The Effect of Insufficient Cover Thickness on Structural Performance of Reinforced Concrete Buildings

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Abstract. Reinforcements used in RC structures lose their load-bearing capacity by suffering from various deteriorations due to external effects. Insufficient cover thickness is one of these reasons. The topic of this study consists of the concept of inadequate concrete cover. Concrete cover values with different thicknesses were chosen, and it was aimed to show how these values affect the performance of a building. Base shear forces, stiffness values and target displacement were obtained for each different concrete cover. A reduction in concrete cover resulted in an increase in the base shear force and stiffness values. Insufficient concrete cover layer will reduce the strength of the reinforcement over time. This will negatively affect the earthquake performance of the building. It should be kept in mind that the main function of a concrete cover is to prevent external effects which adversely affect the strength of the reinforcement. In this study, information was also provided about corrosion caused by the lack of concrete cover, and solutions to the corrosion were presented.

Keywords: Corrosion · Cover thickness · Net concrete cover · Performance

1 Introduction

Reinforced-concrete structures have emerged with the principle of withstanding of concrete and steel jointly against external loads. The general working principle of reinforced-concrete is such that the compressive stresses affecting a building are countered by the concrete, and the tensile stresses are countered by the steel. The position and arrangement of reinforcement used in the RC structural elements directly affect the calculations. The concrete cover used in the structural elements directly affects the effective depth value obtained according to the position of the reinforcement. The concrete layer, which ensures that the reinforcements used in the reinforced concrete bearing elements is completely contained in the concrete, is called the concrete cover. The aim of the concrete cover is to prevent the weakening of the reinforcement by preventing the corrosion of

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the reinforcement used in the bearing element due to external effects. In addition to this, especially against effects like fire, it ensures that the reinforcement has a longer-lasting load-bearing capacity. If the concrete cover is not sufficient, the strength of the reinforcement may decrease, causing the load-bearing capacity to completely disappear over time. Corrosion may be defined as the loss of qualities of metals by degradation as a result of an electrochemical reaction caused by the environment [1–4]. Corrosion of reinforced concrete steel is one of the important problems in the reinforced concrete construction sector. Corrosion of reinforcement used in reinforced concrete causes loss of the cross-sectional area of the reinforcement, formation of expansion pressure caused by cracking of the concrete overcoming the concrete cracking strength, decrease of service life, and cracking and peeling of the concrete covering. As a result, the adherence between concrete and reinforcement is reduced, which degrades the strength of the building. In extreme cases, even the structural integrity may break down [5–10]. In general, different types of corrosion rates directly affect the degree of deterioration [11]. There are various studies on corrosion of reinforcements [12–15]. Therefore, it is important to follow and monitor corrosion in structures where corrosion is likely to occur. This strategy is even more important in buildings with significance. Therefore, building a database by conducting corrosion studies on structures makes traceability more effective. Different methods may be used for this purpose [16–19]. One of the factors that cause corrosion in reinforcements is severe climatic conditions. For this reason, it is recommended that certain precautions are taken in the specifications and regulations related to buildings to protect the concrete's strength by accounting for the calculation of the concrete mixture, material selection, and the concrete cover layer to prevent corrosion [20]. It is important to know the factors that will affect the corrosion rate to eliminate the damage caused by corrosion. In general, the concrete cover prevents the reinforcement used in reinforced concrete from being influenced by temperature differences and prevents the reinforcement from rusting by preventing the contact of reinforcement with water and air. Maintaining the material properties of the reinforcement used in load-bearing elements increases the strength and resistance of the structure against external loads. If the concrete cover is inadequate, reinforcements rust easily and lose their bearing property over time. As a result of this, the life of the building decreases and we end up with buildings which do not have enough strength under additional loads such as earthquakes. Reinforcements can corrode from place to place and cause loss of diameter and quality. There are many reasons why corrosion occurs. Corrosion in reinforced concrete structures means a condition in which the reinforcement loses its strength over time because of rusting. The most important of these is the lack of net concrete cover in concrete elements. The increase in moisture content alongside chlorine ions in the air especially in places close to seashores increases the significant of concrete cover in terms of corrosion. One of the reasons why buildings collapse in earthquakes is the use of concrete covers that are inappropriate and inadequate. The adhesion between the reinforcement and concrete will not be sufficient if the concrete cover is inadequate. Thus, the concrete and the reinforcement cannot withstand the load by themselves. Moreover, the reinforcement exposed to corrosion will lose all of its strength over time. Another function of the concrete cover is to protect the reinforcement from fire. Concrete is more resistant to fire in comparison to steel. The fire resistance of reinforced concrete building elements is directly proportional to the thickness of the concrete cover layer and the quality of the concrete. It is an important point that concrete covers should be emphasized in this regard.

