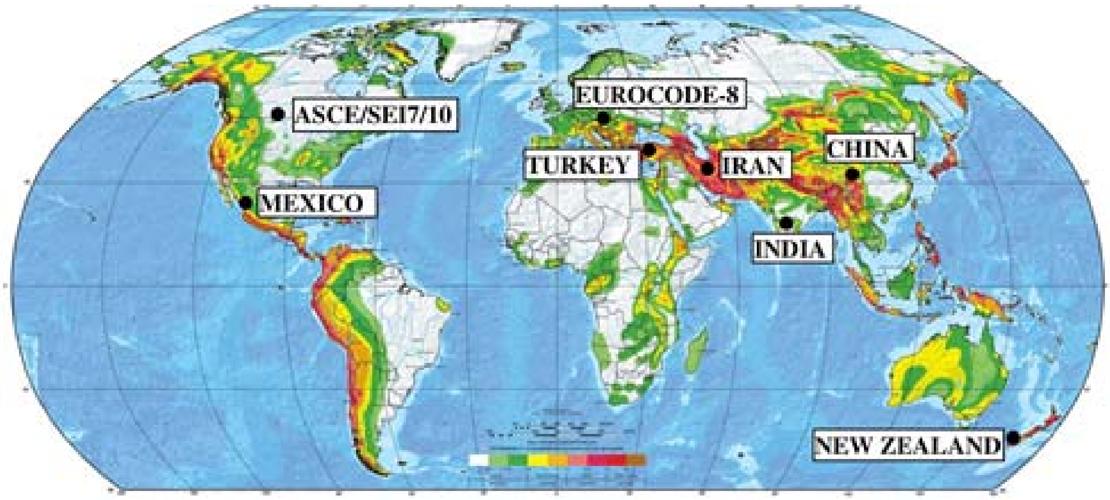

Figure 1. Map of global seismic hazards and the countries covered by the study (Alden, 2017)

During this examination, it is an important criterion that the earthquake codes should be addressed to architects as well as the engineering discipline. Architects participating to the working life after graduating from the Architecture Department of Universities stated that they faced a “wall” that was never mentioned in the education period as they encountered earthquake codes (Ankara Chamber of Architects, 2007). Basically; the biggest difficulty experienced by the architects who encounter earthquake regulations is to interpret the restrictions introduced by definitions and formulas and to make them effective on the products they produce in the architectural design process. The use of visual expression techniques for the design configurations defined by these regulations with a technical language will help to externalize the images created in the architectural design process. In addition, visual models will help the designer in the decision-making process and provide a great convenience to the students in terms of educational functions (Özcan, 1994). In the light of this information, the visual representation techniques of vertical structural irregularity definitions in 8 different earthquake codes were examined.

After the study, a detailed evaluation, which is enriched with visuals on vertical structural irregularities, has been carried out in order to create consciousness in architects and architecture students who are the target audience of the study. In this evaluation, common design decisions that will create irregularities, the difficulties that the irregularities will cause and the measures that can be taken against these irregularities are presented. Each title is supported by simple but illustrative illustrations because of the better understanding of the visual expression in human perception.

3. ANALYSIS OF VERTICAL STRUCTURAL IRREGULARITIES ACCORDING TO DIFFERENT EARTHQUAKE CODES

Damages caused by the effect of earthquake loads emerges firstly at the weak points in the structural system and the main reasons of this weakness are the defects of structural system design resisting to lateral earthquake loads. One of the main causes of building damage and collapse during the earthquake is, as previously mentioned, the structural irregularities caused by architectural design and it could be given many examples of damaged structures having vertical structural irregularities in past earthquakes (İnel et al., 2008; Kim and Elnashai, 2009). In this respect, architects should estimate where earthquake damage might occur in a building's structural system in the design phase.
In this study, vertical structural irregularities formed due to different reasons are examined under three main headings as a result of comprehensive literature reviews:

(1)Inter-storey irregularities; (a) stiffness irregularity (soft storey),
(b) mass irregularity,
(c) strength irregularity (weak storey),
(2) Vertical lateral force-resisting elements irregularity
(3) Vertical geometric irregularity

In this chapter, firstly, the importance of each title is mentioned, the definitions of all types of structural irregularities in the seismic codes are given in tables and architectural design decisions causing these irregularities are explained by examples. Afterwards, each irregularity is visualized by simple but descriptive drawings so that the earthquake codes can be understood clearly by the architects.

3.1. Inter-storey irregularities

One of the most important architectural design errors causing damage on structures during the earthquake is to create sudden changes between adjacent floors. The difference in floor heights, the removal of the partition walls on any floor, the change of the vertical structural member dimensions or the materials used at the basement according to the upper floors for commercial purposes are the examples that cause sudden changes between adjacent floors. To understand whether these irregularities are present in the buildings earthquake codes are used and these codes also contain guiding criteria to take the necessary countermeasures.Irregularities related to the adjacent floors are examined under the sub-headings of (a)stiffness irregularity (soft storey), (b)mass irregularity, (c)strength irregularity (weak storey).

(a) Stiffness irregularity (soft storey)

One of the most important points of the structural design is the stiffness of the system. The more rigid the structure is, the lower the second-order moment effect that will occur when it is subjected to the loads in the horizontal and vertical directions and thus the displacements that may occur will remain at the minimum level. This situation is mostly related to the elements carrying the loads in the vertical direction. The fact that the floor height in the installation floors and generally in the basement floors are different than the other floors, the situation thatthe column length in any floor is less than the other floors and the removal of the partition walls to increase the visuality in the ground floors for commercial purposes are the basic design decisions. The sudden reduction of the rigidity of the storey resulting from architectural and technical reasons causes the non-elastic behavior in the structural members to concentrate at the top of the columns (Tuna, 2000). These storeys are weaker than the upper storeys in terms horizontal displacements (Guevara-Perez, 2012). The most important problems of *soft storey irregularity* due to architectural design decisions are the limited ductility due to the occurrence of hinges at columns, the concentration of all energy consumption in one floor and the difficulties of repair after damage. The relevant definitions under the chapter of stiffness irregularity in the seismic codes and standards examined are given in Table 1.

