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Research Article

An investigation on determining optimum wall ratio–cost relationship of shear walled reinforced concrete buildings

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ABSTRACT

Reinforced concrete walls are very efficient structural elements in terms of carrying the lateral loads that are expected to affect the structures during the service of the buildings. These elements, which are not used for economic reasons in buildings designed in areas with low seismic hazard, can actually provide a significant increase in performance with a very small increase in construction cost. In this study, a total of 9 building models have been created and the relationship between optimum reinforced concrete wall ratio and cost on these buildings has been investigated. The design and analysis of the models were carried out according to the criteria specified in TSC 2018. Three different structural systems specified in TSC 2018 were used in the designed models. These structural systems used; RC frame structures, RC wall-frame structures and RC wall structures. These structures were analyzed by Response Spectrum Method which is linear analysis method and base shear forces were obtained. Then, push-over analysis, which is a nonlinear analysis method, was applied to obtain the base shear forces that the structure can actually carry. After the analysis, the quantities of materials to be used for the construction of the structural systems of the models were calculated and current manufacturing prices and rough costs were calculated. In order to compare the obtained costs with the structural performances, nonlinear shear forces and linear shear forces ratios were calculated and the over strength factors were calculated for each model. In the light of the data obtained from the studies in the literature, when the over strength factors and cost values are examined together, it is concluded that the optimum design for the conditions specified in TSC 2018 will be provided with the RC wall ratio between 0.001 - 0.0016. It is concluded that lateral load carrying capacity of construction increases up to 650% by increasing the construction cost by 17% for the designed models.

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1. Introduction

With the development of building manufacturing technologies, the costs of the buildings constructed have increased in line with the demand and purposes of use. The use of reinforced concrete walls has become an important issue in the design of the structural systems since the lateral forces that affect the buildings will increase with the increase of the building heights. In areas where the potential earthquake hazard is high, not only the presence of reinforced concrete wall elements in the floor plan, but also the positioning of these elements in the floor plan, the cross-sectional areas of the RC walls, the preferred RC wall ratio, etc. values are great importance in the design of the optimum structural system. In this study, it is aimed to compare the seismic strength and behavior of the building models designed by using different RC wall areas and to observe the effect of the change in the building cost on the building performance. It should be noted that it is possible to design different structural systems by keeping the construction cost constant. However, keeping the cost - performance relationship at an optimum level is also important in order to prevent loss of life and property under the effects of earthquakes.

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There are different studies on this subject in the literature. Andinç (2005), in his thesis study; concrete structures designed as high ductility level are considered as structural systems with walls and frames and RC walled structural system and determined the RC wall heights of these buildings up to 20 floors. Then, these RC walls were compared for different heights, different floor numbers, different site classes and seismic zones. In their study, Uçar et al. (2009), designed reinforced concrete walls symmetrically placed in the floor plan according to TDY 2007. Then they placed these elements on the internal and external axes of the floor plan and examined the effects of this positioning on the seismic behavior. Tekelli et al. (2008), have developed different analytical relationships using differential equations developed to calculate the displacement of reinforced concrete structures with framed and framed-framed structural systems. Thus, they have developed a very simple method for calculating structural shifts. Erken (2013), a concrete building designed as a residential building was used in his study. He designed 5 different structural systems in accordance with the architectural plan of this building. He investigated the effect of the changes in the ratio and distribution of reinforced concrete walls in structural systems on the parameters considered in the structure design. Aktan et al. (2010), examined the reinforced concrete walls, which are the most effective elements in carrying the lateral loads affecting on the structures. They emphasized the concepts of stiffness, strength and ductility required in building design and highlighted the importance of these titles in design of the seismic-resistant structures. They investigated behavioral changes obtained by changing the distribution of reinforced concrete walls on 8 different floor plans. Pakoğlu (2009), in his thesis, designed a 100 meter high building with reinforced concrete tube walled structural system and subjected this building to a performance analysis. Madddela et al. (2017) in their studies; they examined the effects of RC wall elements carrying lateral loads on performance by applying static push over analysis on two models with 10 and 15 storey symmetrical floor plans consisting of 5 equal bays in X and Y directions. In his study, Madenci (2019) presented an alternative solution procedure by using variational methods. The mixed-finite element method (FEM) is employed to obtain a beam element. The software (STA4Cad) used in this study uses the same method. Erkan et al. (2019) designed 3 different 5-storey building models with structural system with only frames, structural system with walls and frames and structural system with only RC walls. Then they applied linear static analysis (Equivalent Seismic Load Method) and static push over analysis on these structures. As a result of the study, they examined the effects of different RC wall ratios on the over-strength factors. Doğan (2019) determined 3 different building heights in his thesis. For each building height, 6 different RC wall ratios were determined and a total of 18 types of building models were created. Response Spectrum analysis and static push over analysis were applied on these models. After the analysis, he examined the over-strength factors for each building.