The inadequacy of the concrete cover in RC structures is a problem of workmanship occurring during the construction phase. The inadequacy of the concrete cover becomes an issue due to the fact that people who manufacture the iron and form of reinforcements, which will be used in load-bearing elements, do not show the necessary care. They try to overcome this problem that arises by using a fabrication material like plaster. It should not be forgotten that the concrete cover is a part of the reinforced concrete element. In this study, different concrete cover values were chosen in a sample RC building. The results were compared, and recommendations were made. The purpose of this study was to show the importance of the concrete cover. In this situation, it was the calculation of how a building would react to an earthquake. In the first part of the study, information is given about the terms concrete cover, and net concrete cover as well as the values found in the regulations. Information is given on corrosion, a serious problem resulting from lack of concrete cover. In the study, information is presented about the pushover curves used in structural analyses. Then, analyses were carried out for the selected three-story reinforced concrete structure, using the analyses included in the software.

2 Methodology

Concrete cover (c) is expressed as the distance between the center of gravity of longitudinal reinforcements used in a structural element and the outermost concrete fiber. Net concrete cover (cc) is used to provide the required adherence to reinforcements and protect reinforcements from external effects. Net concrete cover is the distance between the outer surface of the outermost reinforcement and the outermost concrete fiber [21]. The representation of concrete cover and net concrete cover thicknesses in any load-bearing element is given in Fig. 1.

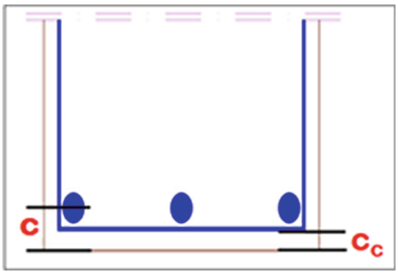

Fig. 1. Concrete cover (c) and net cover concrete (c_c)

As shown in Fig. 1, the relation between the thicknesses of concrete cover and net concrete cover is as follows.

$$c = \phi_l/2 + \phi_w + c_c \quad (1)$$

In this formula, ϕ_l is the longitudinal reinforcement diameter and ϕ_w is the transverse reinforcement diameter. The minimum net concrete cover thicknesses given in TS500 are presented in Table 1. When the effect of fire, corrosion and other harmful external factors may be excessive, the concrete cover thickness should be increased as much as necessary. This value is determined by the person who will design the building. There are no upper limitations in TS500.

Table 1. The required net concrete cover measured from the outside face of the outermost reinforcement [21].

In elements that are directly engaging with the ground	$c_c \geq 50$ mm
In columns and beams exposed to weather conditions	$c_c \geq 25$ mm
In columns and beams inside a structure, which cannot be exposed to external effects	$c_c \geq 20$ mm
In shear walls and floors	$c_c \geq 15$ mm
In shells and folded plates	$c_c \geq 15$ mm

One of the terms used while designing reinforced concrete (RC) structures is the term effective depth (d). Effective depth is defined as the distance from the center of gravity of the longitudinal reinforcement used in a building to the outermost concrete fiber in the compression region. Either of the thicknesses of concrete cover or net concrete cover may be used in the calculation of effective depth. Therefore, the insufficiency of concrete cover will directly affect the reinforced-concrete calculations of reinforced-concrete bearing elements. The effect of the amount of concrete cover to be applied on the calculation of effective depth should not be ignored.