Table 1. The definitions of stiffness irregularity (soft storey) in the different earthquake codes and standards

	Definitions
TBDY-2018	The case where in each of the two orthogonal earthquake directions, except basement floors, Stiffness Irregularity Factor η_{ki}, which is defined as the ratio of the average storey drift at any storey to the average storey drift at the storey immediately above or below, is greater than 2.0. Storey drifts shall be calculated by considering the effects of ± %5 additional eccentricities.
CHINA	The lateral rigidity of this storey is less than 70% of the adjacent upper storey or less than 80% of the average lateral rigidity of the adjacent three storeys.
IRAN	The lateral stiffness of each story shall not be less than 70% of that in the story above or 80% of the average stiffness of the three stories above. The story not complying with these, is considered a "flexible story".
NEW ZEALAND	(severe)- Lateral stiffness of any storey < 0.7 of lateral stiffness of any adjoining storeys; (significant)- < Lateral stiffness of any storey < 0.9 of lateral stiffness of the adjoining storeys; (insignificant)- Lateral stiffness of any storey ≥ 0.9 of lateral stiffness of the adjoining storeys.
INDIA	Soft storey is one in which the lateral stiffness is less than 70 percent of that in the storey above or less than 80 percent of the average lateral stiffness of the three storeys above. Extreme soft storey is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70 percent of the average stiffness of the three storeys above. For example, buildings on STILTS will fall under this category.
ASCE/SEI 7/10	Stiffness-soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. Stiffness-extreme soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above.

In the light of the codes and standards examined, stiffness irregularities are defined according to the horizontal stiffness of the storeys by using the earthquake load design criteria of each seismic code. However, the ranges of the limit values are different. In the Turkish Earthquake Code, average *storey drift ratio* is used; in the codes of China, Iran, New Zealand, India and ASCE; *the ratio of the horizontal stiffness of a floor to the stiffness of the adjacent floor* is defined as stiffness irregularity. Also, a detailed classification is made as severe, significant and insignificant, according to the value of the stiffness ratio in the New Zealand code. However, the Mexican code and Eurocode-8 do not give a definition of this significant irregularity. In terms of addressing the architects; only New Zealand and India codes contains explanatory images that increase the levels of perception and providing interactive learning opportunities (Figure 2).

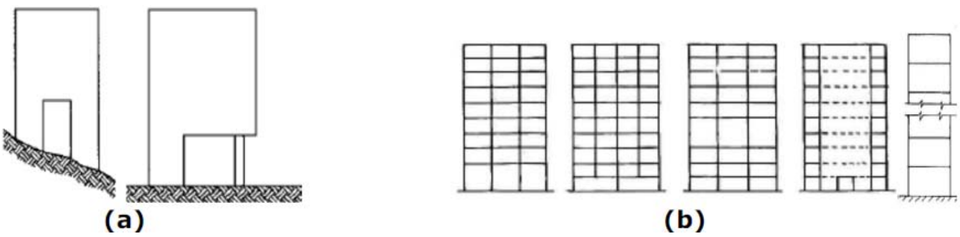

Figure 2. Images related to stiffness irregularity in the earthquake codes of (a) New Zealand, (b) India

(b) Mass Irregularity

The forces that occurred in the structure during the earthquake are inertial forces and these forces depend on total mass an the total acceleration of structure formed by the earthquake vibration (Charleson, 2008). The horizontal loads that will affect the structure in any earthquake are directly proportional to the weight of the structure. In other words, the lighter the structure, the less load affects on a possible earthquake. Therefore, lightness is a very important criterion for earthquake safety. For an effective safety during earthquake, the mass of the structure should be minimized and more importantly distributed homogeneously throughout the construction height. However, due to differences in usage among floors, floor masses may be different. For example; in a factory with heavy machinery or in an education institution having a library on any floor, an irregular mass distribution occurs due to its functions. Or, usage of different floor types cause non-homogeneous distributions in terms of mass (Sadashiva et al., 2009). Mass irregularity occurs where the seismic weight of any storey is much more than the weight of the adjacent storey. The relevant definitions related to the mass irregularity affecting the building behavior negatively in the regulations and codes examined in this study are presented in Table 2.

Table 2. The definitions of mass irregularity in the different regulations and codes

	Definitions
IRAN	Distribution of mass over the height of the building shall be approximately uniform such that the mass of no story, except the roof and loft differ more than 50% of the mass of the story located below.
NEW ZEALAND	(severe)- Mass of any storey < 0.7 of mass of adjoining storey; (significant)- Mass of any storey < 0.9 of mass of adjoining storey; (insignificant)- Mass of any storey ≥ 0.9 of mass of adjoining storey.
MEXICO	The mass of a given floor, including seismic live loads, shall not exceed the mass of the floor below it, and shall not be less than 70 percent of this value. This restriction does not apply for the floor at the top.
INDIA	Mass irregularity shall be considered to exist where the seismic weight of any storey is more than 200 percent of that of its adjacent storeys. The irregularity need not be considered in case of roofs.
EUROCODE-8	Both the lateral stiffness and the mass of the individual storeys shall remain constant or reduce gradually, without abrupt changes, from the base to the top of a particular building.
ASCE/SEI 7/10	Weight (mass) irregularity is defined to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.

It was emphasized that if the mass distributions of the floors are not equal this irregularity would occur but the accepted limit values are different for each earthquake code. The difference of mass between floors is taken as; 50% in the Iranian code, 70% in the Mexican code, 150% in the ASCE code and 200% in the Indian code. The Eurocode-8 regulation mentioned that the sudden changes in mass between the floors should be avoided but do not provide a numerical limitation. The New Zealand code classifies the situation that mass of a floor exceeding the mass of the neighboring floor as severe, significant and insignificant. However, in Turkey Building Seismic Code (TBDY-2018) and China code, there is no definition regarding this type of irregularity. In terms of the components, Explanatory images that may assist in understanding the given definitions by visualizing are presented only in New Zealand and India regulations (Figure 3).

