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Article

Investigation of the Earthquake Performance Adequacy of Low-Rise RC Structures Designed According to the Simplified Design Rules in TBEC-2019

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Abstract: In this study, earthquake performance of the structures was tested which were modeled according to the minimum criteria of simplified analysis approach proposed in TBEC-2019. For this purpose, 144 reinforced-concrete building models were designed according to parameters such as earthquake design class, building height (number of storey), number of spans, soil type and three different simplified formulas suggested in the code. The level of structural performance of buildings models was determined by the linear (L) and nonlinear performance analysis (NL) methods that given in TBEC-2019. The base shear force, top displacements and over-strength factor (Ω) of each structural model were obtained, and performance analysis was performed by comparatively. As a result of the structural analyses, it was seen that some of the buildings model designed according to minimum column sectional criteria given in simplified methods could not meet the suggested seismic performance level. While the number of structural models that provide the controlled damage (CD) level in the L analysis method is 44 (30.55%), it is 107 (74.3%) in the NL analysis method. The insufficient performance was obtained in both L and NL methods in models which have over-strength values below 3. It has been observed that multi-criteria of building performance are not met with the weakening of local soil conditions. It was also seen that the L method chosen in the performance analysis gave more conservative results with this study.

Keywords: simplified design rules; earthquake; linear method; nonlinear method; performance analysis

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1. Introduction

Turkey is located in a region with high seismicity due to its geographical location. Many "sub-standard buildings" in Turkey have not received sufficient or, in some cases, any engineering services and have been built without professional supervision. In sub-standard buildings, there are critical problems such as faulty construction techniques or quality issues relating to use of inappropriate building materials. Earthquakes that caused significant loss of life and property were experienced in Turkey in the 20th century and the first quarter of the 21st century [1–12]. The 1939 Erzincan earthquake (M_w 7.2) and the 1999 Marmara earthquake (M_w 7.4) are the two most destructive earthquakes that occurred in the 20th century [13]. In the first quarter of the 21st century, many earthquakes caused significant losses, such as 2002 Sultandağı Afyon (M_w 6.5), 2003 Bingöl (M_w 6.4), 2011 Van (M_w 7.2), 2020 Elazığ (M_w 6.5) and 2020 İzmir (M_w 6.6) [14,15]. In particular, the 1000 km long North Anatolian Fault line and the 400 km long East Anatolian Fault line within the borders of Turkey, surround the country in east–west and southeast–northeast axes. Severe earthquakes occur at certain repetitions on these fault lines. In addition, a significant part of the existing building stock in Turkey is reinforced concrete, and does not have sufficient earthquake performance due to the reasons mentioned above, which have been mentioned frequently in the literature [16–20]. Continuous improvement studies have been carried out to reduce the destructive effects of earthquakes on structures in Turkey.

Many seismic design codes have been put into effect in Turkey since the 1940s. The codes have been updated on average every eight years since 1940, and 10 codes have entered into force in the last 80 years [21,22]. In 2007, the "Regulation on Buildings to be Constructed in Earthquake Zones (TEC-2007)" [23] came into force, so the nonlinear calculation method in existing reinforced concrete buildings and the Turkish Buildings Earthquake Code in 2019 (hereafter, TBEC-2019) [24] became the most up-to-date. Changes in codes over time and earthquake load calculation methods are shown schematically in Figure 1 and Table 1. These codes contain quite comprehensive and innovative information as of the date of their publication.

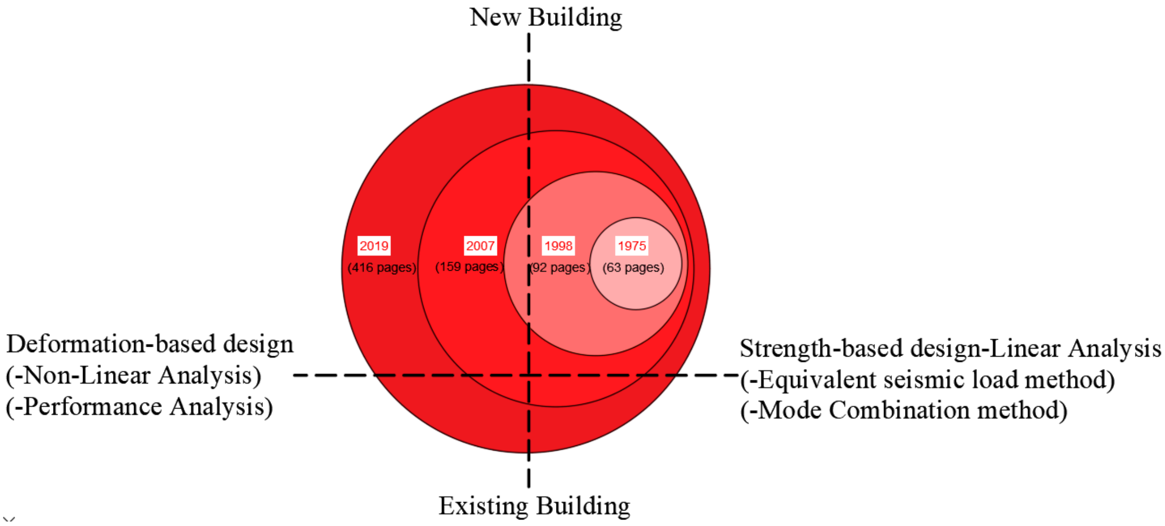


Figure 1. Earthquake codes and analysis methods.

Table 1. Earthquake Code Analysis Methods.

	TEC-1975	**TEC-1998**	**TEC-2007**	**TBEC-2019**
Force-Based Seismic Analysis of New RC Buildings	Eq.Static Anly.	Eq.Static Anly. /Modal Anly/ Time History Anly.	Eq.Static Anly./ Modal Anly/ Time History Anly.	Eq.Static Anly./ Modal Anly/ Time History Anly.
Deformation Based Seismic Analysis of New RC Buildings	—	—	—	NL Resp.Hist. Anly/ NL Static Pushover Anly.
Seismic Analysis of Existing RC Buildings	—	—	NL Static Pushover Anly.	NL Resp.Hist. Anly/ NL Static Pushover Anly.

Finally, in the current code, the TBEC-2019, radical changes have been made compared to the previous code (TEC-2007). New earthquake hazard maps have been updated in the current code. In addition, map spectral acceleration coefficients (S_S, S_1), spectral acceleration coefficient (S_{DS}), earthquake design classes (EDC, in Turkish DTS), local ground effect coefficients (F_S, F_1), and building height classes (BHL in Turkish BYS) started to be used for design and calculations. New concepts such as building usage classes (BUC in Turkish BKS), building performance levels, design according to strength (DGT), evaluation and design according to deformation (in Turkish ŞGDT), over-strength factor (Ω in Turkish D) and effective section stiffness are defined in the current code.

It is seen that studies on linear (L) and nonlinear (NL) behavior of buildings related to the TBEC-2019 are sufficient when the literature is examined. Studies are generally in the form of a comparison between the last two seismic design codes. Base shear forces, building displacements, periods and acceleration spectrum were investigated with the L comparisons made with NL analyses. Moreover, studies were carried out to determine the performance of buildings. L using the equivalent earthquake load method or mode superposition method as analysis by Aksoylu and Arslan [25], Özmen and Sayın [26], Korkmaz [27], Başaran and Hicyilmaz [28], Doğan [29], Aksoylu and Arslan [30,31], Bayrakcı and Baran [32], Başaran [33], Işık and Velioğlu [34], conducted research for frame and frame + shear walled buildings. In addition, Karaca et al. [35] compared five reinforced concrete buildings located in the city centre of Niğde and designed according to the TBEC-2019 in the context of structural design according to the last two codes. As a result of the structural analyses, it has been observed that more concrete will need to be used in a building to be designed according to the 2018 earthquake code, but there is a tendency to decrease the amount of reinforcement in general. Ünsal et al. [36] investigated the effect of building height on base shear force and top displacement according to the TEC-2007 and TBEC-2019 codes. They observed that if the base shear force values obtained according to the last two codes are close, the maximum displacement obtained based on the TBEC-2018 is much larger than the maximum displacement obtained based on the TEC-2007. Studies have also been carried out on static pushover analysis for nonlinear analysis [37] and time history analysis. Güllü [38], Çoban and Çeribaşı [39], Aydemir and Jakayev [40] carried out studies using time history analysis. Furthermore, Kasap [41], Özer and Yüksel [42], Işık [43], Çolakoğlu [44], used static pushover analysis, while Dalyan and Şahin [45], investigated building performances by using modal pushover analysis. Kap et al. (2019) [46] determined the capacities of the load-bearing elements in an existing school building, which was exposed to the 1999 Marmara and Düzce earthquakes, by performing an earthquake performance analysis according to the TBEC-2019. Aksoylu et al. [47] investigated reinforced concrete frame-type buildings of different elevations using ETABS, according to linear equivalent seismic load method for the TEC-2007, TBEC-2019 and ASCE 7–16. As a result of the study, the closest results for the three codes occurred on the softest soils. Kürkçü [48] designed a 20-storey reinforced concrete structure according to the TBEC-2019 and determined the earthquake performance with the calculation method in the time history. In the study conducted by Akçora [49], a 30-storey RC high-rise building was examined according to the TBEC-2019. As a result of analyses, it was determined that the plastic deformation and rotation values obtained for the sections met the limits given in the TBEC-2019. Capa [50] determined the earthquake performances of the three, five and seven storey buildings, which he took into account together with the linear and nonlinear calculation methods given in the TBEC-2019, and compared the obtained results with each other. Severcan and Sinani [51] determined the earthquake performance of an existing eight storey RC building using static pushover analysis according to the TEC-2007 and Eurocode-8 (2004). As a result of the evaluation, it has been seen that the performance levels of the elements are close to each other, especially in the vertical bearing elements, but the TEC-2007 is on the safer side compared to Eurocode-8. Ulutaş (2019) [52], compared the 2007 and 2018 earthquake codes in terms of sectional damage limits. As a result of the examination, it was concluded that the TBEC-2019 is safer in terms of earthquake safety than the TEC-2007 earthquake code. Sarı [53] determined the earthquake performance of an existing residential building according to the TBEC-2019 and TEC-2007 by static pushover analysis. According to both codes, the type of residence examined determined that the building met the target performance level. Ayaz [54] investigated the nonlinear behavior of a building strengthened according to the TEC-2007 and TBEC-2019. It was determined that the building met the requirements of the TBEC-2019 by conducting performance analyses according to DD-1 and DD-3 earthquake ground motion levels. Seşetyan et al. [55] carried out seismic hazard analysis for the Marmara Region according to new data. Sianka et al. [56] conducted seismic analysis for the Marmara Region, and they determined a good agreement with the updated Turkish

Earthquake Hazard Map. It is seen that these studies are generally focused on mid-rise or high-rise buildings.