The information regarding concrete covers in the TS500 Standard is rather incompatible with the equivalent European standards. EUROCODE 2 specifies the minimum concrete cover thicknesses according to environmental effect classes. Determining the thickness of concrete cover according to environmental effects is a necessary process for the service life of a building. It is more appropriate for designers to achieve this value as a result of calculation while choosing a concrete cover thickness. Concrete characteristic strength (f_{ck}), type of reinforcement, maximum diameter of reinforcement, environment exposure class, design working life member with slab geometry, concrete cast against uneven surface, special quality control of the concrete production, nominal aggregate size greater than 32mm and nationally defined parameters were taken into account as the input data for calculating the nominal concrete cover (c_{nom}) [22]. These data were used for calculation of structural class, concrete cover for durability ($c_{min,\ dur}$), and concrete cover bond ($c_{min,b}$). With these data, the minimum concrete cover (cmin) was calculated. The nominal concrete cover was obtained by adding the allowance for the deviation value (Δc_{dev}) to the obtained minimum concrete cover (c_{min}). The minimum cover may be reduced or increased for special conditions [22]. The concrete cover layer is obtained as a result of calculations in some parameters as well as limit values in EC2. In TS500, only the type of structural element is taken into consideration that given Table 1 for net concrete cover. There is no calculation method for concrete cover, therefore, the necessary modifications should be made on TS500 for the calculation-based thickness of concrete cover.

In this study, pushover analysis was used for determining the earthquake performance of building models. Pushover analysis is the common name for a type of procedure that uses simplified nonlinear analysis. Pushover analysis investigates the behavior of structures under earthquake loads in a non-linear manner. Sufficient information may be obtained about the seismic demands of structural systems and components resulting from design ground motion with pushover analysis. This method is a static procedure and practical way of showing a building's behavior in the inelastic region. The base shear force and peak displacement obtained from this analysis provide the capacity curve of the building. The pushover curve is a diagram obtained by geometrically combining the intersection points on an interaction diagram of the roof displacement values corresponding to the base shear forces under the applied load by increasing the structure from zero to unstable (Fig. 2). The pushover curve becomes meaningful by transforming it into modal capacity diagrams and calculating the maximum inelastic displacement capacity of the structure. Conventional pushover analysis is employed in the estimation of the horizontal capacity of structures implying a dynamic response that is not significantly affected by the levels of deformation incurred (i.e. the shape of the horizontal load pattern, which aims at simulating dynamic response, can be assumed as constant). It is automatically incremented by the program until it reaches the user-defined limit or a numerical error [23–34].

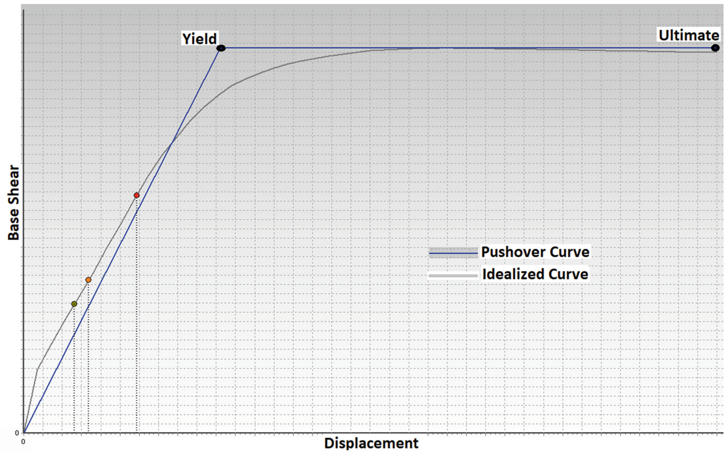

Fig. 2. Typical pushover and idealized capacity curves

In the study, a three-story reinforced concrete structure was selected and modelled three-dimensionally. The blueprint of the examined structure is shown in Fig. 3. A symmetrical building was chosen for ease of calculations.