This study was carried out in order to determine the optimum wall ratio and cost relation in concrete reinforced concrete buildings. A total of 9 models were created within the scope of the study. One of them is the reference model without RC wall in its structural system, the remaining 8 models with structural systems that contain RC walls in the floor plan. The designed models were subjected to dynamic analysis with the Response Spectrum method. The analyses were performed in accordance the conditions specified in TSC 2018. The RC wall ratios in the analysis models range from ‰0.96 to ‰3.2, except for the reference model.

2. Analysis Study

2.1. Analysis models

In this study, 9 different building models were created in accordance with the analysis and design conditions specified in TSC 2018. One of these models is designed as a model with a structural system consisting of reinforced concrete frame elements (model with a wall ratio of 0). This model was used as a reference model to compare the results of other analyzes. Afterwards, 4 different models consisting of structural system with RC walled frames and 4 more different models consisting of structural system with only reinforced concrete walls were created. In TSC 2018 of the reference model, the response modification coefficient is given as R=8, the response modification coefficients of models consisting of structural systems with RC walled frames are given as R=7 and the response modification coefficients of models consisting of structural systems with only RC walls are given as R=6.

In the study, the h/b ratio of the smallest of the reinforced concrete wall dimensions used was determined as 6 and this ratio increased up to 20 (h: long face; and b: short face of shear wall).

RC wall ratio increased with the increase of preferred RC wall cross-sectional areas in the design of structural systems. In TSC 2018, the definition of RC wall ratio is given as; "the ratio of the total cross-sectional area of the reinforced concrete shear elements in any selected earthquake direction to the total gross area of all floors in the building". In addition to this ratio being equal to or greater than 0.002, it is accepted that if the ratio of design base shear force to total wall area is less than half of the f_{ctd} value of the concrete used in the structure design, the structural systems of the buildings consist of only RC walls (TSC 2018). The structural systems of buildings which cannot fulfill any of these conditions but still have RC walls in their structural systems are considered as RC walled frames.

Common geometric properties of models; all columns are 40x40 cm and all beams are 25x50 cm. Slab thickness was chosen as 15 cm and slab type was preferred as beamed plaque. The floor plans consist of 5 bays in each X and Y direction, 5 meters each. Total building height is 15 meters for all models with story heights of 3 meters. Concrete used for these models is C25 (25 MPa) and reinforcing rebar is S420 (420 MPa). All of the elements in structural systems are designed as frame elements so meshing process is not necessary for analyzes. Nomenclature of models in this study; The reference model was selected as Model 1 and continued until Model 9 for other RC walled models. The designed floor plans of these models are given in Fig. 1. Table 1 shows the selected RC wall sizes and RC wall ratios for each model. Fig. 2 shows the 3D views of the models.