If the RC building stock is divided into low-, mid- and high-rise according to the height of the structural system (Figure 2), some buildings should be made low-rise, especially due to architectural constraints and seismic zone. In low-rise buildings, having a regular load-carrier system may be preferred due to simpler design details. However, the design of low-rise buildings according to earthquake effects is easier than medium and high-rise buildings. It is also easier for these buildings to show the theoretically expected performance in a real earthquake. For this reason, there are very limited studies on low-rise RC buildings. Although easier to design, Erberik [57] stated that the recent devastating earthquakes in Turkey have shown that low-rise buildings are very sensitive to seismic effects. Particularly, the low-rise building design should be at a level that can easily meet the seismic actions (especially shear forces and displacements demanded by the earthquake). Therefore, consideration of seismic effects is as critical in the design of low-rise buildings as in the design of mid- and high-rise buildings. In addition, skyscrapers (which are taller than 70 m in a high seismic hazard zone, 91 m in a moderate seismic hazard zone and 105 m in a low seismic hazard zone), that occupy a very small place in the building stock but need to receive very important engineering services, are generally buildings with 30 storeys and above and are considered as part of the high-rise category. The design criteria for skyscrapers are completely different. Three-stage earthquake calculations are required for such buildings in the TBEC-2019. Performance analysis is conducted for DD-2 in the first stage (preliminary design stage), DD-3 and DD-4 in the second stage (evaluation of immediate occupancy), and DD-1 in the third stage (evaluation of near collapse or collapse prevention). The performance target expected from the structure at each stage is different. The first two stages are force based; the last stage is deformation-based analysis. In the last stage, 11 different ground motion records are used for time history analyses. Time history analysis is a step-by-step analysis of the dynamic response of a structure to a specified loading that may vary with time.

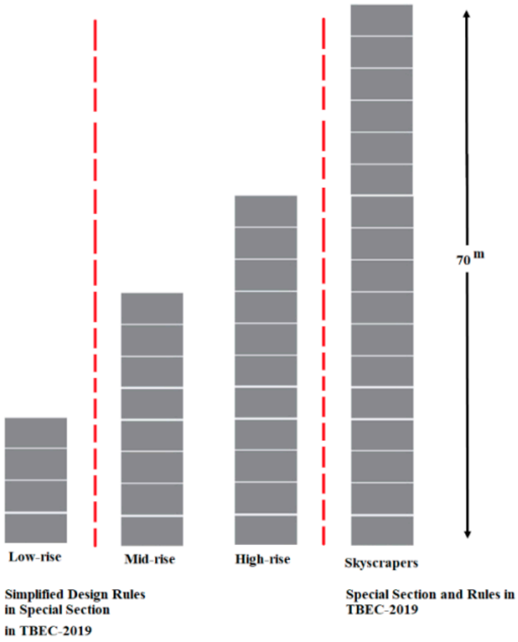


Figure 2. Schematic representation of buildings according to their heights.

One of the most remarkable innovations with the TBEC-2019 is the presence of a new section in which the analysis procedure for the design of simple low-rise structures, which will be carried out without detailed earthquake load calculations, is explained. These simplifying approaches, new to the TBEC-2019, are described by İlki et al. [58,59]. In the document prepared by the National Institute of Building Sciences for Development of Simplified Seismic Design Procedures in 2010 (NIBSDSSDP, 2010) [60] "The project's engineers are aware of the complexity of the existing regulation rules. Especially it was initiated to respond to concerns that earthquake resistant structure design for buildings reduces the effectiveness and reliability of the buildings" [59]. Additionally, in this document (NIBSDSSDP, 2010) it is recommended to continue work on the development of simplified design rules for earthquake resistance. Apart from that, ASCE 7–10 (2010) [61], and FEMA 450–2003 [62], separate simple shear walls or frame systems into simplified alternative structural design criteria [58,59]. A simplified calculation of the earthquake base shear force is given in these codes. In addition, after the base shear force is distributed to the storeys, the distribution of these shear forces to the load-carrier member is made by considering the relative lateral stiffness of the elements separately for flexible and rigid diaphragm behaviors. The document ISO/TC 71/SC5–2010 [63], "Guidelines for Simplified Seismic Assessment and Rehabilitation of Concrete Buildings" has given alternative simple approaches to find load-bearing element capacities and has made a suggestion for the simple calculation of lateral displacement ratios of buildings. The document also defines limits for lateral displacement ratios for different types of load-carrier systems. With these developments, simplified design rules for regular and straightforward cast-in-place RC buildings have been addressed in the TBEC-2019. Studies in the related literature are quite limited. To the authors' knowledge, only Balun et al. [64] has taken into account the simplifying design method in the TBEC-2019; the base shear forces of a structure for two different DTS were compared using the ETABS v18 program. Local soil classes and building height are determined as a variable within the boundaries of this section. As a result of the analysis, it was stated that the earthquake design class, local soil class and the number of storeys of the building made a difference between the simplified earthquake load calculation and the standard earthquake calculation. As a result, it is stated that only the shear forces obtained from the simplified calculation are on the safe side by obtaining higher values than the sole shear forces obtained by the standard method.

As can be seen from the comprehensive literature review above, although this issue concerns Turkish building stock, it is an area that has not been evaluated much. The question of whether the complex procedure in the earthquake codes is necessary in the design of simple structures can always be asked. Based on this problem, a simplified design process for low-rise buildings and minimum codes for calculations were proposed in the TBEC-2019, unlike other codes in the world. The main motivation for this study was this question: will the earthquake performance be sufficient for the buildings that were modeled according to the minimum criteria of the simplified design rules for low-rise RC buildings? Therefore, in this study, the authors wanted to investigate whether the earthquake performance of buildings designed with a simple method would be sufficient, especially since there is a very detailed calculation procedure in determining the earthquake performance. In particular, the relationship between the over-strength coefficient (Ω, in Turkish D) of the buildings and structural performance was examined, and how the over-strength coefficients change when low-rise buildings are designed according to minimum conditions was also investigated.

The determination of the behavior of RC structures can sometimes be difficult, because the earthquake load and behavior of RC are quite complex, especially under earthquake loading. For this reason, there are many assumptions in earthquake codes to facilitate these calculations, even though these assumptions sometimes contain important errors in mid- and high-rise buildings, having complex geometry. They can give predictable results in simple planned and relatively low-rise buildings. The TBEC-2019 has proposed a series of analysis procedures in which RC sections can be determined without making detailed earthquake calculations, for RC structures with simple geometry and limited building height. However, there is no study in the literature that indicates whether these provisions in the TBEC-2019 ensure that the structure has sufficient strength and ductility in terms of earthquake performance. Therefore, this study contains originality in terms of the subject it deals with. In this study, the simplifying rules given in the TBEC-2019 were examined through created structural models according to a set of parameter groups [65]. For this purpose, 144 RC building models with different parameters such as DTS, building height (H_N), number of spans, and soil type were used with the simplified formulas in the relevant part of the code, using ProtaStructure [66] (a software that gives the same results as SAP2000 v23.3.1 (2012) [67]. Then, the level of the structural performance of these designed buildings was determined by linear (L) and nonlinear analysis (NL). At the end of this study, the base shear force of the structures for earthquake calculation was performed, and the structural performance and over-strength were obtained by comparing with the capacity of the structures. As a result of a detailed performance analysis, the performance levels of the structural models for L and NL were determined, according to the damage levels of the structural elements. As a result, the findings were evaluated in the context of structural-earthquake engineering and suggestions were made.

2. Design Procedure of TBEC-2019/Section 17

Earthquake-resistant structure design is a very complicated and multi-unknown problem. Design engineers prefer application-oriented calculations that can be terminated with simple computations rather than a multiplicity of calculations [68]. Notably, the "Simplified Design Rules for Regular Cast-in-situ Reinforced Concrete Buildings" section in the TBEC-2019 includes simple formulas and approaches that engineers can use in building design. In the relevant section of the code, it is foreseen that simplified design rules can be used in the design of buildings with a simple and symmetrical floor plan, without irregularities in the plan, and vertically, that adversely affect the earthquake performance, and with limited building height. The simplified design rules facilitate the structural design stages for engineers, as they offer a more practical solution for RC buildings, which are designed quite simply and constitute an essential part of the building stock in Turkey.

In the TBEC-2019, the structural design is created according to DTS, S_{DS}, BOC, and BHL in the relevant section. DTSs are determined based on S_{DS} and BHL. According to this, the DTS values of the buildings are calculated for the appropriate location from the web application of the Turkey Seismic Hazard Maps [69]. A building's DTS value takes one of the numbers 1, 2, 3 and 4 from the highest to the lowest according to S_{DS} and the building importance coefficient values [70]. In addition, the building has the status of being 1a, 2a, 3a, and 4a depending on the building occupancy class: BOC = 1, 2 and 3. Here, the index "a" indicates the importance of the structure. Therefore, while classes DTS 1 and 1a represent an ordinary and significant building located in a critical earthquake zone, 4 and 4a are structures built in the area with the lowest earthquake risk. BHL takes BHL 1 to BHL 8, depending on the building's total height (H_N) and DTS. BHL 1 represents the highest and BHL 8 the lowest height structures in this classification.