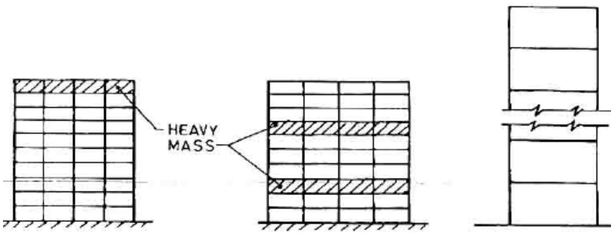

Figure 3. Images related to Mass irregularity in the India earthquake code

(c) Strength irregularity (weak storey)

During the earthquake, at each level a horizontal force acts on the structures. These horizontal forces are transferred to lower floors through the structural elements and then to the foundation. To allow the horizontal forces to be delivered to the ground safely, each storey must have a sufficient effective shear capacity. This shear capacity consists of cross-sectional areas of vertical bearing elements, that is, columns and shear walls. In addition, the infill walls between the frames also contribute a little to the shear capacity of the structures. (Kaplan, 2008). In the light of this information, it should be noted that the shear forces increase downwards to the ground floors, and it emerges a need to check the strength of the elements, especially at lower floors. The situations of having no walls in the buildings on the ground and entrance floors for commercial purposes or having walls that do not contribute to transmission of the horizontal loads for aesthetics reasons make the related floors be significantly weaker in terms of the shear strength compared to the other floors. If this situation is not considered in the design phase, strength irregularity i.e. weak storey occurs on that floor and such structures will be at a great risk in terms of earthquake stability (Guevara-Perez, 2012). In this respect, the definition of this irregularity, which is effective in the behavior of the structures under horizontal shear forces, is given in Table 3.

Table 3. The definitions of strength irregularity (weak storey) in the different regulations and codes

	Definitions
TBDY-2018	In reinforced concrete buildings, the case where in each of the orthogonal earthquake directions, total strength irregularity factor η_{ci}, which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, is less than 0.80.
CHINA	The inter-storey shear capacity of lateral-force-resisting structure is less than 80% of the adjacent upper storey.
IRAN	The lateral strength of each story shall not be less than 80% of that in the story above. The story strength is the total strength of all elements resisting the story shear in the direction under consideration. The story not complying with this, is considered a "weak story".
MEXICO	The lateral shear stiffness of a given story shall not exceed twice the value of the story below it.
INDIA	Weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above. The storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction.
EUROCODE-8	In framed buildings, the ratio of the actual storey resistance to the resistance required by the analysis should not vary disproportionately between adjacent storeys.
ASCE/SEI 7/10	*Discontinuity in lateral strength–weak story irregularity* is defined to exist where the story lateral strength is less than 80% of that in the story above. The story lateral strength is the total lateral strength of all seismic-resisting elements sharing the story shear for the direction under consideration. *Discontinuity in lateral strength–extreme weak story irregularity* is defined to exist where the story lateral strength is less than 65% of that in the story above. The story strength is the total strength of all seismic-resisting elements sharing the story shear for the direction under consideration.

In the reviewed regulations and standards, the strength irregularity is defined according to the design criteria of the seismic force of each regulation; the effective shear area in the floors and the horizontal strength of the floors are taken into consideration. Firstly, it is seen that there are similarities between the accepted values. According to the seismic codes in Turkey, China, Iran and India; it is stated that the strength irregularity which is defined as the ratio of the effective shear area of any storey to the effective shear area of the storey immediately above, should be less than 0.80. For the Mexican code, the corresponding value between the adjacent storeys is given as 2. ASCE / SEI 7/10 rated this irregularity in two categories as 80% and 65% according to the obtained values. The Eurocode-8 standard also provides a recommendation without giving any limiting criterion. In the New Zealand code, such a definition is not given for the mentioned irregularity. Furthermore, no explanatory visuals or figures for strength irregularities could be reached in any of the regulations reviewed.

3.2.Vertical force-resisting elements irregularity

While the forces acting on the structure are transferred to the foundation, especially the vertical structural elements must be continuous throughout the construction height. When these vertical forces are not transferred to the lower storeys regularly because of discontinuity of members, it occurs excessive stress in the junction points and other structural members (Öztürk et al., 2015). Furthermore, the distortion of the symmetries of the columns and shear walls in the vertical direction by displacement of their locations or completely removal of them at some floors causes the structure to be adversely affected by the earthquake loads (excessive displacement, collision effect) (Tekin and Pala, 2016). The main reason for this irregularity, as in many other structural irregularities, is the desire to obtain large volumes and openings on some floors due to architectural demands. Table 4 lists the regulations and standards for the discontinuity of the vertical elements of the structural system.

In the definitions of vertical force-resisting elements irregularity in the regulations and standards examined; the standards of Turkey, China and Eurocode-8 mentions that the vertical elements of the structural system must be continuous, and it is presented some restrictions about vertical discontinuities in the Turkey Building Seismic Code (AFAD, 2018) in detail. The code of India emphasize that this type of irregularity emerges for the situation that when the change of position of the vertical members according to the adjacent storeys is larger than the length of the member and ASCE/SEI 7/10 states that this type of irregularity causes overturning forces on the other structural members. In Iran and New Zealand regulations, there are no such restrictions about mentioned irregularity. In terms of transfer the knowledge of this irregularity to the architects efficiently; explanatory visuals are reached only in the TBDY-2018 and India regulations. (Figure4)

Table 4. The definitions of vertical force-resisting elements irregularity in the different regulations and codes

	Definitions
TBDY-2018	The cases where vertical structural elements (columns or structural walls) are removed at some stories and supported by beams or gusseted columns underneath, or the structural walls of upper stories are supported by columns or beams underneath. (a) The columns are never allowed to be seated on cantilever beams or on the gussets of the bottom columns at any floor of the building. (b) In the case where a column rests on a beam which is supported at both ends, vertical earthquake calculation is sufficient. (c) In no case the walls shall be permitted to rest on columns underneath. (d) Structural walls shall in no case be permitted in their own plane to rest on the beam span at any storey of the building.
CHINA	The internal force of vertical lateral-force-resisting components (columns, seismic walls and seismic bracing) is transmitted downward through horizontal transmission components (beam and truss).
MEXICO	For a given floor the area delimited by the exterior faces of its vertical resisting elements shall not exceed the area of the floor below it, and shall not be less than 70 percent of this value. This restriction does not apply to the floor at the top.
INDIA	In-plane offset of the lateral force resisting elements greater than the length of those elements.
EUROCODE-8	All lateral load resisting systems, such as cores, structural walls, or frames, shall run without interruption from their foundations to the top of the building or, if setbacks at different heights are present, to the top of the relevant zone of the building
ASCE/SEI 7/10	In-plane discontinuity in vertical lateral force-resisting elements irregularity is defined to exist where there is an in-plane offset of a vertical seismic force-resisting element resulting in overturning demands on a supporting beam, column, truss, or slab.