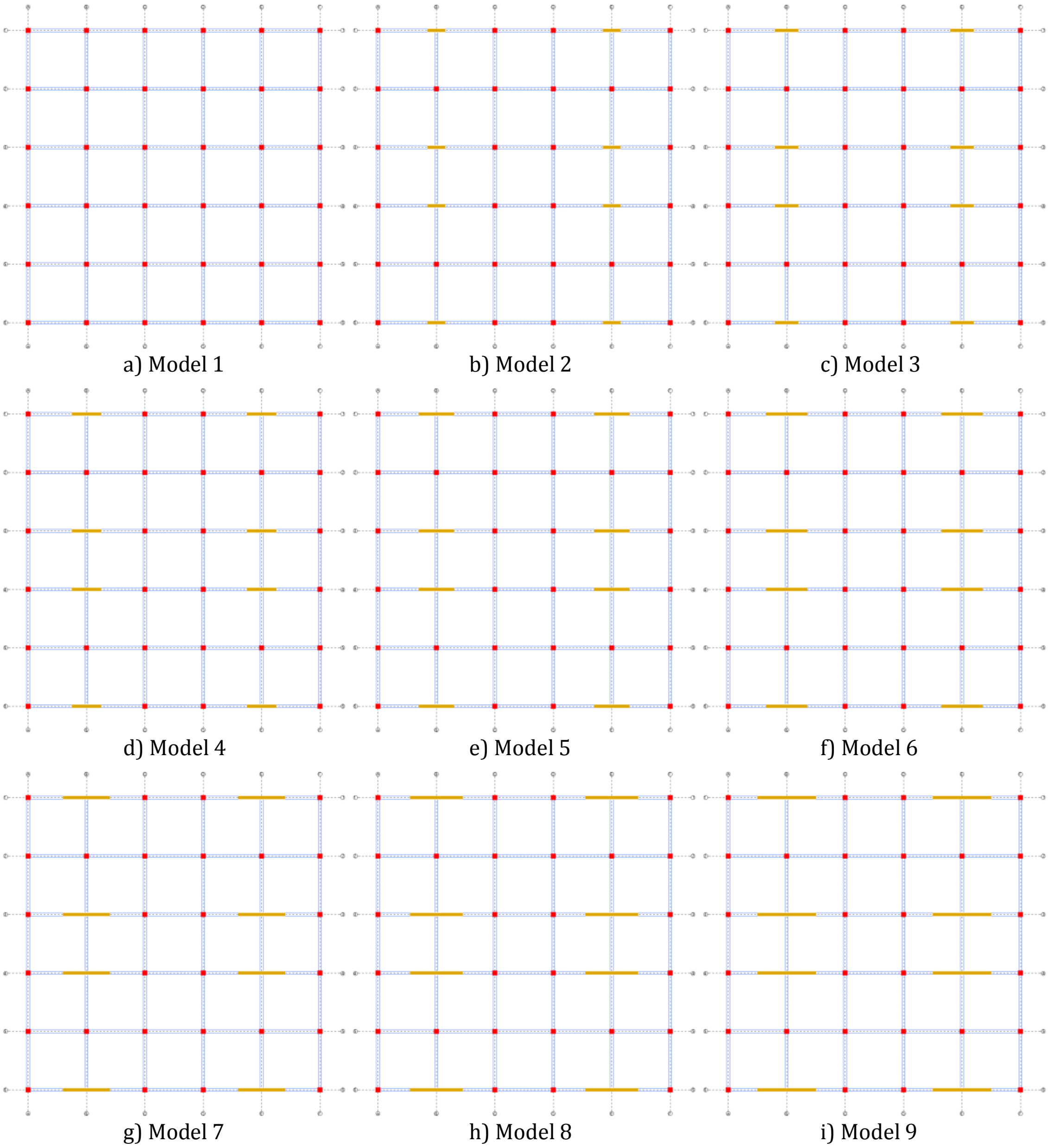
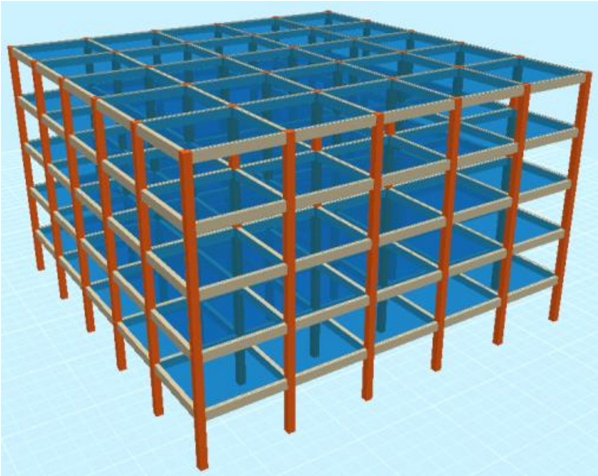


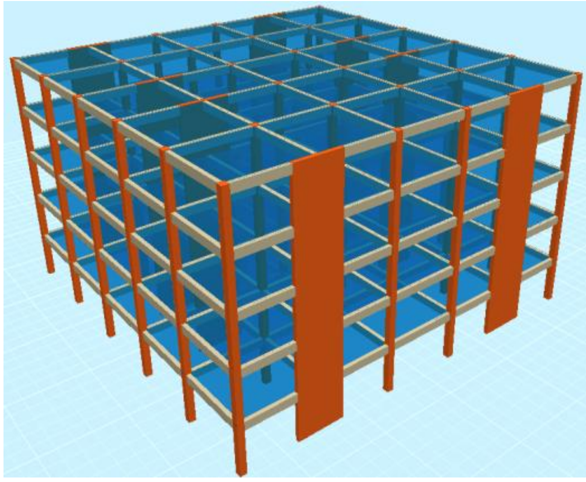
Fig. 1. Floor plans of the model.

Table 1. RC wall properties of the models.