The TBEC-2019/Section 17 is valid only for RC buildings with a BOC value of 3, and the structures in which the simplified calculation can be applied are dimensionally limited. In order to apply the design rules in the TBEC-2019, the limit values of the D, BOC, BHL, and building floor plan model that the building model must have, as well as the general rules, dimensioning of the building elements, and the lower limit values of the reinforcement of the elements are explained in this section. The relevant section in the TBEC-2019 requires that the buildings in which the design rules will be used have a floor plan close to rectangular. In addition, the section requires that there be no discontinuity or off-axis shift in the axes of the load-carrier system and that there should be at least two spans in each direction of the load-carrier system. In addition, specific approaches for dimensioning vertical load-bearing members in the simplified design of cast-in-situ RC buildings are given according to the DTS value. Building heights are limited for workplaces and residences as BHL $\geq$ 6 for DTS = 1 and 2 and BHL $\geq$ 7 for DTS = 3 and 4. In addition, framed buildings with high acceptable ductility levels and frame + shear wall buildings are expressed in terms of DTS. The cross-sectional areas of the columns are limited according to the choice of the load-bearing system, considering the axial compressive stresses and sufficient shear strength (Figure 2). It has been stated that the (g + q) value, which is the sum of the average distributed dead load and average distributed live load values to be used in determining the cross-sectional areas of the vertical bearing members, cannot be taken less than 15 kN/m^2, and the (g + 0.3q) value cannot be taken less than 13 kN/m^2. However, the distributed dead load values should also include the weight of the lateral beam, vertical load-bearing elements (column and shear wall), and non-bearing elements (infill walls) along with the slab loads. The live load acting on the roof of the building should also include the reduced snow load with a load factor of 0.3. The smallest square column cross-section should be 30 cm × 30 cm. It is stated that the ratio of the long side to the short side of the columns should not be more than 2. The minimum width should be 30 cm for beam cross-sections, and the minimum height should be 50 cm.

The TBEC-2019 proposes three different formulas for sizing columns (Figure 2). For buildings with high ductility levels whose structural system consists of frames, the A_{ci} value in the first and second formulas represents the cross-sectional area of the column taken into account, and for the column whose ΣA_{oi} value is considered, the sum of the area shares accumulated along with all floors. The value of $\Sigma(I_i/H_i^2)$ in the third formula represents the sum of the values in the direction taken into account on the ground floor (column cross-section moment of inertia / the square of the storey height), and the value of ΣA_{pi} represents the sum of the storey areas of the building. The simplified design rules of the TBEC-2019 for reinforced concrete buildings are summarized in Figure 3.

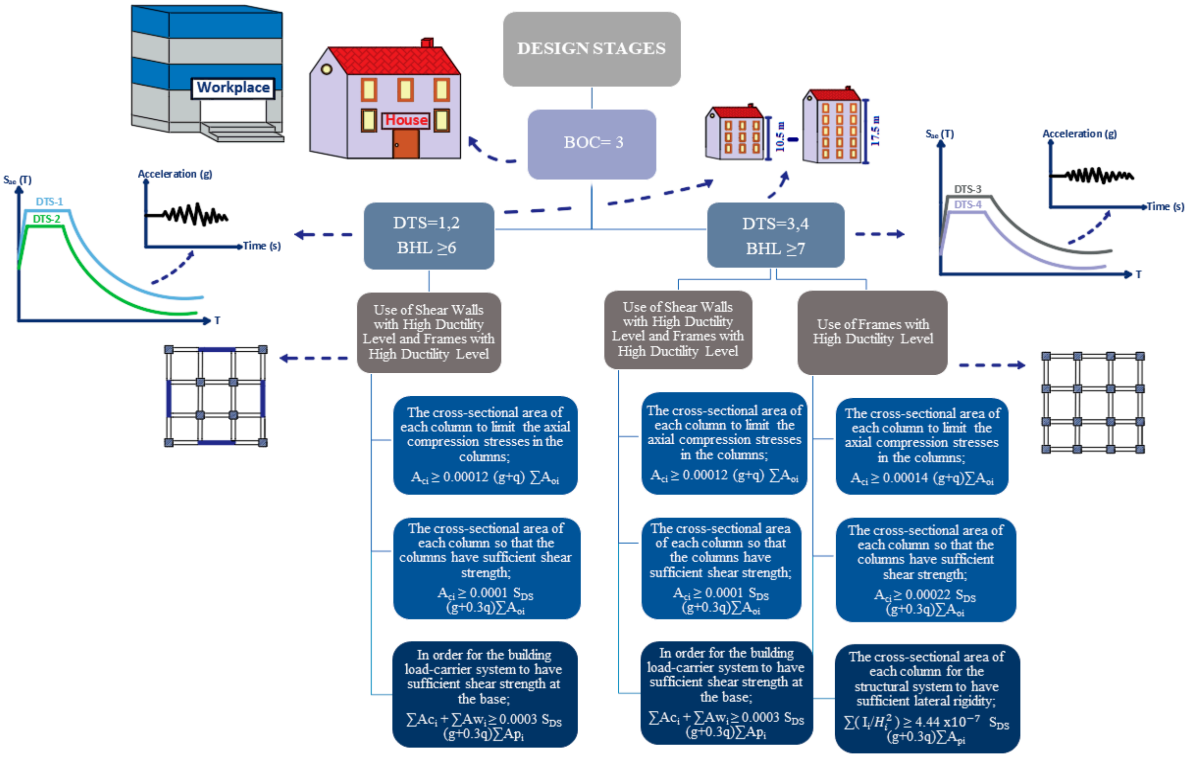


Figure 3. Simplified calculation procedure in TBEC-2019.

According to the relevant section of the TBEC-2019, it is stated that if the column is square, the longitudinal reinforcement ratio (ρ_t) should not be less than 1%, and the transverse reinforcement ratio ($\rho_{sh} = A_{sh}/s_b$) in the middle of the column should not be less than 0.165%. These ratios can be at least 1.5% and 0.25% in rectangular cross-section columns, respectively. In addition, in beam support sections where columns or shear walls join beams, the beam upper and lower longitudinal reinforcement ratios ($\rho = A_s/b_w.d$) vary from 0.6% and 0.4%, respectively, to the transverse reinforcement ratio in the beam middle region ($\rho_w = A_{sw}/b_w.s$) should not be less than 0.25%. The beam height should not be less than 1/11 of the spanning in buildings whose carrier system consists of frames and 1/12 of the spanning in buildings whose carrier system consists of shear walls and frames. It is also desirable that the beam height should not be more than 1/4 of the simple supported beamed span. If the slab-on-beam system is used in the building, the slab thickness should be at least 15 cm. The code states that in buildings to be designed with simplified design rules, a concrete grade with strength lower than 25 MPa or higher than 50 MPa and reinforcing steel other than S420 or B420c classes, cannot be used. In Figure 4, the geometric boundaries given in the TBEC-2019 are summarized through an example.

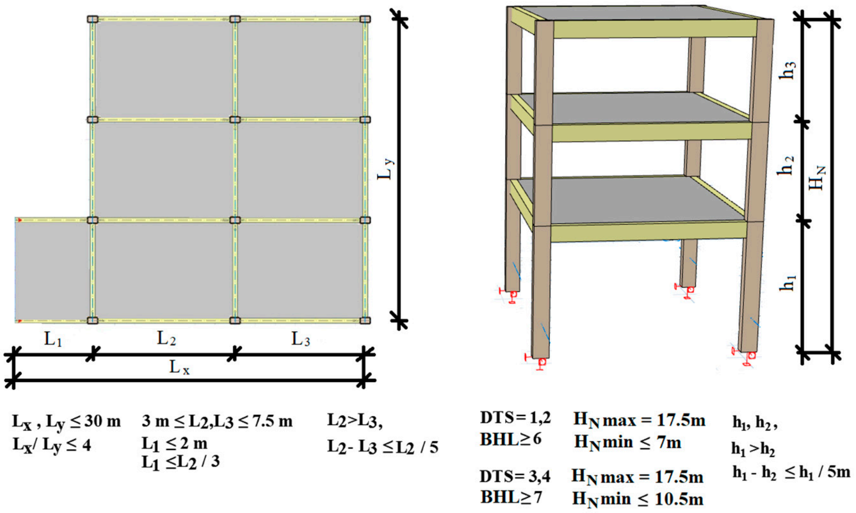


Figure 4. Building height limits according to building floor model plan limit values and earthquake design classes.

3. Numerical Analyses

Models with different parameters have been prepared to examine and control the behavior of the designed structures using the simple calculations in the related section of the TBEC-2019. A total of 144 building models were designed, depending on five different parameters: building models DTS, number of storeys, soil type, span length, and column cross-section calculation formula. Earthquake performance levels of the models were determined according to L and NL analysis methods in the Prota-Structure 2021 program. Prota-Structure is used for structural analyses. The analyses result of this program are the same as the results of SAP2000. It has been reported in the relevant sources [71,72] that it is precisely the same as SAP2000 v.23.3.1. While designing the building models, DTS = 3 and 4 were chosen. In the TBEC-2019, since the heights of the buildings are limited to be BHL $\geq$ 6 for D = 1 and 2 and BHL $\geq$ 7 for D = 3 and4, the building models have equal floor heights meeting the BHL $\geq$ 7 limit, and 3.5 m has been chosen, and three storeys (10.5 m), four storeys (14 m), five storeys (17.5 m). In the study, four different soil classes given in the TBEC-2019 were considered as ZA, ZB, ZC and ZD, from weak to vigorous, respectively. In selecting soil classes, ZE and ZF type soils, which are very weak soil classes with a high probability of liquefaction, were not considered because they require special designs.