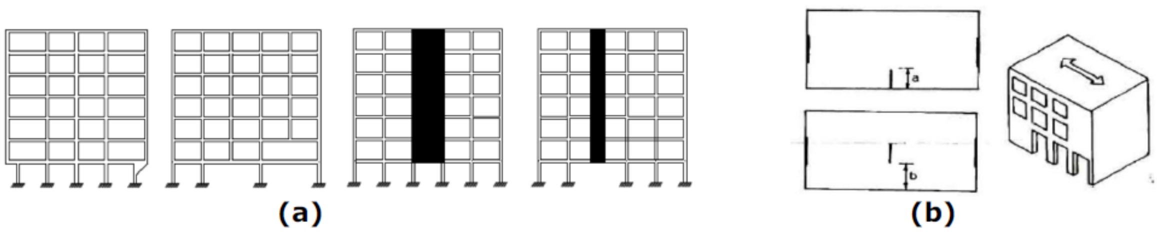

Figure 4. Images related to Vertical force-resisting elements irregularity in the earthquake codes of (a) Turkey, (b) India

3.3. Vertical geometry irregularity

In earthquake resistant structure design; simplicity, continuity and symmetry are the most desirable features in vertical plan as it is in horizontal geometry. However, new quests for building form design in today's architecture have become popular due to aesthetic concerns (Sarkar et al., 2010). In the simplest sense, the building geometry is not maintained in the same way throughout the building height, but steps are set in the vertical plane as offset and setback form. This step formation is preferred in order to provide adequate daylight and ventilation in areas with close-range buildings, to comply with the limitations of the building floor area and to increase the usage area in the upper floors. This irregularity can be defined as the deviation from the vertical plane of an outer wall of the building in a horizontal direction. Ambrose and Vergun (1985), states the earthquake sensitivity that arises from the search for a different form which lead to unpredictable behavior in the earthquake as “determination of the effects of seismic forces on the building is largely related with the buildings form design”. For example; because the buildings having offset and especially setback form prevents the overlapping of the center of gravities of the upper and lower floors, and hence occurs an irregularity in the height of the structures in this type of design. These floors do not oscillate at the same frequency with other regular floors during the earthquake and cause stress accumulations with the effect of displacement in the opposite direction (Ambrose and Vergun, 1985). The effect of these recess parts depends on the proportions of adjacent floors and the dimensions of these parts. The definitions of regulations and standards for vertical geometry irregularity are shown in Table 5.

Table 5. The definitions of vertical geometry irregularity in the different regulations and codes

	Definitions
CHINA	Except for the top storey or the small buildings outside roof, the horizontal size of partial take-in is larger than 25% of the adjacent lower storey.
NEW ZEALAND	(severe)- Any element contributing > 0.3 of the stiffness/strength of the lateral force resisting system discontinues vertically; (significant)- Any element contributing > 0.1 of the stiffness/strength of the lateral force resisting system discontinues vertically; (insignificant)≤ Only elements contributing ≤0.1 of the stiffness/strength of the lateral force resisting systems are discontinuous vertically.
INDIA	Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral force resisting system in any storey is more than 150 percent of that in its adjacent storey.
EUROCODE-8	When setbacks are present, the following additional conditions apply: a) for gradual setbacks preserving axial symmetry, the setback at any floor shall be not greater than 20 % of the previous plan dimension in the direction of the setback; b) for a single setback within the lower 15 % of the total height of the main structural system, the setback shall be not greater than 50 % of the previous plan dimension; c) In this case the structure of the base zone within the vertically projected perimeter of the upper storeys should be designed to resist at least 75% of the horizontal shear forces that would develop in that zone in a similar building without the base enlargement; d) if the setbacks do not preserve symmetry, in each face the sum of the setbacks at all storeys shall be not greater than 30 % of the plan dimension at the ground floor above the foundation or above the top of a rigid basement, and the individual setbacks shall be not greater than 10 % of the previous plan dimension
ASCE/SEI 7/10	Vertical geometric irregularity is defined to exist where the horizontal dimension of the seismic force-resisting system in any story is more than 130% of that in an adjacent story.

In terms of restrictions covered in the standards under the title of vertical geometry irregularity; it is seen that China, ASCE/SEI 7/10 and India codes refer to the ratio of the horizontal dimension of structural system in vertical geometry between adjacent storeys. The limit values of this ratio are 125%, 130% and 150%, respectively. In Eurocode-8, it is given a more detailed explanation and defined the restrictions of irregularity by giving limiting ratios both in the horizontal and the vertical geometry of the building. To make it more clear, Eurocode-8 states such criteria that differ according the axial symmetry such that recess and the changing of setbacks should be within the lower 15% of the total height of the structure. In the New Zealand code, this irregularity is classified as severe, significant and insignificant according to the stiffness/strength ratio of lateral force resisting members. On the other hand, Turkey, Iran and Mexico seismic codes impose no restriction or identification of this type of geometrical irregularity. Descriptive images of this irregularity, which have the most visuals compared to other irregularities, were obtained in New Zealand, India and Eurocode-8 regulations (Figure 5).