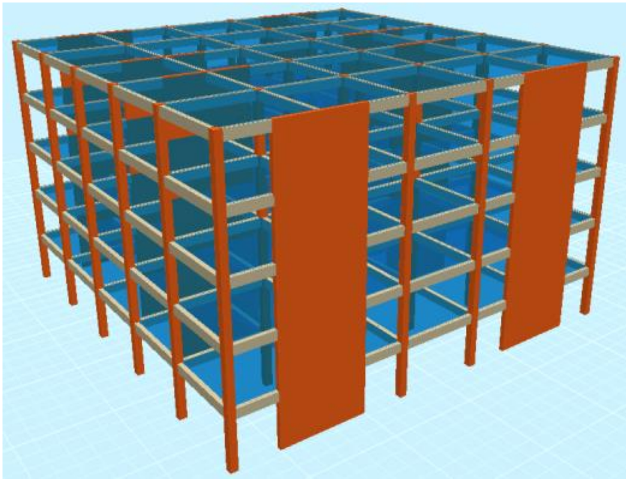
Models	Number of RC Walls	Wall Dimensions (cm x cm)	Wall Ratio
Model 1	0	0	0
Model 2	8	25 x 150	0.00096
Model 3	8	25 x 200	0.00128
Model 4	8	25 x 250	0.00160
Model 5	8	25 x 300	0.00192
Model 6	8	25 x 350	0.00224
Model 7	8	25 x 400	0.00256
Model 8	8	25 x 450	0.00288
Model 9	8	25 x 500	0.00320



a) Model 1



b) Model 5



c) Model 9

Fig. 2. 3D views of Model 1, Model 5 and Model 9.

2.2. Analysis methods

Following the design of the building models with floor plans and RC wall features, the analysis operations using STA4CAD v14 software were started (STA4Cad). The structures were first analyzed by the Equivalent Seismic Load Method and the base shear forces were obtained by linear calculation. The conditions given in the TSC 2018 for the application of this analysis are given in Table 2. In this table; *SDC* stands for seismic design class, *I* coefficient of significance, *BHC* stands for building height class, *BUC* stands for building use class and *n* is the live load multiplier.

Table 2. Conditions placed in TSC 2018.

SDC	1	*BUC*	3
I	1	*n*	0.3
BHC	5	Site Class	ZC

Response Spectrum analyzes were performed in accordance with the conditions given in TSC 2018. In similar studies in the literature, they used Equivalent Seismic Load Method as linear analysis method. However, Doğan (2019) compared Equivalent Seismic Load and Response Spectrum methods in his thesis and stated that more statistical and satisfactory results were obtained with Response Spectrum Method. Therefore, Response Spectrum method was chosen as the linear analysis method in this study. Using the interactive web application prepared for the Earthquake Hazard Maps in Turkey (AFAD, 2018), seismic parameters for the selected coordinates in Ankara - Çankaya were obtained. The obtained values are shown in Table 3. Selected coordinates was chosen because Ankara is the capital city of Turkey, and carries moderate risk in terms of seismic hazard.

Table 3. Seismic properties for selected coordinates.

S_S	0.340	S_1	0.118
S_{DS}	0.442	S_{D1}	0.177
PGA	0.148	*PGV*	9.981

Loads predicted to affect structures; G=2 kN/m^2 as dead loads, Q=2 kN/m^2 as live loads and G_W=5 kN/m as brick wall loads. Since the purpose of the buildings is residential, the live load multiplier in the load combination used for mass calculation is taken as *n*=0.3 from TSC 2018.

After the linear analysis, static push over analysis, which is a nonlinear analysis method, was started. The parameters of plastic hinges, which are one of the most important requirements of static push over analysis, have been determined in accordance with TSC 2018. A displacement value of 4% of the building height was loaded to the rigid diaphragm on the top floor of the building in a horizontal direction to obtain the base shear capacity of the structures. The term 'plastic hinge' should not be confused with the 'hinge' term commonly used in structural engineering. Because the hinge means a moment-free and freely rotating element. However, a plastic hinge means a cross-section of a member with a certain moment capacity, which carries moment until this capacity is reached and which can rotate under constant momentum when the capacity is reached. If we define the plastic hinge acceptance more theoretically; ductility coefficient, known as the ratio of the maximum deformations of the building element or model, with the deformations at the stage of yielding, where this coefficient value is high, the nonlinear deformations are restricted in a narrow area and the nonlinear bending deformations accumulate in certain regions known as plastic hinges; it can be assumed that the system or element sections other than those regions exhibit linear-elastic behavior. This acceptance is called as lumped plastic hinge. In line with these assumptions, static push over analyzes were performed on 9 different building models. Base shear forces obtained as a result of static push over analysis and base shear forces obtained from linear analyzes performed as the first step of the analysis study were compared and over-strength factors (D) were determined. The increase in the over-strength factors (D) is also examined in the results section due to the increase in the RC wall ratio.

2.3. Calculations of construction costs

After the analyses were performed on the models, the manufacturing quantities and costs of these structures were compared. Manufacturing quantities are only calculated for concrete (as m^3), reinforcing rebar (as tons) and mold (as m^2). The comparisons were made according to the over-strength factors. While calculating these costs, current pricing values are used by using the quantities calculated for the models. The obtained values are examined in relation to the increase in RC wall ratios in the results section. One of the main objectives of this study is to correlate the increase in building cost and the change in over-strength factors.