The relevant section states that there should be at least two spans in both directions of the floor plan and that the spans should be at least 3 m and at most 7.5 m. Therefore, in the study, two different building floor plans were designed, three spans in both directions (6.66 m with equal span lengths) and four spans in both directions (5 m with equal span lengths), respectively. The regulation stipulated that the longest side of the floor plan should be 30 m at most. The building floor plan is square in both models in the study, and 20 × 20 m long was chosen. In the relevant section, it is requested that the carrier system typically consist of frames with high ductility levels or non-void walls with high ductility levels and frames with high ductility levels together. In the study, the structural system type of the models was chosen as the frame system with high ductility level, and the models were designed using three different column cross-section calculation formulas given in Figures 3 and 5, which are stipulated by the regulation for frames with high ductility level of the structural system type. The concrete grade was chosen in the models as C35 (characteristic compressive strength, f_{ck} = 35 MPa) and the reinforcement class as B420c (characteristic yield strength, f_{yk} = 420 MPa). The parameters taken into account in the design of the models are given in Table 2 in detail.

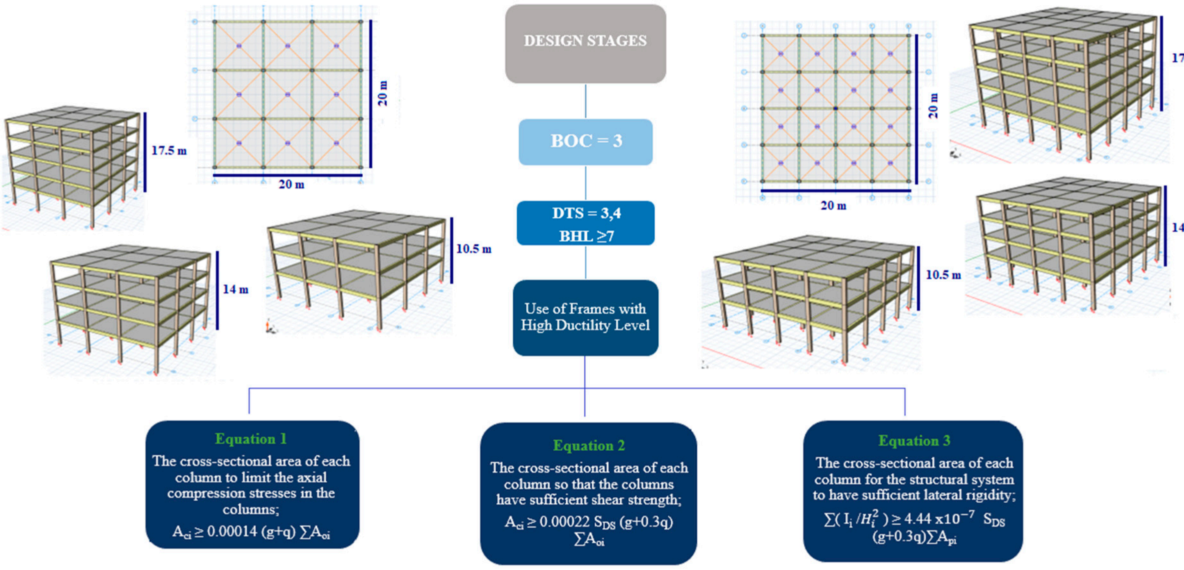
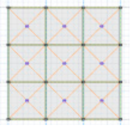
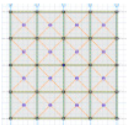
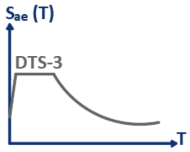
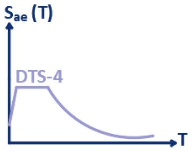


Figure 5. Flow chart of the formulas used in the building floor plan.

Table 2. Parameters used in building models design.

Plan Type/Span (m)	DTS	Soil Type	Number of Storeys and Building Height (H_N)	Equations Used in Calculation of Column Cross-Sectional Area
 **/6.66 m**  **/5 m**	  	**ZA** **ZB** **ZC** **ZD**	   	EQUATION 1 $A_{ci} \geq 0.00014\,(g + q)\,\sum A_{oi}$ EQUATION 2 $A_{ci} \geq 0.00022\,S_{DS}\,(g + 0.3q)\,\sum A_{oi}$ EQUATION 3 $\sum(I_i/H_i^2) \geq 4.44 \times 10^{-7}\,S_{DS}\,(g + 0.3q)\sum A_{pi}$

In Figure 5, there are visuals of two different floor plan models, designed as three-span (6.66 m) and four-span (5.00 m), designed as three storey, four storey, and five storey. The models' dead and live load values were chosen as g = 13 kN/m^2, q = 2 kN/m^2. Since the study aims to see how the building behaves for minimum values, columns, beams and slabs are dimensioned and designed according to the minimum values to meet the code. The width and height of the beams were chosen as 30 × 60 cm for three-span models and 30 × 50 cm for four-span models. Due to the requirement in the TBEC-2019 that the beam height will not be less than 1/11 of the span in buildings whose structural system consists of frames, the beam height was chosen as 61 cm in three-span models. The thickness of slabs with beams was chosen as 15 cm. Table 3 shows the beam reinforcement values calculated according to the code's relevant section reinforcement lower limits.

Table 3. Selection of beam reinforcements according to the general rules of TBEC-2019 (Section 17).

Model Type	**Beam Longitudinal Reinforcements**		
	Upper	**Bottom**	**Stirrups**
3 Spans	6Φ16	4Φ16	Φ8/13/10
4 Spans	6Φ14	4Φ14	Φ8/13/10

The same names are given to the columns with an equal sum of the area shares accumulated along all the slabs supported by the column, which is considered when calculating the across-sectional column areas. In addition, columns with an equal share of the accumulated area throughout all floors are shown with the same colour. For three-span building models and four-span building models, columns with an equal sum of accumulated area shares along all floors are shown in Figure 6.

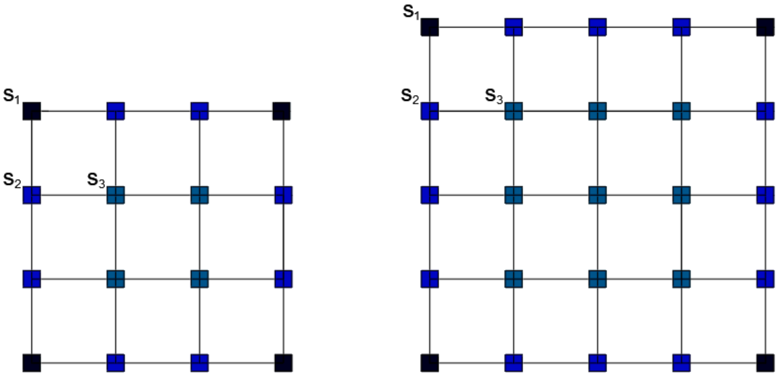


Figure 6. Location of columns S_1, S_2 and S_3 in plan, whose cross-sections are calculated for three-span and four-span building models.

The structural models designed in this study were named depending on the parameters. The criteria for naming the building models according to the parameters are explained in Figure 7.

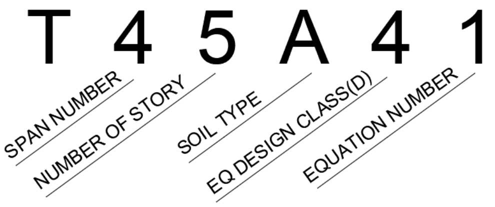


Figure 7. Codes of structural models.

In the relevant section of the TBEC-2019, the columns are dimensioned and reinforced using three formulas and reinforcement lower limits for the dimensioning of vertical load-bearing elements in the models selected as framed structural systems with high ductility levels. Since the formulas used in this study do not depend on the soil type, the column dimensions and reinforcement amounts do not change depending on the soil type. For this reason, 144 models depending on the parameters were analyzed in this study. However, only 36 of these models have different column cross-sections. Column dimensions and selected reinforcements of 36 models with different column cross-section values are shown in Table 4.

Table 4. Column dimensions and reinforcements details for each model.