Each story had an equal height and taken as 3 m. The material grades used for all structural elements was selected as C20 grade for concrete and S420 for steel grade in the software. All columns were selected as 0.40 * 0.50 m and beams were selected as

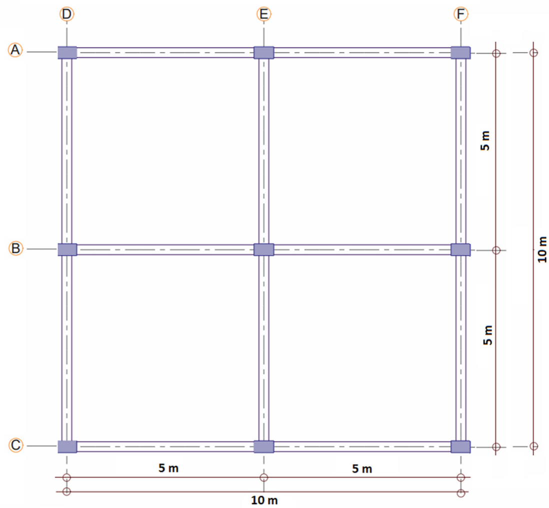

Fig. 3. The blueprint of the selected RC building.

0.25 * 0.60 m. The transverse reinforcements used in both elements were selected as ϕ10/10. The reinforcements used in the beams and columns were selected as ϕ14. The columns and beams used in the structure are shown in Fig. 4. The damping ratio was taken as 5% in all structural models. The ZA soil type which given in Turkish Building Earthquake Code (TBEC-2018) was chosen as the local ground class. The importance of structure was taken into consideration as Class II. Only the concrete cover thickness was selected as variable. All other values were the same in all models. The slabs were selected as rigid diaphragms.

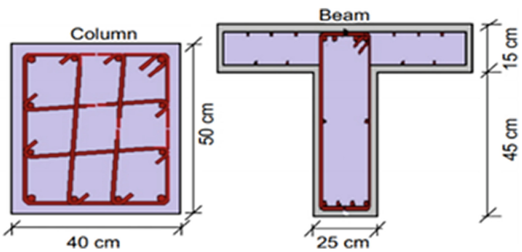

Fig. 4. The column's and beam's cross sections.

Different concrete cover thicknesses were chosen while making calculations about concrete cover. The calculations were made in the X direction by taking 0.001 m, 0.01 m, 0.02 m, 0.025 m, 0.03 m, 0.035 m and 0.040 m as the concrete cover values. It is not possible to select zero in the software. This value was chosen as the minimum possible value is 0.001 m. The Seismostruct software [35] was used to make the calculations. Permanent and incremental loads were applied to the structure in the software. Incremental load values of 11.11 kN and permanent load values of 5.00 kN were taken into consideration. The target displacement was selected as 0.18 m. All these values were taken as the same in all models that were used in this study. The three-dimensional model obtained in the software for the structure and the loads that were applied are given in Fig. 5.

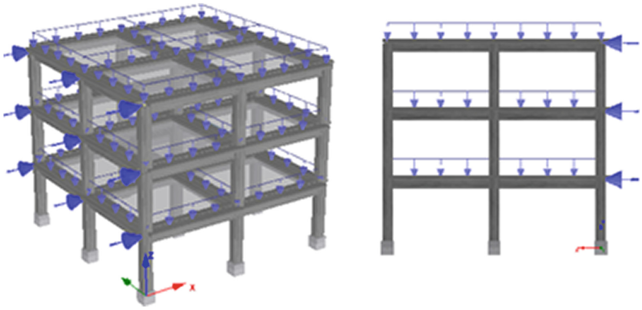

Fig. 5. The 3D and 2D models of the building

Three different situations were taken into consideration in this study. Firstly, the change of the concrete cover layer for a single column on the ground floor was examined. Secondly, only one beam on the ground floor was considered. Finally, different concrete cover thicknesses were considered in all columns and beams. The considered column and beam representations are shown in Fig. 6.