3. Analysis Results

3.1. Linear analysis

In the section of the analysis methods, the necessary data of the building models and the conditions specified in TSC 2018 are explained. Table 4 shows the base shear forces, total building weights and period values for the first 3 modes of the structures obtained from the linear analysis using these data. When these values in Table 4 are considered, it is seen that the linear base shear forces, which are predicted to affect the structure, increase with the increase of the ratio of reinforced concrete walls used in the buildings. This increase is valid as long as the decreasing period value is equal to or greater than the TA value in the acceleration spectrum with increasing stiffness. Building weights and base shear forces obtained as a result of linear analysis of the structures are compared in Fig. 3. It is seen that with the increase of RC wall ratio, the structural system weight of the buildings were increased by 5% and the shear forces were increased by 335% due to the increase in structural rigidity.

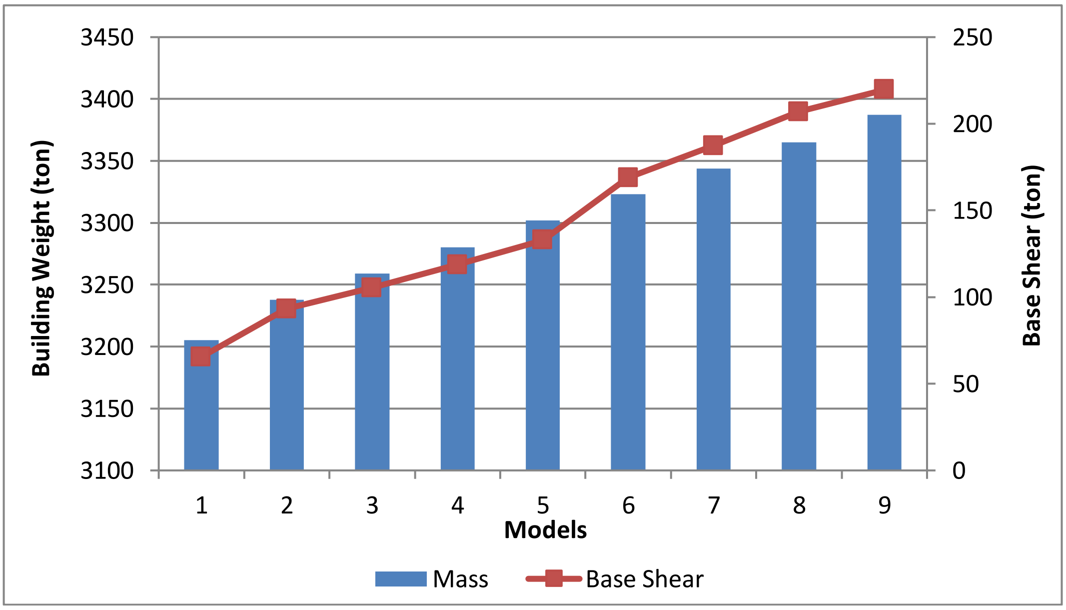


Fig. 3. Comparison of building masses and base shear forces.

Table 4. The results of linear analysis.

Models	Model Weight (ton)	Base Shear V_{tx} (ton)	Mod Periods (sec.)	Modal Mass Participation Ratios (%)
Model 1	3205	65.48	1.0042 (Y)	83.32
			1.0042 (X)	83.32
			0.8575 (T)	83.271
Model 2	3238	93.19	1.0480 (Y)	83.486
			0.8053 (X)	78.437
			0.7546 (T)	79.729
Model 3	3259	105.39	1.0467 (Y)	83.391
			0.7152 (X)	75.944
			0.6887 (T)	77.471
Model 4	3280	118.62	1.0453 (Y)	83.284
			0.6346 (X)	74.194
			0.6261 (B)	75.652
Model 5	3302	132.8	1.0443 (Y)	83.173
			0.5682 (B)	74.372
			0.5632 (X)	73.116
Model 6	3323	168.98	1.0434 (Y)	83.058
			0.5154 (T)	73.563
			0.5008 (X)	72.521
Model 7	3344	187.41	1.0429 (Y)	82.946
			0.4679 (T)	73.103
			0.447 (X)	72.247
Model 8	3365	206.89	1.0424 (Y)	82.833
			0.4257 (T)	72.893
			0.4011 (X)	72.187
Model 9	3387	219.6	1.0420 (Y)	82.721
			0.3887 (T)	72.857
			0.3621 (X)	72.269

X: represents the mode in X direction, Y: represents the mode in Y direction, T: represents the mode in torsion