Model Type	Column Sections			Column Longitudinal Reinforcement			Column Lateral Reinforcement		
	S_1 (cm)	S_2 (cm)	S_3 (cm)	S_1	S_2	S_3	S_1	S_2	S_3
T45A41	30	36	51	8Φ14	6Φ14 + 2Φ16	8Φ16 + 4Φ18	Φ8/15/10	Φ8/16/10	Φ8/20/10
T45A42	30	30	31	8Φ14	8Φ14	8Φ14	Φ8/15/10	Φ8/15/10	Φ8/15/10
T45A43	36	36	36	6Φ14 + 2Φ16	6Φ14 + 2Φ16	6Φ14 + 2Φ16	Φ8/16/10	Φ8/16/10	Φ8/16/10
T35A41	34	48	68	8Φ14	12Φ16	16Φ18 + 4Φ14	Φ8/17/10	Φ8/20/10	Φ8/20/10
T35A42	30	30	41	8Φ14	8Φ14	2Φ14 + 6Φ18	Φ8/15/10	Φ8/15/10	Φ8/20/10
T35A43	41	41	41	2Φ14 + 6Φ18	2Φ14 + 6Φ18	2Φ14 + 6Φ18	Φ8/20/10	Φ8/20/10	Φ8/20/10
T45A31	30	36	51	8Φ14	6Φ14 + 2Φ16	8Φ16 + 4Φ18	Φ8/15/10	Φ8/16/10	Φ8/20/10
T45A32	30	31	43	8Φ14	8Φ14	8Φ18	Φ8/15/10	Φ8/15/10	Φ8/20/10
T45A33	43	43	43	8Φ18	8Φ18	8Φ18	Φ8/20/10	Φ8/20/10	Φ8/20/10
T35A31	34	48	68	8Φ14	10Φ14 + 4Φ16	16Φ18 + 4Φ14	Φ8/17/10	Φ8/20/10	Φ8/20/10
T35A32	30	41	58	8Φ14	2Φ14 + 6Φ18	4Φ14 + 14Φ16	Φ8/15/10	Φ8/20/10	Φ8/20/10
T35A33	48	48	48	10Φ14 + 4Φ16	10Φ14 + 4Φ16	10Φ14 + 4Φ16	Φ8/20/10	Φ8/20/10	Φ8/20/10
T44A41	30	32	46	8Φ14	8Φ14	6Φ16 + 4Φ18	Φ8/15/10	Φ8/16/10	Φ8/19/10
T44A42	30	30	30	8Φ14	8Φ14	8Φ14	Φ8/15/10	Φ8/15/10	Φ8/15/10
T44A43	35	35	35	8Φ14	8Φ14	8Φ14	Φ8/17/10	Φ8/17/10	Φ8/17/10
T34A41	31	43	61	8Φ14	8Φ18	10Φ16 + 4Φ24	Φ8/15/10	Φ8/20/10	Φ8/19/10
T34A42	30	30	36	8Φ14	8Φ14	6Φ14 + 2Φ16	Φ8/15/10	Φ8/15/10	Φ8/16/10
T34A43	39	39	39	8Φ16	8Φ16	8Φ16	Φ8/15/10	Φ8/15/10	Φ8/15/10
T44A31	30	32	46	8Φ14	8Φ14	4Φ14 + 8Φ16	Φ8/15/10	Φ8/16/10	Φ8/19/10
T44A32	30	30	39	8Φ14	8Φ14	8Φ16	Φ8/15/10	Φ8/15/10	Φ8/15/10
T44A33	41	41	41	2Φ14 + 6Φ18	2Φ14 + 6Φ18	2Φ14 + 6Φ18	Φ8/20/10	Φ8/20/10	Φ8/20/10
T34A31	30	43	61	8Φ14	8Φ18	10Φ16 + 4Φ24	Φ8/15/10	Φ8/20/10	Φ8/19/10
T34A32	30	36	52	8Φ14	6Φ14 + 2Φ16	8Φ18 + 4Φ16	Φ8/15/10	Φ8/16/10	Φ8/20/10
T34A33	46	46	46	4Φ14 + 8Φ16	4Φ14 + 8Φ16	4Φ14 + 8Φ16	Φ8/19/10	Φ8/19/10	Φ8/19/10
T43A41	30	30	40	8Φ14	8Φ14	8Φ16	Φ8/15/10	Φ8/15/10	Φ8/20/10
T43A42	30	30	30	8Φ14	8Φ14	8Φ14	Φ8/15/10	Φ8/15/10	Φ8/15/10
T43A43	32	32	32	8Φ14	8Φ14	8Φ14	Φ8/16/10	Φ8/16/10	Φ8/16/10
T33A41	30	37	53	8Φ14	8Φ16	14Φ16	Φ8/15/10	Φ8/16/10	Φ8/20/10
T33A42	30	30	32	8Φ14	8Φ14	8Φ14	Φ8/15/10	Φ8/15/10	Φ8/16/10
T33A43	36	36	36	6Φ14 + 2Φ16	6Φ14 + 2Φ16	6Φ14 + 2Φ16	Φ8/16/10	Φ8/16/10	Φ8/16/10
T43A31	30	30	40	8Φ14	8Φ14	8Φ16	Φ8/15/10	Φ8/15/10	Φ8/20/10
T43A32	30	30	33	8Φ14	8Φ14	8Φ14	Φ8/15/10	Φ8/15/10	Φ8/15/10
T43A33	38	38	38	8Φ16	8Φ16	8Φ16	Φ8/15/10	Φ8/15/10	Φ8/15/10
T33A31	30	37	53	8Φ14	8Φ16	4Φ16 + 8Φ18	Φ8/15/10	Φ8/16/10	Φ8/20/10
T33A32	30	31	45	8Φ14	8Φ14	4Φ16 + 8Φ14	Φ8/15/10	Φ8/15/10	Φ8/20/10
T33A33	43	43	43	8Φ18	8Φ18	8Φ18	Φ8/20/10	Φ8/20/10	Φ8/20/10

4. Numerical Analyses Results

Both L and NL analysis methods have been performed for structural analysis to determine the building performance. Earthquake ground motion level was chosen as DD-2, since simple buildings were analyzed according to the simplifying rules of the TBEC-2019. Structural analyses were performed only for the design earthquake (DD-2) with a 10% probability of exceedance in 50 years (the repetition period for which is 475 years). The code was adapted for the DD-2 earthquake level for residential buildings and stated in the relevant section that the controlled damage (CD, in Turkish KH) level was sufficient for this earthquake ground motion level. The building knowledge level has been chosen extensively. The multipliers of dead loads, live loads, and earthquake loads are considered 1.0, 0.3, 1.0 (G + Q+E) respectively. Snow load is neglected in the roof in all the structural models. Considering that the vertical earthquake effect is small, it is assumed that the structures are not exposed to vertical earthquakes. The base shear force–top displacement relationship and performance points were calculated for each model, respectively. These calculations were determined as shown in Figure 8.

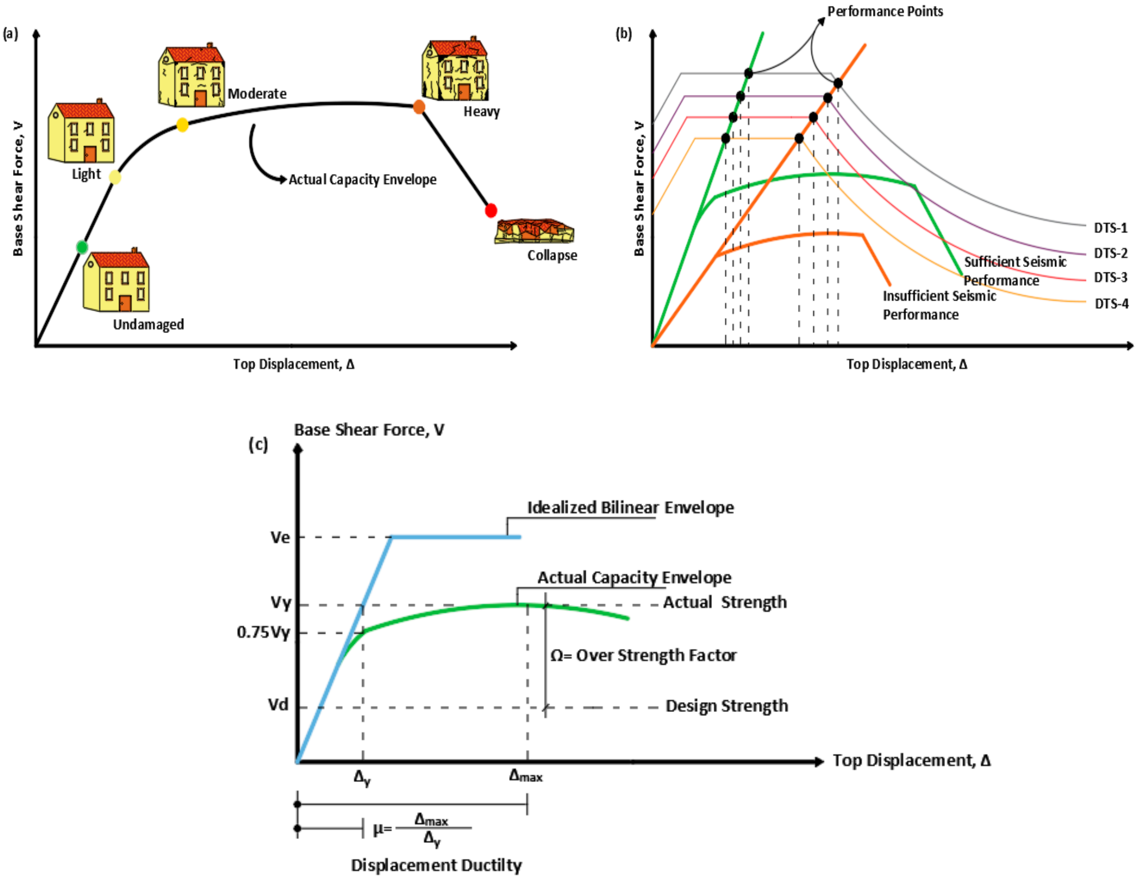


Figure 8. Lateral load–top displacement curve under earthquake and determination of performance point: (**a**) building performance levels; (**b**) comparison of capacity curves; (**c**) V_d/V_y.

The damage situation is determined according to the point where the structure is located on the capacity curve, drawn depending on the displacement of the structure under the effect of earthquake force in the graph (a) considering Figure 8. Graph (b) compares the capacity curves of the strong building and the weak building. Spectrum curves are elastic curves. The spectrum curves of the buildings do not intersect with the inelastic force–displacement graph. The force–displacement graphs obtained as a result of the pushover analysis are linearized, perpendiculars are drawn to the force–displacement graph from the point where they cut the elastic design spectra, and the displacement values that will occur in the structures under the influence of the force coming to the structures during the earthquake are seen. The point where the linearized force–displacement graph and the spectrum curve intersect is called the performance point. On the other hand, graph (c) shows how much the force (V_d) that may occur to the structure under the effect of an earthquake is below the actual strength (V_y) for which the structure is designed. The ratio of the actual strength of the structure to the design strength (V_y/V_d) is defined as the over-strength factor (Ω or D) [73,74]. It is foreseen as 3 in the TBEC-2019 for "buildings where reinforced concrete frames cover all the earthquake effects with high moment transmitting ductility level". The predicted value for Ω in the TBEC-2019 was evaluated by comparing the values obtained from the study.

4.1. Performance Parameters of Building Models

Existing buildings were analyzed according to both analysis methods L and NL. The behavior of the models, which vary depending on the number of storeys of a building, soil type, over-strength factor (Ω), column cross-section formula, and the number of spans in the building floor plan, are investigated. As a result of the analysis of buildings with different parameters, building shear capacities (V_y) and base shear forces (V_d) were determined, and Ω was calculated. As a result of the performance analyses of the existing buildings, the building performance levels were determined according to the damage conditions. In the TBEC-2019, for all buildings that are not classified as tall buildings, an ordinary performance target is set as CD under DD-2. In the results of the analysis, CD or collapse prevention (CP) was evaluated depending on the plastic rotation limits, and building performance levels were obtained. The relative storey drift values were also calculated from the ratio of the displacements of the buildings to their heights.