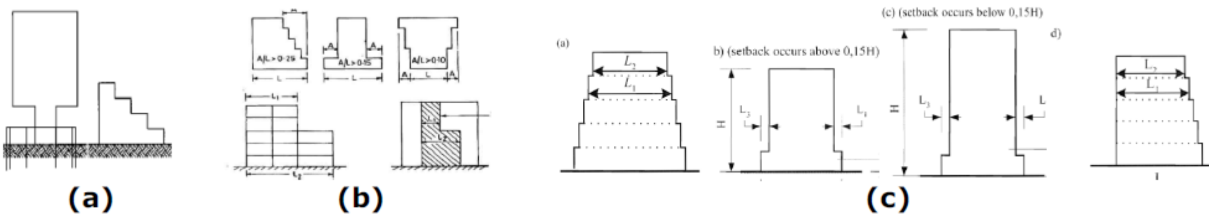

Figure 5. Images related to Vertical geometry irregularity in the earthquake codes of (a) New Zealand, (b) India and (c) Eurocode-8

4. DISCUSSION

In the design of the structural system that withstands the earthquake forces, the decisions taken on the sections and facades of the structure are of great importance in determining the load distribution and ensuring that the structure is safe against the earthquake by transferring these forces to the ground. For this reason, in the earthquake codes of the countries the criteria related to regularity in the vertical plane are included and it is emphasized that vertical structural irregularities should be avoided. It is considered that most of the earthquake codes are similar in terms of irregularity criteria. However, depending on the seismic history of the regions, the economic situation of the countries and their attitudes towards the structure design, each country has different restrictions under different sub-headings. In this study, within the scope of structural irregularity definitions in vertical plane; earthquake code of the countries having different seismic experience; Turkey (AFAD, 2018), China (MOHURD, 2010), Iran (BHRC, 2007), New Zealand (NZSEE, 2014), Mexico (FDGM, 1995), India (BIS, 2002); ASCE/SEI 7-10 (ASCE, 2016) and (Eurocode-8 (CEN, 2004)standards followed by European countries with active fault lines have been examined in detail. The reasons for all structural irregularities that may occur with design decisions in vertical plane are determined, and Table 6 shows which irregularities the codes are mentioned. In addition, it is aimed to contribute to the architectural design process with simple but explanatory drawings that will strengthen the perception of architects and architectural students.

Table 6. Evaluation results of vertical structural irregularities according to different earthquake codes

		TURKEY	CHINA	IRAN	NEW ZEALAND	MEXİCO	INDIA	EUROCODE-8	ASCE/SEI 7-10
Inter-storey irregularities	Stiffness irregularity	√	√	√	√	-	√	-	√
	Mass irregularity	-	-	√	√	√	√	√	√
	Strength irregularity	√	√	√	-	√	√	√	√
Vertical lateral force-resisting elements irregularity		√	√	-	-	√	√	√	√
Vertical geometry irregularity		-	√	-	√	-	√	√	√
	(shaded)	Explanatory visual for the irregularity was used.							

After the evaluation, each of the following items are discussed within the scope of the problems that these irregularities causes on the structure in practice, the negative effects on the building behavior and the precautions to be taken against these irregularities.

- Stiffness irregularity (Soft story) causing from the sudden reduction of storey stiffness with respect to adjacent storeys; is a significant irregularity heading among the eight codes with the exception of Mexico and Eurocode-8 codes. As a result of this irregularity; the total displacement occurring under the influence of the earthquake forces in the structure is not shared between the floors and hence the floors having less rigidity experience larger displacements (İnan and Korkmaz, 2012). Therefore, non-elastic displacements occur on the structural elements which cause the formation of plastic hinges on the vertical elements which are difficult to repair. (Figure6a,6b) The most basic solution for avoiding this irregularity in which the earthquake energy is concentrated on a single floor with the effect of the lateral earthquake loads; is to ensure that the occurrence of plastic hinges is transposed on beams instead of columns when excessive displacements occur during earthquakes. In this respect, increasing the cross-sections of the vertical structural elements at the floor with soft floor irregularity (Figure 6c), or providing these elements more closely located stirrups (Figure 6d). Furthermore, additional vertical bearing elements or bracings can prevent this irregularity (Figure 6e) (Dowric, 1987; İnan and Korkmaz, 2012). The visual expression technique, which is considered to be an effective way for the perception of this irregularity, especially for the discipline of architecture, has been found only in New Zealand and India codes. However, for this irregularity, more understandable information transfer will be provided by the drawings as in Figure 6 that expresses both the type of damage and the solution suggestions.

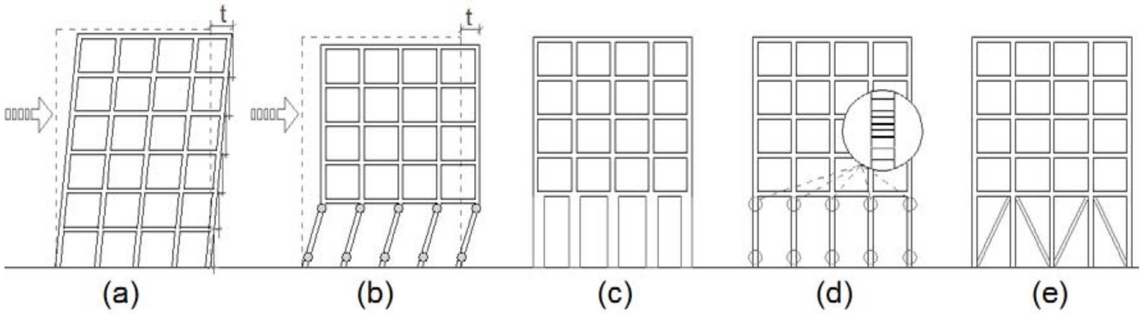

Figure 6. Explanatory figures for stiffness irregularity suggested in this study

- Heavy masses which are added to the structure for architectural or technical reasons cause the lateral forces to increase. This situation causes excessive loads during the earthquakes on the beams and columns near the heavy masses and hence increases the damage risk of the system at an earthquake. As a result of moving away from the principle of minimizing the structure mass and its homogenous distribution, mass irregularity emerges. The basic precautions that can be taken against for this irregularity dealt with in six earthquake codes, except ones for the China and Turkey are; to provide a homogeneous mass distribution during the design phase (Figure 7b), expanding the cross-sections of the load-bearing elements (Figure 7c) or additional load-bearing elements (columns, shear walls, bracings) (Figure 7d). In this regard, the explanatory visuals are given only in the Indian seismic code in terms of supporting the subject with visual expression techniques. However, with the drawings as in Figure 7, it will draw attention to this irregularity and the precautions to be taken during the design phase.