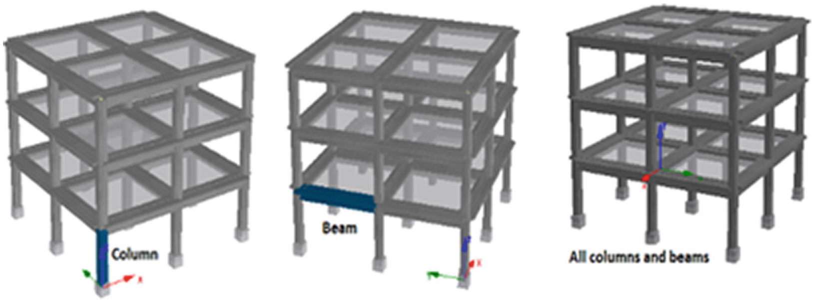

Fig. 6. The considered column and beam conditions in this study

The nonlinear concrete model [36] and steel model [37] were used for concrete and steel material. The stress-strain relationship of the material models considered in this study was given in Fig. 7.

Base shear forces for each construction model were calculated separately for both directions. Values were obtained for three different points on the idealized curve as displacement values. The first value refers to displacement at the moment of yield, the second value refers to the intermediate (d_{int}) displacement and the third value refers to the target displacement. The stiffness values of RC structural elements differ from the

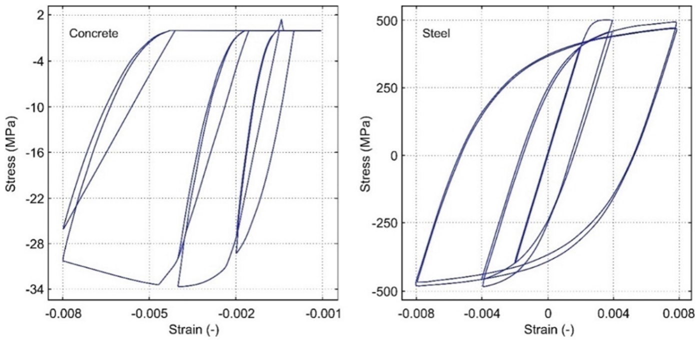

Fig. 7. The stress-strain relationship of material models for concrete and steel [35]

predicted stiffness values under the effect of an earthquake. Therefore, effective cross-sectional stiffness values are used in the design and analysis of these structural elements. The stiffness of cracked sections is taken into account to determine RC structural systems' performance under earthquake loads. The effective stiffness of cracked sections was obtained by using the prescribed stiffness reduction coefficients of the elastic stiffness value [38–40]. Elastic stiffness (K_elas) and effective stiffness (K_eff) values were also calculated separately for all models. It is crucial to determine the target displacements for damage estimation when certain performance limits of structural elements are reached in performance-based earthquake engineering. In the structural analysis, the limit states given in Eurocode-8 (Part 3) [41, 42] were taken into consideration for damage estimation used worldwide. All these displacements are shown in Fig. 8. Three different cases are stated for the damage cases in the software. These are considered as near collapse (NC), significant damage (SD) and damage limitation (DL). These values were calculated for all the structural models.

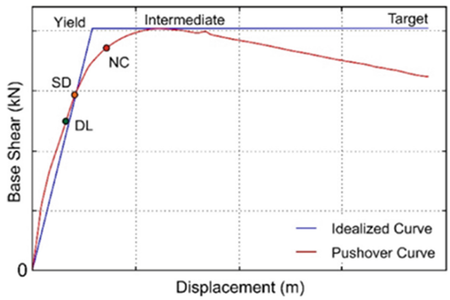

Fig. 8. Typical pushover and idealized curves and target displacements [43]

3 Results

For the selected sample reinforced concrete building, firstly, the change of the concrete cover for a single column located on the ground floor was considered. The pushover curve obtained due to the change of concrete cover on a single column is shown in Fig. 9 for the X direction.