4.2. Comparisons of Parameter Results

The results obtained from the structural analysis for models and the effects of different parameters, such as Ω, number of storeys of a building, number of spans in the building floor plan, soil type, and the column cross-section formula used on the building performance, were examined. The performance analysis results of three storey, four storey and five storey models are given in Figure 9, respectively. The figures show the number of buildings with a CD (i.e., adequate performance) level depending on the respective soil type and the methods used. The columns show the total number of models (NM) designed for each soil type and how many of these models reached the CD level in L and NL. In terms of the number of building slabs, it is seen that the five storey models meet the performance target more than the three and four storey models. It is seen that the models belonging to ZA and ZB soil types are more likely to provide target performance among three different building storeys. It is seen that the target performance of the three storey models of the ZC and ZD soil types is relatively low. When the linear analysis results for the models of three different building floors are examined, it is seen that the amount of buildings providing the target performance is low, especially in the three storey models. As a result of nonlinear analysis in ZC and ZD soil types, it is seen that the number of models that provide target performance is relatively high for five storey models.

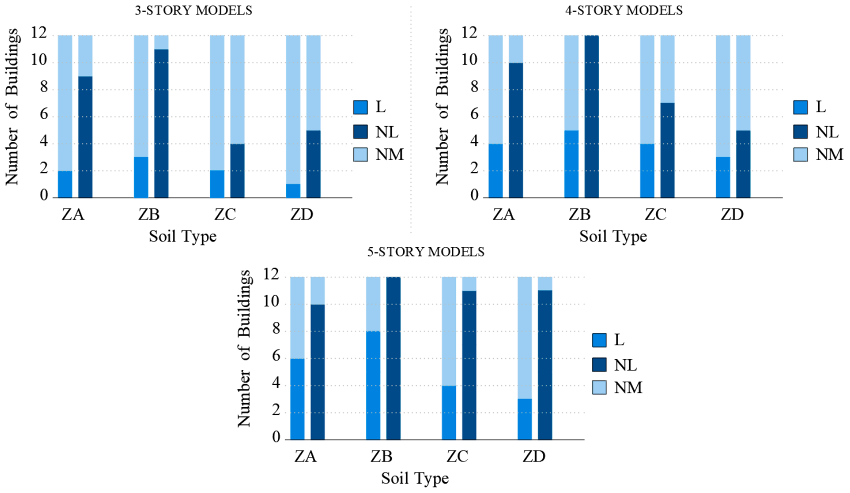


Figure 9. Distribution of buildings with sufficient performance according to the storey number/soil type parameters.

The analysis results of the models obtained according to Formulas 1, 2 and 3 in the TBEC-2019 are given in Figure 10. In the figures, the number of buildings with CD level is shown depending on the number of storeys of the respective building and the methods used. The columns show the total number of models designed for each column cross-section formula and how many of these models reach the CD level in L and NL. In the models designed using three different column cross-section formulas, it is seen that the number of building models that provide the target performance value is higher as a result of the L and NL analyses in the buildings calculated using the first and third formulas. When the analysis results of the models designed with the second formula are examined, it is seen that the second formula is not very sufficient. In the design with Formula 3, side and corner columns take higher values than side and corner columns. In Formulas 1 and 2, smaller cross-sections are obtained in columns calculated by using the second formula in the column cross-section formula. Since smaller column cross-section values were obtained in the models designed using the second formula, these models could not provide the target performance.

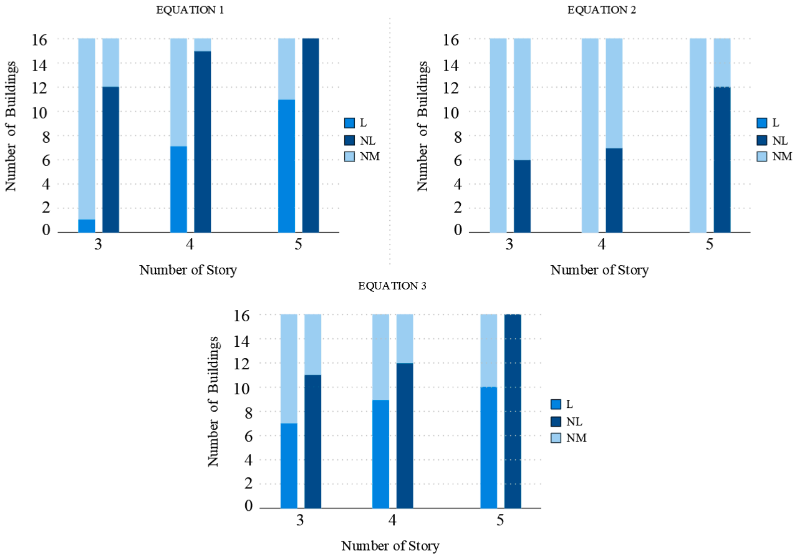


Figure 10. Distribution of buildings with sufficient performance according to the storey number / equation types.

Figure 11 shows the analysis results obtained by designing three different building storey numbers based on $S_{DS} < 0.33$ and $S_{DS} < 0.5$ values. The figures show the number of buildings with CD level depending on the number of slabs and the methods used for the relevant S_{DS} value. It is seen that the number of building models that provide the target performance is higher in the models designed for the $S_{DS} < 0.5$ value. Especially since the second and third formulas depend on the S_{DS} value, it is thought that the increase in the S_{DS} value contributes to the increase in the column cross-section. As the number of storey of the building increases, the number of models that provide the target performance within both S_{DS} values increases.

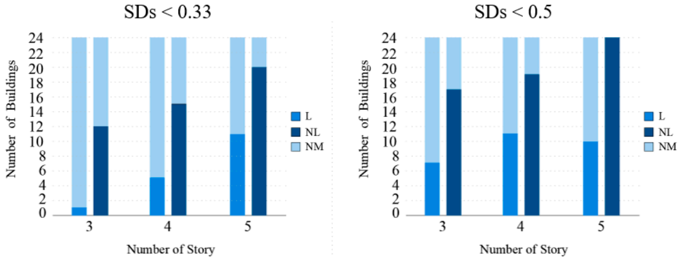


Figure 11. Distribution of buildings with sufficient performance according to the storey number/S_{DS}.

The analysis results for three storey, four storey and five storey building models with three spans (6.66 m) and four spans (5 m) are given in Figure 12. The figures show the number of buildings with CD levels depending on the number of spans involved and the methods used. The columns show the total number of models designed for each aperture number and how many of these models reached the CD level in the L and NL method. When the graphs are examined depending on the number of spans, it is seen that the number of buildings providing the target performance is higher in the four-span models. When investigate the number of storey in the two spans, it is seen that the number of models that provide the target performance is higher in five storey models.

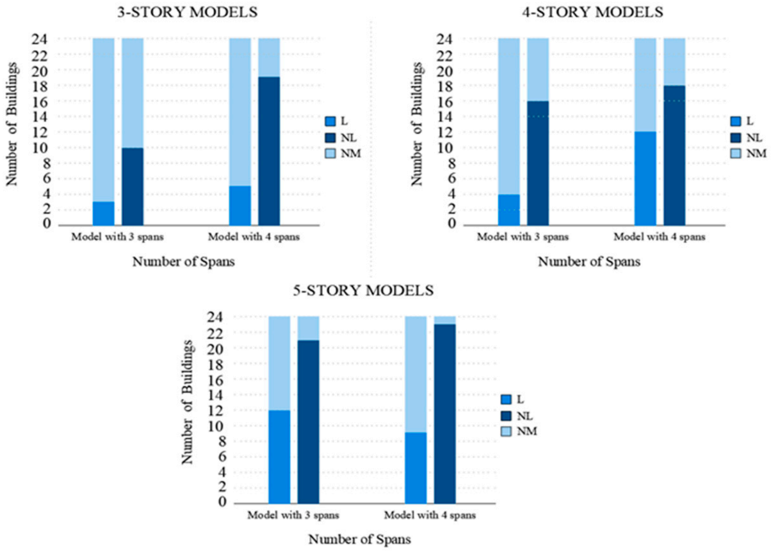


Figure 12. Distribution of buildings with sufficient performance according to the storey number/number of spans.

Figure 13 shows the analysis results of three storey, four storey and five storey building models calculated using the three different column cross-section formulas envisaged in the TBEC-2019. The figures show the number of buildings with a CD level based on the column cross-section formulas and the methods used for the number of storey in the relevant building. The columns show the total number of models designed for each column cross-section formula and how many of these models reached the CD level in the L and NL method. In general, it is seen that the models designed with the use of the first and third formulas in three different building storey are more likely to provide the target performance. In the models designed using the second formula, it is seen that no building model provides the target performance as a result of the linear analysis. It is seen that five storey models among three different building storeys provide the target performance more. It is seen that the number of models providing both analysis methods is high in four storey and five storey models designed using the first and third column cross-section formula. It has been observed that the column cross-section values calculated with three different formulas are larger in five storey models due to the larger area share. For this reason, it can be said that five storey models provide more target performance.

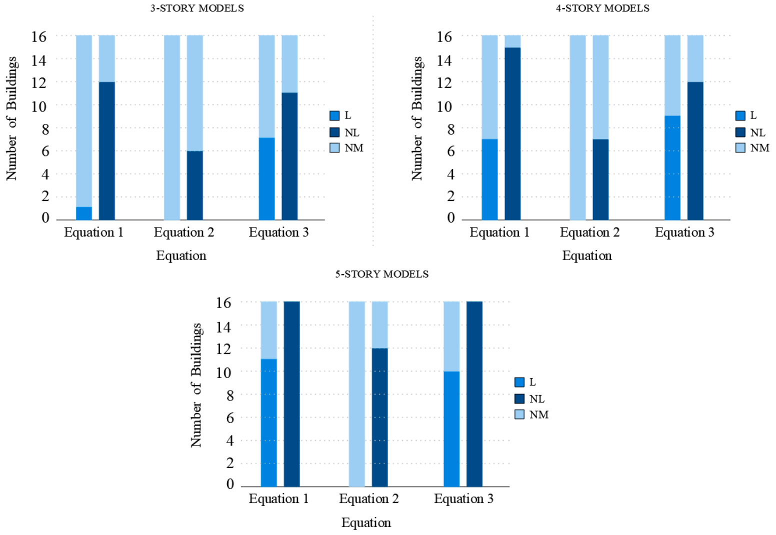


Figure 13. Distribution of buildings with sufficient performance according to the equation types/number of storeys.