3.2. Nonlinear analysis

After the linear analysis, static push over analysis step which is the second step of the analysis was started. In this analysis method; a horizontal displacement value determined by the height of the building is applied to a selected joint at the top level of the building. As a result of the analysis, the shear forces and plastic hinges that will occur on the structure are determined. Static push over analysis is based on obtaining the seismic performance of the structure by observing the base shear force that the structure can bear and the status of the plastic hinges formed on the structural system elements. The pushover curves obtained as a result of static pushover analysis of the structure models created on STA4CAD v14 program are given in Fig. 4. When these curves are examined, it is seen that the increase in shear rate and the increase in base shear forces become more pronounced compared to linear analyzes. RC wall elements, increase the stiffness of the structures against horizontal displacements and at the same time increase the base shear forces that the structure can bear. According to these data in Fig. 4, it is seen that the linear parts of the curves given for each structure, i.e. the stiffness of the structures, increase with the increase of the RC wall ratio.

Fig. 5 shows the ratio of the moment values that the RC walls meet to the total moments that affect the structure. These ratios increased with the increase in the amount of RC wall as shown in the Fig. 5. However, according to Fig. 5 it can be said that the increase in the slope of the curve is higher in the first four models, that are, the models with response modification coefficients R=7 compared to the models with R=6.

Table 5 shows the over-strength factors (D=V_{tx} / V_{tx}) obtained by the ratio of the base shear forces (V_{rx}) determined by the static pushover analysis, which is the nonlinear calculation method, to the base shear forces (V_{tx}) obtained by linear analysis. The aim of this study is to determine the most efficient structure design by comparing the over-strength factors and building costs together. The desired design of the structure was selected for the RC wall ratio and the distribution of the RC walls in the floor plan.

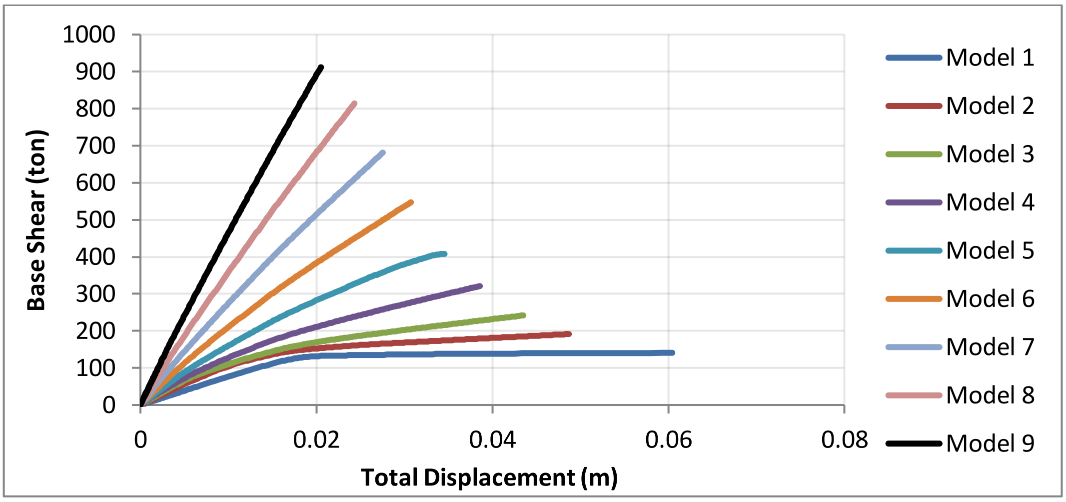


Fig. 4. Push-over curves for all models.

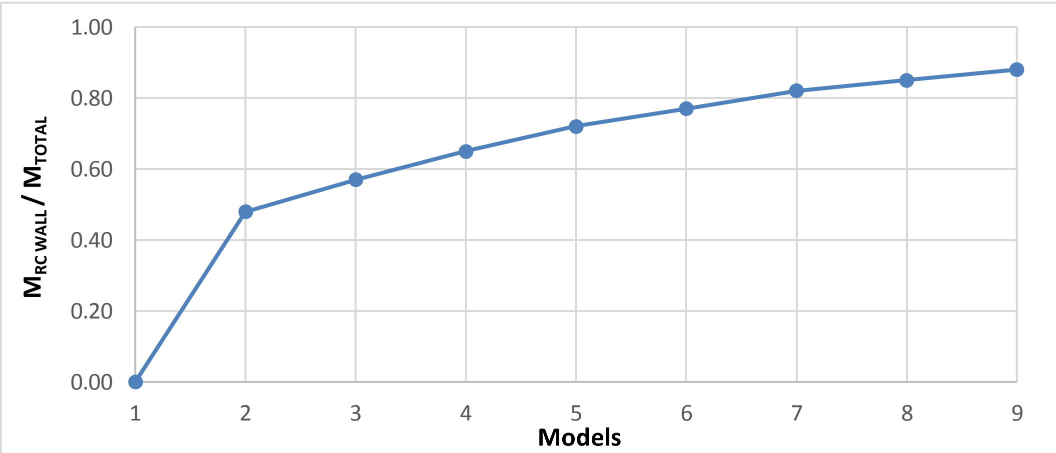


Fig. 5. The ratio of RC wall base moment to total turning moment.