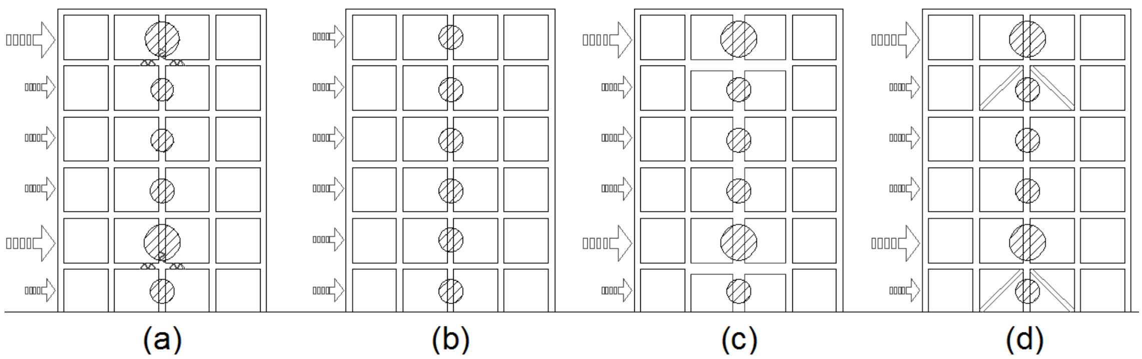

Figure 7. Explanatory figures for mass irregularity suggested in this study

- Strength irregularity (weak storey) is the type of structural irregularity that is included in the most of the earthquake codes except for the New Zealand code. In contrary to this situation, this irregularity has not been supported with the visual expression techniques in any of the codes. In order to understand this irregularity of the vertical load bearing elements in meeting the increasing forces as moving down to the ground floors, the use of the drawings as illustrated in Figure 8 will provide great convenience. Precautions to be taken to prevent this irregularity, in addition to the measures mentioned in the stiffness irregularities (Figure 6) are; using the same wall materials on all floors with the same configuration (Figure 8b) or in all floors, by isolating the walls from the columns and beams making the frame independent from the walls (Figure 8c) (Guevara-Perez, 2012). Moreover, the rearrangement of the reinforcements of all columns and shear walls on the floors where this irregularity is present will also increase the horizontal load strengths (Figure 8d).

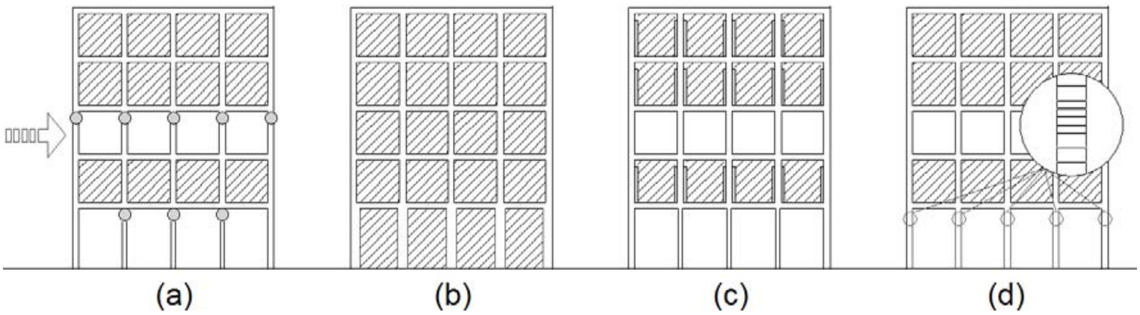

Figure 8. Explanatory figures for strength irregularity suggested in this study

- Six of the reviewed earthquake codes (Turkey, China, Mexico, India, Eurocode-8 and ASCE/ SEI 7/10) among the total of eight include definitions and limitations related to the discontinuity of the vertical load-bearing members (Figure 9a) causing from the axial misalignment due to architectural or technical reasons during sizing or configuration of these members. The basic solution of this irregularity is the continuation of the forces acting on the structure without interruption and / or sudden reduction during the transmission to the ground (Figure 9b) (Dražić and Vatin, 2016).By designing the load bearing system in a regular and continuous manner, the load capacity and number of plastic hinges will be increased and the energy dissipating part of the structure will grow beyond the limit of elastic behavior during an earthquake (Öğütçü, 2016). This issue, which directly affects the building behavior in the face of the earthquake, needs to be meticulously handled during the architectural design phase. However, only two of the six codes (Turkey and India) contain images for explaining this irregularity to the architects. However, a drawing as in Figure 9 which embodies the technical description will provide an effective benefit to the perception of this irregularity.

Figure 9. Explanatory figures for vertical lateral force-resisting elements irregularity suggested in this study

- Vertical geometry irregularity formed by changing the building boundaries throughout the building height; is the least mentioned structural irregularity among the eight examined codes. However, setbacks and offset along the height of the structure form are common practice. It should not be forgotten that there will be a stiffness change between the upper and the lower floors where the geometric difference occurs (Guevara-Perez, 2008). The best precaution to avoid this irregularity when moving from a large mass to a small mass (i) is separating the masses at a sufficient distance from each other (Figure 10b). With the dilatation, which is defined as the space separating the structural system between the building units, it is prevented negative impact of masses on each other that have different dynamic behavior characteristics and also unexpected damage as a result of collision. If dilatation cannot be made, stress accumulations arising from the formation of setbacks or offsets (Figure 10a) should be prevented. In this regard, to use larger vertical load bearing elements which provide more rigidity to the structure against torsion and separation behavior at the joining corners (Figure 10c), or provide smoother transitions rather than right angles at the joint corners (Figure 10d) are other solutions.

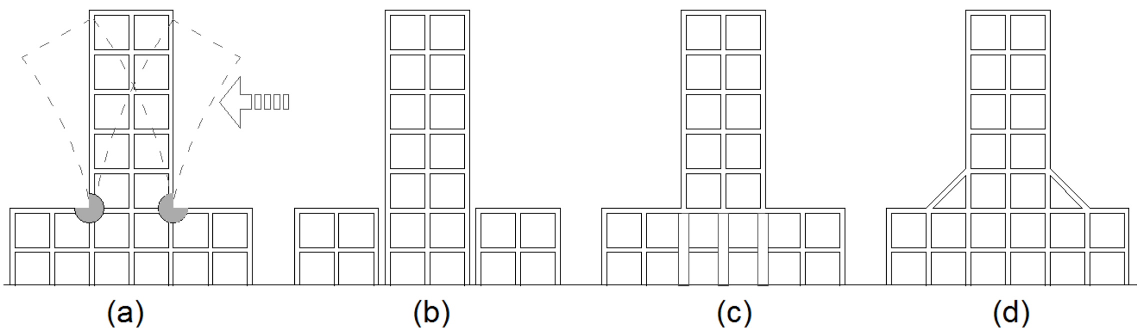

Figure 10. Explanatory figures for vertical geometry irregularity suggested in the study

This irregularity, which complicates the behavior of the structure against the earthquake forces, is the topic supported by the highest number of visuals, although the coverage is least included in the codes. As an alternative to the illustrative drawings in New Zealand, India and Eurocode regulations, a more comprehensible information transfer related to this irregularity will be provided with the drawings as in Figure 10.