Figure 14 shows the analysis results obtained by designing models with three different building floors according to three spans (6.66 m) and four spans (5 m). The figures show the number of buildings with a CD level, depending on the number of storeys and the methods used for the number of spans involved. The total number of models according to the number of building floors designed for each number of spans and how many of these models reached the CD level in the L and the NL are shown in the columns. It is seen that models with four spans provide more target performance than models with three spans in three different building storey. In the models with four spans, it is seen that the number of buildings providing the target performance is close to each other in the NL results within three different building storey. It is thought that the number of buildings providing target performance decreases as the span length increases. It is seen that the number of models that provide target performance decreases considerably with the increase in the span length, especially in three storey models.

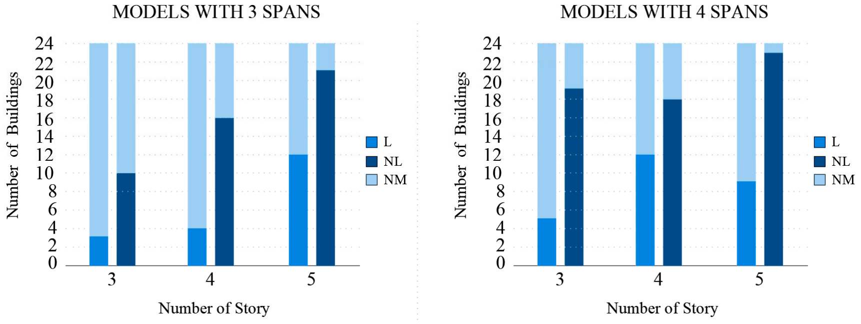


Figure 14. Distribution of buildings with sufficient performance according to the span number/number of storeys.

Figure 15 shows the analysis results for $S_{DS} \leq 0.33$ and $S_{DS} \leq 0.5$ for three storey, four storey and five storey models. The figures show the number of CD buildings based on the respective S_{DS} class and the methods used. The vertical axis shows the total number of models designed for each S_{DS} value, and how many of these models reached the CD level in the L and the NL method. In five storey models designed for $S_{DS} \leq 0.33$ and $S_{DS} \leq 0.5$ values, similar numbers of buildings provide target performance for both S_{DS} classes. For both S_{DS} values, it is seen that the number of building models that provide the target performance of the five storey models is higher than the number of buildings that provide the target performance of the three and four storey building models. When examining the three and four storey models, it is seen that the number of building models that provide the target performance of the models with the $S_{DS} \leq 0.5$ value is higher than the number of the building models that provide the target performance, especially in the linear analysis, the building models with the $S_{DS} \leq 0.33$ value.

Figure 16 shows the analysis results for four different soil types models. The figures show the number of buildings with a CD level, depending on the number of storey and the methods used for the respective soil types. The columns show the total number of models designed for different building floors for each floor class and how many of these models reached the CD level in the L and NL methods. Among the models with three different storeys, the target performance ratio is higher in ZA and ZB soil types. In models with ZC and ZD classes, it is seen that the amount of achieving the target performance for five storey buildings is high, while this amount is much lower in three and four storey models. In general, it is seen that the number of building models that provide target performance is higher in five storey models within four different soil types. It can be interpreted that the number of models providing target performance increases as the soil gets stronger.

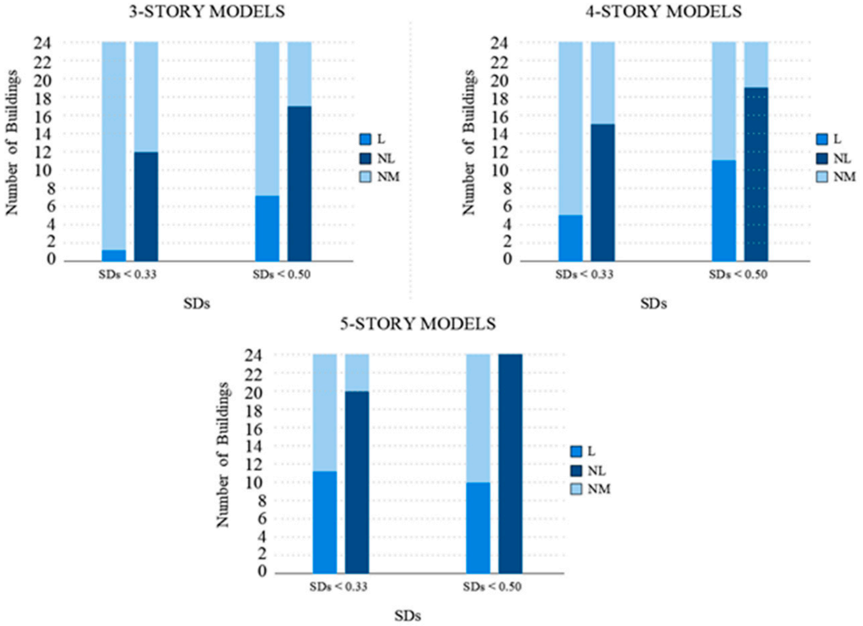


Figure 15. Distribution of buildings with sufficient performance according to the S_{DS}/storey number.

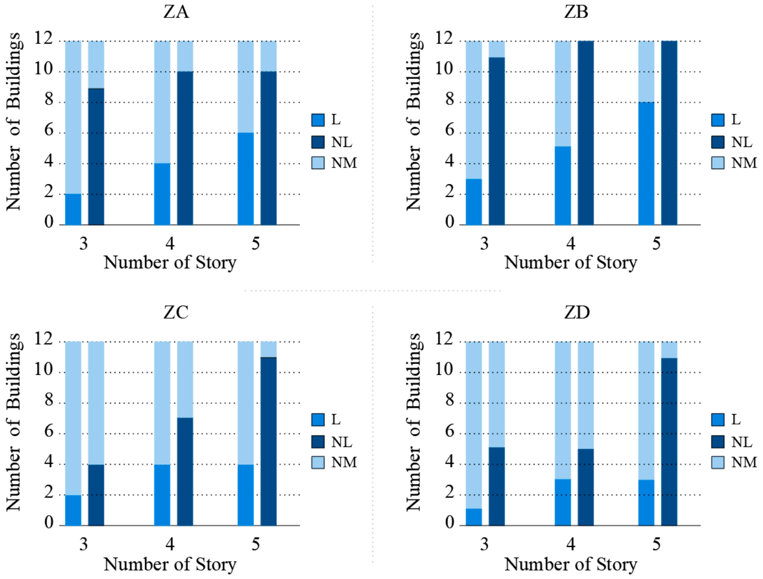


Figure 16. Distribution of buildings with sufficient performance according to the soil type/storey number.

Figure 17 shows the Ω coefficients obtained from the analysis of the models obtained by using three different column cross-section formulas predicted by the TBEC-2019. In the TBEC-2019, the number of storeys with Ω coefficients is foreseen as three for reinforced concrete buildings with carrier system-type frames. When the graphics are examined, it is seen that most of the models designed with the use of the first and third formulas have a coefficient of Ω of 3 and above 3. It is seen that approximately half of the models designed with the use of the second formula have a coefficient of Ω of 3 and above. It can be said that the reason for this situation may be that smaller column cross-sections are obtained as a result of using the second formula compared to other formulas.

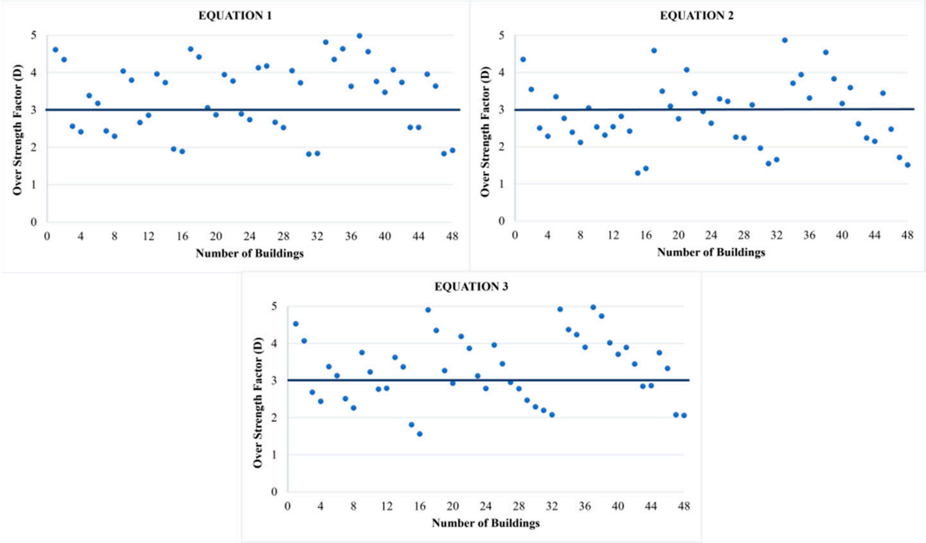


Figure 17. Distribution of the over-strength factor of the models of buildings designed different equations.

Figure 18 shows the relative storey drift values obtained according to the four different soil types and the number of building storeys. It is seen that the relative storey drift values for ZA and ZB soil types are also less for three different building storeys. For the ZD soil type, it is seen that this value is higher than other soil types. In the three and four storey models, it is seen that the relative storey drift values are quite high, especially in the ZC and ZD classes. In general, it is seen that the relative storey drift values of the five storey models are less. It is seen that the majority of the relative storey drift values of the models are generally 2‰–10‰.