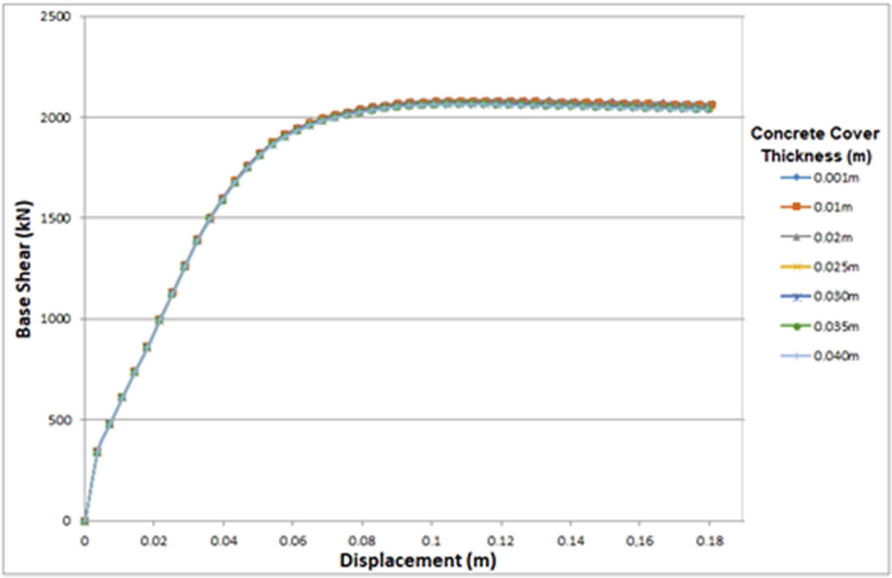

Fig. 9. Pushover curves obtained in the X direction due to concrete cover change for a single column on the ground floor

The comparison of all values obtained in the X direction as a result of the structural calculations for a single column is given in Table 2.

For the selected sample reinforced concrete building, secondly, the change of the concrete cover for a single beam located on the ground floor was considered. The pushover curve obtained due to the change of concrete cover on a single beam is shown in Fig. 10 for the X direction. The comparison of all values obtained in the X direction as a result of structural analyses for a single beam is given in Table 3.

As the concrete cover increased based on the analyses for changing the concrete cover on a single column or a beam on the ground floor, there is almost no difference in the base shear force. The period values were the same in all of these building models. An important change was not obtained on the elastic stiffness (K_elas) and effective stiffness (K_eff) values of the single column or beam models. The expected levels of performance are the same for all concrete covers. There was no change for the target displacement for performance criteria. The change in concrete cover was taken into account on all the columns and beams forming a concrete structure selected in the study. The pushover curves obtained due to the change of concrete cover on all the columns and beams are shown in Fig. 11 for the X direction. Table 4 shows the comparison of all values that were obtained in the X direction in case the same concrete cover value was selected for all columns and beams in the structure.

Table 2. Comparison of the results of analysis of concrete cover change for a single column

Concrete cover thickness (m)	Period (s)	Base Shear (kN)	Displacement (m)	K_elas (kN/m)	K_eff (kN/m)	DL (m)	SD (m)	NC (m)
0.001	0.2307	2086.05	0.0515	94835.83	40530.75	0.0131	0.0168	0.0292
			0.1086					
			0.1826					
0.010	0.2307	2080.20	0.0513	94832.83	40525.18	0.0132	0.0169	0.0293
			0.1084					
			0.1820					
0.020	0.2308	2074.04	0.0512	94755.05	40518.29	0.0132	0.0169	0.0293
			0.1081					
			0.1802					
0.025	0.2309	2071.00	0.0511	94694.87	40515.93	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.030	0.2309	2068.54	0.0510	94555.34	40501.58	0.0132	0.0169	0.0293
			0.1080					
			0.1798					
0.035	0.2309	2065.53	0.0510	94421.69	40499.14	0.0132	0.0169	0.0293
			0.1078					
			0.1796					
0.040	0.2309	2063.45	0.0510	94418.32	40486.27	0.0132	0.0169	0.0293
			0.1077					
			0.1794					