With this section, it is wanted to prevent the structural irregularity conditions in many codes to be seen as information to be memorized. It has been proposed contributory solutions to the architects, who are both considered technical and designer persons, related to architectural designs and corresponding structural system they will implement in the regions with earthquake risk.

5. CONCLUSIONS

The component that will ensure the resistance of the structure to the earthquake is the structural system decisions taken in a rational manner in the architectural design process prior to the civil engineering calculations. The presence of irregularities in the structural systems, which are formed according to architectural design decisions, creates weakness under the effects of earthquakes, and earthquakes cause damage in such locations by focusing at weak points in the building configuration. In the light of the lessons taken from the past earthquakes, it can be said that if the buildings are not intended to be damaged in the earthquake, architects should avoid structural irregularities in the pre-design phase and should choose as much regular configurations as possible. If there is an inevitable structural irregularity arising from the necessity of the design, architect should predict those weak points that may cause damage and propose solution suggestions for this irregularity. The present structural irregularities in the buildings may be removed if the measures are not taken during the architectural design phase, but it will not be economical and even may not possible to eliminate after exceeding a certain limit. Structural irregularities are among the first issues that should be considered to reduce the cost of buildings in earthquake zones. In the light of this information; the design and cost limitations for earthquake-resistant buildings have importance in the architectural design especially in the pre-design phase.

The seismic codes, which define the minimum conditions for the production of seismically safe and functional buildings, contain a technical language due to their nature, and often address the work areas of structural engineers and are incomplete in terms of the directions relating to architects. This creates a fragmentary approach rather than being holistic in building production. However, it is an essential requirement for architects to have a serious knowledge of earthquake safety and to benefit from their knowledge during design phase of the structure.

In this study, it was examined how design decisions in vertical plane were dealt with in current earthquake codes and how the issue of forming regular structures is addressed to the architects was investigated. In this direction, the structural irregularities in the vertical plane mentioned in the eight different earthquake codes in the countries on active fault lines with different seismic history were compared with the tables and the results were evaluated. Total of five criteria (stiffness irregularity, mass irregularity, strength irregularity, Vertical lateral force-resisting elements irregularity, Vertical geometry irregularity) have been obtained as a result of literature research which will cause irregularity. Three of these five criteria in Turkey, Iran, New Zealand and Mexico codes; four of them in Eurocode-8 and China codes; and all of them in India and ASCE/SEI 7/10 codes are mentioned. In the evaluation of the codes with respect to the explanatory visuals as a tool for the discipline of architecture to have a guiding structure; it was observed that the drawings for the regular building design defined in the codes of China, Iran, Mexico and ASCE / SEI 7/10 were not included. Visuals relating to vertical structural irregularities are included in Turkey, New Zealand, India and the Eurocode-8 codes. In fact, the ratio of the vertical structural irregularity criteria supported by the visuals within the total criteria is shown to be 1/3, 2/3, 4/5, 1/4 for these codes, respectively. Summary of this situation; the Indian code’s successful approach is noteworthy.

After stating that the codes include incomplete or not clearly understandable expressions for architects, the situations in which vertical structural irregularities are expected are discussed comprehensively. Besides, suggested visual representations for each irregularity topic are given in detail. This study, which emphasizes the importance of the information that is perceived more easily by both text and visual, draws attention to the necessity of similar tendency in codes. As a result, understanding earthquake codes will help architects to integrate important knowledge into their practical skills, to unite their knowledge and imagination without compromising structures and to leave a secure structure stock of heritage to future generations.

REFERENCES

AFAD (Prime Ministry Disaster and Emergency Management Authority) (2018) "Turkish Building Earthquake Code (TDBY-2018)", Prime Ministry Disaster and Emergency Management Authority, Ankara, Tukey.

Alden, A. (2017) “The World's Major Earthquake Zones”, [online] Available at: https://www.thoughtco.com/seismic-hazard-maps-of-the-world-1441205 [Accessed: 25 August 2018]

Ambrose, J., Vergun, D., (1985), Seismic Design of Buildings, John Wiley & Sons, New York, USA.

ASCE (American Society of Civil Engineers) (2016) "Minimum Design Loads for Buildings and Other Structures (ASCE Standard ASCE/SEI 7-10)", American Society of Civil Engineers, Reston, USA.

Ankara Chamber of Architects (2007) “Sürekli Mesleki Gelişim Merkezi Öneri Eğitim Programları”, (Continuing Professional Development Centre Suggestion Training Programs) [online] Available at: www.mimarlarodasiankara.org/dosya/SMGM-kitap.doc [Accessed: 20 August 2018] (in Turkish)

BHRC (Building and Housing Research Center) (2007) "Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800)", Building and Housing Research Center, Tehran, Iran.

BIS (Bureau of Indian Standards) (2002) "Indian Standard Criteria for Earthquake Resistant Design of Structures (IS 1893-Part 1)", Government of India, Ministry of Earth Sciences, New Delhi, India.

CEN (European Committee for Standardization) (2004) "Eurocode 8: Design of Structures for Earthquake Resistance — Part 1: General Rules, Seismic Actions and Rules for Buildings (BS EN 1998-1:2004)", European Committee for Standardization, Brussels, Belgium.

Charleson, A. (2008) “Seismic Design for Architects: Outwitting the Quake”, 1st ed., Architectural Press, Oxford, UK.

De Stefano, M., Pintucchi, B. (2008) “A review of research on seismic behaviour of irregular building structures since 2002”, Bulletin of Earthquake Engineering, 6(2), pp. 285-308.

Dowrick, D. J. (1987) "Earthquake Resistant Design: For Engineers and Architects", 2nd ed., John Wiley & Sons, Chichester, USA.