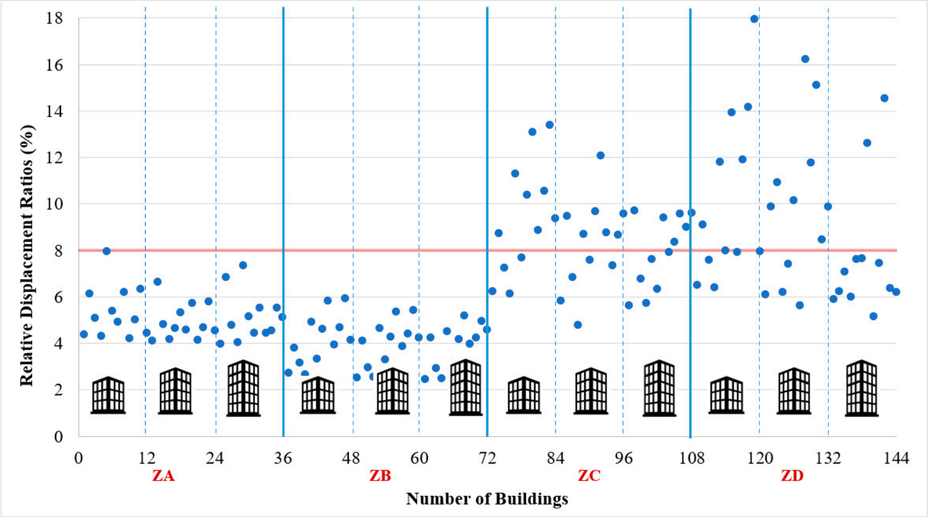


Figure 18. Distribution of the relative storey drift of all models according to the number of buildings and soil types.

In the TBEC-2019, if the infill walls are connected to the frame members without any flexible joints or gaps, the relative storey drift limit value is determined as 8‰.

In Figures 19 and 20, the values of Ω obtained according to the four different soil types and the number of building storeys of all designed models are shown. Ω (or D) is foreseen as 3 in reinforced concrete frame buildings in the TBEC-2019. In Figure 18, models that are below this value and cannot achieve the target performance (CD) due to the L analysis are scanned in red. In Figure 19, models with a coefficient of Ω below 3 and failing to provide CD due to NL analysis are scanned in red. When investigating the results of the models in general, it varies between 2.28–4.6 for ZA, 2.11–3.38 for ZB, 2.31–4 for ZC, and 1.29–3.96 for ZD in five storey models, respectively. For ZD, this ratio can give quite different results and remain below the desired value. For ZA, ZB and ZC models with 4 floors, the range is 2.5–4, and the desired value is generally provided. In models with ZD soil type, a few models are in the range of 2.5–4, and most of the models have an excess of strength below the desired value. In three storey models, it is seen that the excess strength coefficient of most of the models belonging to ZA, ZB and ZC soil types is generally 3 and above 3. For the ZD soil type, it is seen that there are models with an Ω above 3, as well as models with a range of 1.5–2, far below. In general, it is seen that the Ω value of the models belonging to the ZA and ZB floor classes in three and four storey models is both greater than the desired value and more than the five storey models. It is seen that the number of floors with Ω of the models belonging to the ZD soil type is relatively low.

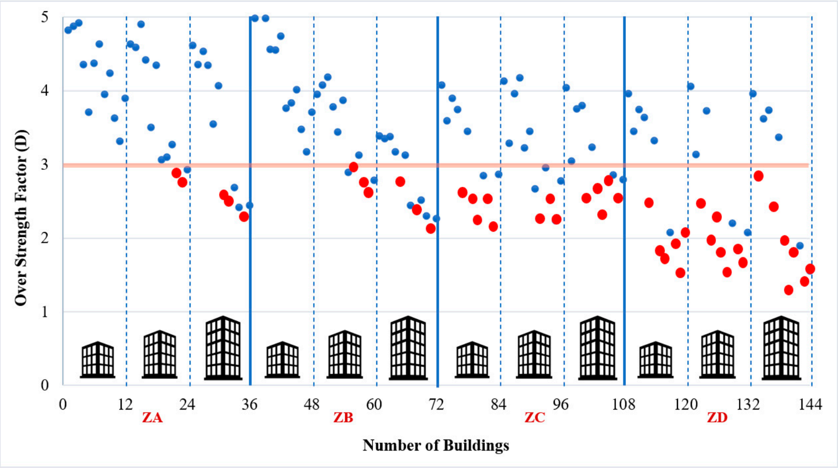


Figure 19. Distribution of the over-strength factor for all models according to the number of buildings and soil types (for linear analysis).

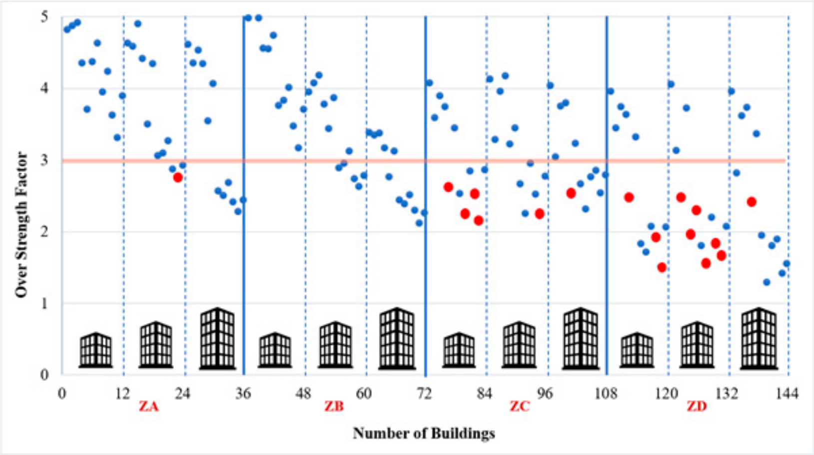


Figure 20. Distribution of the over-strength factor for all models according to the number of buildings and soil types (for nonlinear analysis).

5. Conclusions

In this study, a comprehensive numerical study was carried out with the performance analyses of 144 RC buildings, which were designed according to minimum column sectional criteria given in simplified methods of low-rise RC structures in the TBEC-2019. Models with different parameters (building models DTS, number of storeys, soil type, span length, and column cross-section) were prepared, to examine and control the behavior of the designed structures using the simple calculations in the related section of the TBEC-2019. The main findings of the study are summarized below;

- According to the analysis results, the number of models providing the CD performance level in the L analysis method is 44 (30.55%) and 107 (74.30%) in the NL analysis method. As a result, in the building designed according to minimum column sectional criteria given in simplified methods of low-rise RC structures, the performance criteria of the code cannot be met according to at least one method. It is noteworthy that such different results were obtained for the two analysis methods stipulated by the code.
- For different soil types, it is seen that the rate of achieving the target performance is higher in ZA and ZB soil types among models with three different building storeys. In the models with ZC and ZD classes, it is seen that the amount achieving the target performance for the five storey building model is high, while this amount is much lower in the three and four storey models.
- For the models designed using three different column cross-section formulas, it is seen that the number of building models that provide the target performance value is higher as a result of the L and NL analyses in the buildings calculated using the first and third formulas. When the analysis results of the models designed with the second formula are examined, it is seen that Formula 2 is not very sufficient due to the smaller column cross-section values obtained. For this reason, the relative storey drifts of the models were smaller in the models designed with the first and third formulas.
- For models designed with two different spans, when buildings with four spans (5 m) and three spans (6.66 m) are examined, it is seen that the building model that meets the performance target is higher in models with four spans. It can be said that the reason for this situation is that there are 25 columns in the four-span models, while 16 columns are included in the three-span models.
- For the models designed with two different S_{DS} values, it is seen that the models designed with the $S_{DS} < 0.5$ value reach the target performance more. For both S_{DS} values, it is seen that the number of building models that provide the target performance of the five storey models is higher than the number of buildings that provide the target performance of the three and four storey building models.
- For Ω, it is seen that the excess strength coefficient value for three and four storey models, especially for ZA and ZB soil types, generally reaches and exceeds the desired value of 3 in the TBEC-2019. In the five storey models, the coefficient of over-strength reached the value of 3 in general, but the results were not as high as in the three and four storey models. It is seen that the coefficient of over-strength is higher in the models designed with the first and third formulas. In addition, it is among the significant findings that the buildings with the over-strength coefficient below "3" will most likely not provide the performance level requested by the code.
- For the relative storey drift values, it is seen that the relative storey drift values of the five storey models are less than the three and four storey models. It is thought that in five storey models, the column cross-section values increase as the area share along all floors in the formula increases, and as a result, the relative storey drift is less than in three and four storey models. In terms of soil class, it is seen that the relative storey drift values are less for ZA and ZB soil types. It is seen that the relative storey drift values of the models designed with Formula 2 are relatively larger and they provide the code limit relative storey drift value less than the other formulas.
- For different building storeys, it is seen that the number of models that provide performance in five storey building models is higher than in three and four storey models. It is thought that this situation is due to the fact that the displacements of the three and four storey models are higher, although over-strength is large.
- Since the structures discussed in the study are new structures to be built, it is thought that the results obtained will change positively if the expected compressive strength of the concrete with 35 MPa characteristic compressive strength selected in the modelling is taken as the basis in the performance analysis.

- The simplified method proposed in the TBEC-2019 allows buildings that meet the relevant requirements to be designed very quickly without detailed seismic analysis. However, it is seen that the earthquake performance may not be sufficient in some of these structures designed according to minimum column sectional criteria.
- In this respect, the strength of the designed procedure explored in this study is simple and useful, and the weak side is that the desired earthquake performance of structures that are designed according to the simplified rules given in other parts of the TBEC-2019 could not be fully achieved in some buildings, especially with performance analysis where relatively complex analyses are required. The authors consider that while the simplifying rules are useful for engineers, the linear and nonlinear performance analysis section in the same code is partly complex for engineers. In this respect, structures designed according to minimum column sectional criteria, cannot meet a criteria of performance analysis which have complex rules, and this caused the results to be unsatisfactory.
- Differences in performance analysis approaches and acceptances in earthquake codes (such as Eurocode 8, etc.) will cause different results in modelling the same structures according to other codes.
- It is clear that the results will change if the structure systems are designed according to the detailed analysis procedure.

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