Table 5. Nonlinear analysis results and over-strength factors.

Models	V_{rx} (ton)	V_{tx} (ton)	Over-strength Factors (D = V_{rx}/ V_{tx})
Model 1	140.891	65.48	2.15
Model 2	191.545	93.19	2.06
Model 3	241.836	105.39	2.29
Model 4	320.989	118.62	2.71
Model 5	407.73	132.8	3.07
Model 6	547.178	168.98	3.24
Model 7	681.362	187.4	3.64
Model 8	814.14	206.9	3.93
Model 9	911.743	219.6	4.15

3.3. Calculation of construction costs

The strength coefficients of the analysis models designed within the scope of the study and subjected to certain analysis operations were made by considering the base shear forces. The ratio of the over-strength factors to the rough cost values of the structures were determined and comparisons were made between the structures. Mentioned rough costs of building models are calculated as; multiplying the quantities of rebar, concrete and the mold elements of the structural systems were determined and the current unit price values. Fig. 6 shows the comparison of the rough costs of concrete, mold and rebar between models.

In order to observe the most accurate situation, the over-strength factor values and the roughly calculated costs of the structures were compared in a common diagram. These values are given in Table 6 for each building model. Then, the ratio of the over-strength factors to the rough costs of each structure was calculated. The values obtained with this ratio are compared in Fig. 7. D/$ values also increased with the increase in RC wall ratio, since the over-strength factors and building costs showed a consistent increase.

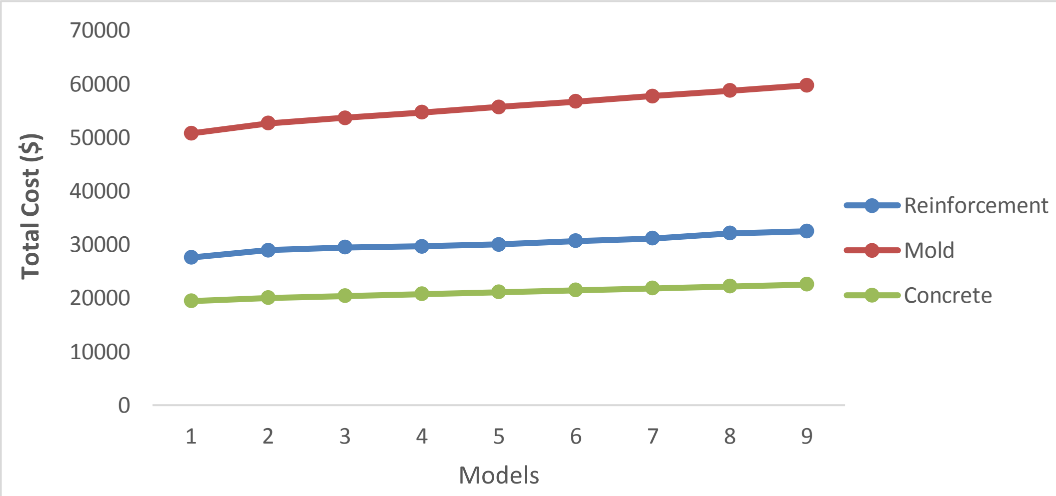


Fig. 6. Comparison of total costs of the models.

Table 6. Nonlinear analysis results and over-strength factors.

Models	Roughly Calculated Total Costs ($)	Over-strength Factors (D)	(D / $)
Model 1	97764.8	2.15	2.19916×10^{-5}
Model 2	101639.9	2.06	2.02676×10^{-5}
Model 3	103531.8	2.29	2.21188×10^{-5}
Model 4	105098.3	2.71	2.57854×10^{-5}
Model 5	106817.2	3.07	2.87407×10^{-5}
Model 6	108851.1	3.24	2.97654×10^{-5}
Model 7	110690	3.64	3.28846×10^{-5}
Model 8	112987.9	3.93	3.47825×10^{-5}
Model 9	114750.7	4.15	3.61654×10^{-5}