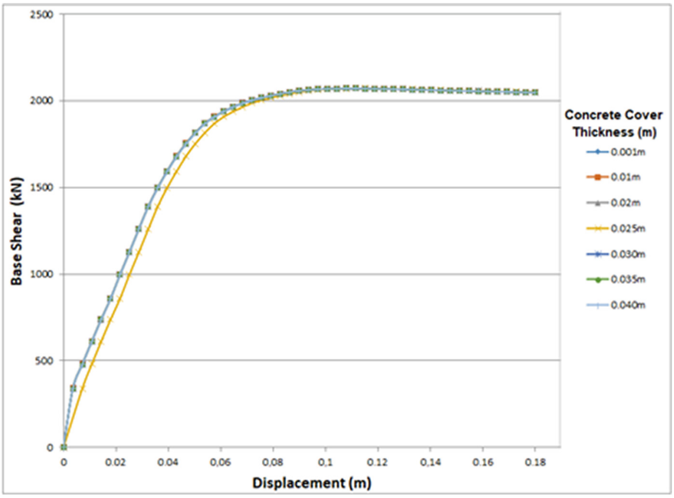

Fig. 10. Pushover curves obtained in the X direction due to concrete cover change for a single beam on the ground floor.

Table 3. Comparison of the results of analysis of concrete cover change for a single beam

Concrete cover thickness (m)	Period (s)	Base shear (kN)	Displacement (m)	K_elas (kN/m)	K_eff (kN/m)	DL (m)	SD (m)	NC (m)
0.001	0.2309	2071.00	0.0511	94907.59	40617.93	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.010	0.2309	2071.13	0.0511	94827.68	40583.53	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.020	0.2309	2071.13	0.0511	94471.08	40545.49	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.025	0.2309	2071.00	0.0511	94694.87	40515.93	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.030	0.2309	2071.00	0.0511	94658.52	40509.00	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.035	0.2309	2071.00	0.0511	94633.71	40488.71	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.040	0.2309	2071.00	0.0511	94591.15	40463.18	0.0132	0.0169	0.0293
			0.1077					
			0.1794					

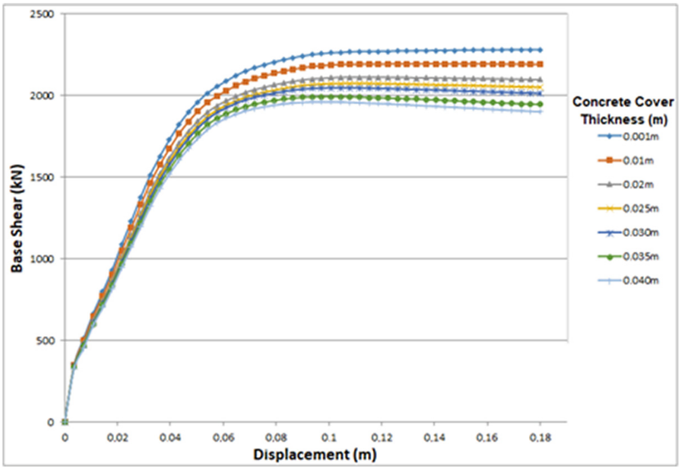

Fig. 11. Pushover curves obtained in the X direction for all columns and beams

Table 4. Comparison of the results of analysis of concrete cover change for all columns and beams

Concrete cover thickness (m)	Period (s)	Base shear (kN)	Displacement (m)	K_elas (kN/m)	K_eff (kN/m)	DL (m)	SD (m)	NC (m)
0.001	0.2267	2277.53	0.0539	97540.40	42244.05	0.0126	0.0162	0.0281
			0.1800					
			0.1800					
0.010	0.2285	2192.43	0.0523	96407.48	41938.20	0.0127	0.0163	0.0283
			0.1404					
			0.1800					
0.020	0.2305	2110.20	0.0516	95307.04	40907.65	0.0130	0.0167	0.0290
			0.1152					
			0.1800					
0.025	0.2309	2071.00	0.0511	94694.87	40515.93	0.0132	0.0169	0.0293
			0.1080					
			0.1800					
0.030	0.2317	2045.57	0.0507	94525.14	40368.05	0.0133	0.0170	0.0294
			0.1044					
			0.1800					
0.035	0.2324	1991.00	0.0499	93099.36	39928.57	0.0134	0.0172	0.0297
			0.1008					
			0.1800					
0.040	0.2334	1960.70	0.0499	91245.33	39267.17	0.0136	0.0174	0.0302
			0.9072					
			0.1800					