Dražić, J., Vatin, N., (2016). “The influence of configuration on to the seismic resistance of a building”, Procedia Engineering, Volume 165, pp.883-890.

FDGM (Federal District Government of Mexico) (1995) "Mexico City Building Code: Complementary Technical Norms for Earthquake Resistant Design", [online] Available at: http://iisee.kenken.go.jp/worldlist/Web/33_Mexico.htm [Accessed: 21 September 2018]

Guevara-Perez T., (2008). “Seismic Regulations Versus Modern Architectural And Urban Configurations”, Proceedings of 14th World Conference on Earthquake Engineering, October 12-17, Beijing, China.

Guevara-Perez T., (2012). "Soft-story and weak story in earthquake resistant design: A multidisciplinary approach", Proceedings of 15th World Conference on Earthquake Engineering, September 24-28, Lisbon, Portugal.

Harmankaya, Z. Y., Soyluk, A. (2012) "Architectural Design of Irregular Buildings in Turkey", International Journal of Civil & Environmental Engineering (IJCEE-IJENS), 12(01), pp. 42-48.

IAEE (International Association for Earthquake Engineering) "Regulations for Seismic Design - A World List", [online] Available at: http://www.iaee.or.jp/worldlist.html [Accessed: 20 August 2018]

İlerisoy, Z. Y., Tuna, M. E. (2018) "Effects of Height and Plan Geometry on the Costs of Tunnel Form Residential Buildings", Periodica Polytechnica Architecture, 49(1), pp. 29-37.

İnan, T., Korkmaz, K. (2012), "Düşey doğrultudaki yapı düzensizliklerinin incelenmesi", (Investigation of vertical structural irregularities), Erciyes University Journal of Institute of Science and Technology, 28 (3),pp. 240-248. (in Turkish)

İnel, M., Ozmen, M. B., Bilgin, H., (2008). "Re-evaluation of building damage during recent earthquakes in Turkey", Engineering Structures, 30(2), pp.412-427.

Kaplan, S. A., (2008). "Dolgu Duvarların Betonarme Taşıyıcı Sistem Performansına Etkisi", (Effect of infill Walls on Reinforced Concrete structural System Performance), Türkiye Mühendislik Haberleri, Vol:452, pp 49-62. (in Turkish)

Kim, S. J., Elnashai A. S. (2009). "Characterization of shaking intensity distribution and seismic assessment of RC buildings for the Kashmir (Pakistan) earthquake of October 2005". Engineering Structures, 31(11), pp.2998-3015.

Mezzi,M., Parducci, A., Verducci, P.,(2004). "Architectural and Structural Configurations of Buildings with Innovative Aseismic Systems", Proceedings of 13th World Conference on Earthquake Engineering, August 1-6,Canada.

MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China) (2010) "Code for Seismic Design of Buildings (GB 50011-2010)", Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing, China.

NZSEE (New Zealand Society for Earthquake Engineering) (2014) "Assessment and Improvement of the Structural Performance of Buildings in Earthquakes", [online] Available at: https://www.nzsee.org.nz/db/PUBS/2006AISBEGUIDELINESCorr3_(incl_2014_updates).pdf [Accessed: 21 September 2018]

Öğütçü, T. F., (2016). "Sünek Olmayan Betonarme Çerçevelerde Yumuşak Kat Oluşumu Üzerine Deneysel Bir Çalışma",(An Experimental Investigation on Soft

Story Formationat The Nonductile Rc Frames), MSc thesis, Selçuk University, Konya, Turkey. (in Turkish)

Özcan, O., (1994)."Mimari Tasarım Acısından Bilgisayar Modeli Maketin Yerini Alabilir mi?", (Can the Computer Model Replace Real Models in terms of Architectural Design?) CAD+, Vol: 12 (February), pp. 34-37. (in Turkish)

Özmen, C., Ünay, A. İ. (2007) "Commonly Encountered Seismic Design Faults due to the Architectural Design of Residential Buildings in Turkey", Building and Environment, 42(3), pp. 1406–1416.

Özmen, C. (2008) "A Comparative Structural and Architectural Analysis of Earthquake Resistant Design Principles Applied in Reinforced Concrete Residential Buildings in Turkey", PhD Thesis, Middle East Technical University, Ankara, Turkey.

Öztürk, T. (2011) "A study of the effects of slab gaps in buildings on seismic response according to three different codes", Scientific Research and Essays, 6(19), pp. 3930-3941.

Öztürk, O., Aksoylu, C., Arslan, M. H., (2015). "Çerçeve Türü Betonarme Binalardaki Taşıyıcı Sistemin Düşey Elemanlarının Süreksizliği Üzerine Bir İrdeleme",(An investigation on the Discontinuity of Vertical Elements of Structural System in Reinforced Concrete), Buildings International Burdur Earthquake & Environment Symposium (IBEES2015), May 7-9, Burdur/Turkey. (in Turkish)

Sadashiva, V. K., Macrae, G. A., Deam, B. L., (2009). "Determination of Structural Irregularity Limits – Mass Irregularity Example", Bulletin Of The New Zealand Society For Earthquake Engineering, 42(4), pp. 288-301.

Sarkar P., Prasad A. M., and Menon D., (2010). "Vertical geometric irregularity in stepped building frames," Engineering Structures, 32(8), pp. 2175-2182.

Tekin, Ö. F., Pala, M., (2016). "Taşıyıcı Sistemde Düşey Eleman süreksizliğinin sismik çarpışma anında yapı üzerine etkisi", (The effect of the vertical element discontinuity on the structure at the time of the collision), 4th International Symposium On Innovative Technologies In Engineering And Science(ISITES2016), November 3-5, Antalya/Turkey. (in Turkish)

Tezcan, S., (1998). Depreme Dayanıklı Tasarım için Bir Mimarın Seyir Defteri, (An Architect's Logbook for Earthquake Resistant Design), Türk Deprem Vakfı,1st ed., İstanbul, Turkey. (in Turkish)

Tuna, M. E., (2000). Depreme Dayanıklı Yapı Tasarım, (Earthquake Resistant Design for Buildings), 2nd ed. Tuna Eğitim ve Kültür Vakfı, Ankara, Turkey. (in Turkish)