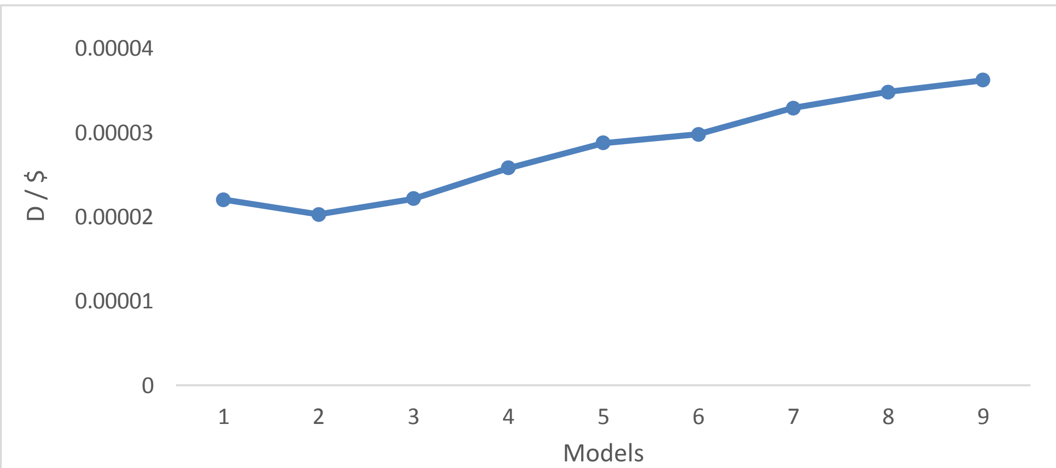


Fig. 7. ‘Over-strength factor / total cost’ values for each model.

4. Conclusions

Within the scope of the study, the models subjected to linear and nonlinear analyzes; base shear forces, over-strength factors, structural system quantities and rough costs were obtained. The base shear forces obtained in linear analyzes were obtained by using the Response Spectrum Method and the base shear forces obtained in the nonlinear analyzes were obtained by static pushover analysis. As shown in Table 5, the over-strength factors of the structures were obtained by the ratio of base shear forces obtained from nonlinear analysis to base shear forces obtained from linear analysis. According to TSC 2018, for structures with response modification coefficient R=8, the over-strength factor is D=3, for structures with response modification coefficient R=7, the over-strength factor is D=2.5 and for structures with response modification coefficient R=6, the over-strength factor is D=2.5. Models examined within the scope of this study; Model 1 with R=8 and Model 2 and Model 3 with R=7 remained below the over-strength factor values given in TSC 2018 and over-strength factors obtained for all other models were above the values placed in TSC 2018. It should not be understood that the structures do not provide the desired strength if the over-strength factor value is below the values specified by the regulations. The over-strength factor is a value obtained by ratio of yield strength to design strength of a building or structural element. It is understood that in all cases where this value is greater than 1, the structure can carry more loads than the design loads.

After the design and analysis procedures, in order to compare the costs of the structures, quantity calculations were made for the structural elements (concrete, rebar, and formwork). Rough costs of the structural systems of the models have been calculated by taking into consideration the current unit price values. As can be seen from Fig. 6, the cost for all buildings increased with an increase similar to the linearity with the increase in the ratio of the RC wall used. In particular, it is seen that the cost of formwork is higher than concrete and rebar. This is due to the fact that although the mold material is reusable up to a certain level of wear, the quantity of the mold is calculated for each floor without using this in consideration of the quantity calculations.

In the analysis, the rigidity of the structure increased as the RC wall ratio increased. As a result, the period of the models along the earthquake direction was reduced as expected and the seismic load affecting the structure was increased. However, as the stiffness of the building increased with the increasing RC wall ratio compared to the seismic force affecting the structure, the over-strength factor (D) also increased. Although the minimum D=2.5 given in TSC 2018, after Model 4, this value increases above 5. The model providing the results closest to the D value given in TSC 2018 was found to be Model 4 with a RC wall ratio of ‰1.4. Doğan (2019) found this value to be quite consistent with the optimum RC wall ratio of ‰1.

According to the results of the analysis, the increase in the weight of the structural systems of the models is due to the increase of the RC wall dimensions. With the increase of RC wall ratio, the shear strength of the structures increased approximately 6.5 times. Likewise, the increase in the structural system weight of the buildings by 5.6% increased the rough cost of construction by 17%. Accordingly, the weight of the structural system of the Model 1 (reference model with RC framed structural system) is 3205 tons, while the weight of the structural system of the model with the RC wall ratio of ‰3.2 (Model 9) has reached 3387 tons. As a result of this, it is seen that small increases in the dimensions of the vertical structural elements of the structure, significantly increase the strength of the structure against seismic effects.

Over-strength factors and rough construction costs of the structural systems are calculated by the analyses applied on the buildings. For the general purpose of the study, these two situations were handled together and an examination was made on the optimum design of the structures. If Table 6 and Fig. 7 are examined together, among the models designed and analyzed in accordance with the design principles specified in TSC 2018, the values obtained by the ratio of the over-strength factor value to the building cost of the Model 4 with the wall ratio ‰1.6, it was found that Model 4 provides the most efficient results for this study.

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