In case the value of concrete cover was the same for all the columns and beams of the building, the base shear force of the building was increased in the X direction due to the reduction of the concrete cover amount. When the cover was increased from 0.01 m to 0.40 m, the base shear force decreased by 11%. One of the reasons for this is that the effective height value decreases when the cover is increased. The increase in the effective depth was due to the small thickness of the concrete cover layer that was used. As the effective depth value increases, the amount of moment to be withstood by the structure will also increase. Considering the final damage conditions of the building models, it was determined that the amount of damage in the structure was increased as the concrete cover thickness decreases. This was due to the large base shear forces occurring at low concrete cover values. As the concrete cover thickness decreases, the stiffness value increases and depending on this increase, the period value has taken lower values. When the cover was increased from 0.01 m to 0.40 m, the period of building increased by 2%. This was due to the change in the effective depth value. Since the target displacement in the structure was chosen the same, this value was the same for all construction models. However, as the concrete cover layer increased, other displacement values in the structure decreased. A significant change was obtained on the elastic stiffness (K_elas) and effective stiffness

(K_eff) values of these models. When the concrete cover was increased from 0.01 m to 0.40 m, the stiffness of building decreased by 5%. This shows that the earthquake resistance of the structure decreases as the number of structural system element with insufficient concrete cover layer increases. With the increase of the concrete cover, the performance levels expected from the building also increased. As a result, the increase in the concrete cover layer decreases the effective depth and thus all structural calculations were affected. The selection of concrete cover values will directly affect the shear forces and damage conditions.

4 Conclusions

In this study, an attempt was made to show how changing the value of the concrete cover affects the performance of a building. For this purpose, a sample reinforced concrete structure was modelled with the help of a structural software. While the material class, sections, and loads remained the same, the thickness of concrete cover was chosen as variable. Pushover curves were obtained for each concrete cover value. The curves that were obtained were compared, the differences were observed, and the importance of the correct selection of the concrete cover thickness was emphasized. In this study, the importance of changing the concrete cover, which greatly affects the durability and performance of the structure, was clearly stated. Insufficient concrete cover reduces the life of a building and makes it vulnerable to earthquakes.

The minimum concrete cover thicknesses given in the TS500 standard are applied for all kinds of structures without any calculations. In Eurocode-2, the thickness of the concrete cover layer is decided according to the nature of the construction used and the environmental effects it will be exposed to. This study is important in that TS500, like Eurocode-2, should also set a calculation-based concrete cover thickness.

With TS500, which entered into force in 2000, the net concrete cover thickness has been expressed for the first time, and it has removed hesitations about the concrete cover. This added meaning to the basis of calculations of reinforced concrete structures. Any doubts that arise from the fact that the variations of transverse and longitudinal reinforcements have not been taken into consideration before have been removed. Studies should be carried out to determine the net concrete cover thickness, which is expressed independently of the transverse and longitudinal reinforcement, based on a calculation in the Turkish regulation.

In order for the concrete cover not to disappear, it is necessary to use fabricated elements instead of commonly used construction waste products. The concrete cover must be in sufficient quantity to fulfill the functions expected from it - to protect the reinforcement from fire, to prevent reinforcement corrosion and to ensure the adherence between concrete and concrete. Additionally, not using the concrete cover values specified on the project will change the obtained results to a large extent. This should not be ignored. The concrete cover directly affects the effective depth value used in the calculations of building elements. The elements used to provide the concrete cover are used to both protect the reinforcement against corrosion and increase the strength of the concrete against external effects. It is necessary for these elements to have the right material, shape and quantity depending on the place of use. If any of these are faulty and incomplete, problems arise during and after concrete casting. Therefore, the functions expected from the concrete cover layer will not be realized.

Adherence is one of the reasons why concrete and steel work together. An inadequate concrete cover layer affects adherence negatively. Therefore, the bond between the concrete and the steel will not be sufficient. This will cause loss of strain /stress transfer between the reinforcement and the concrete.

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