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Research Article

Performance based study on the seismic safety of buildings

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ABSTRACT

In the scope of this study, information has been provided on the Static Pushover Analysis which is a nonlinear deformation controlled analysis method and the Capacity Spectrum Method used to determine the performance point. In this study, static pushover analysis was made on a six-storey building with reinforcement concrete frame system by changing the materials, steel rebars and soil characteristics. The building's capacity curves were drawn and decided according to different concrete and reinforcement groups. Furthermore the performance points of different classes of concrete were studied according to three seismic effect levels. In the case of a decrease in the reinforcement strength, a decrease of approximately 30% occurs in the base shear force. If the concrete strength is increased, an increase of 11% occurred in the base shear force. Consequently, in the comparisons made with five different concrete groups and two different reinforcement groups, rather than the increase in the strength of the concrete, an increase in the reinforcement strength was observed to be more effective on the structural capacity. Furthermore, local soil classifications were observed to be the most significant point regarding peak displacement.

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1. Introduction

The concept of performance is a newly developed concept in earthquake engineering and was developed in the first place to determine the safety of the existing buildings. However, the possibility to use this method in new buildings came into question. It is estimated that in addition to classic rules, dimensioning principles based on the concept of performance that require a more detailed examination shall be included in the future earthquake regulations. Performance based design can be seen as an expansion of the classic design concept (Celep and Kumbasar, 2004).

It has been known for a long time that the constructional damage which occurs during earthquakes is not directly related with the fact that structural elements' current strength capacity has been exceeded under the equivalent seismic loads described by the regulations, but with the fact that the deformation capacity of structural elements which are expected to display ductile behaviour has been exceeded (ATC, 1996; FEMA, 1997-2000).

The global pushover curve obtained as a result of the pushover analysis indicates the nonlinear change of the base shear strength according to the horizontal displacement at the topmost storey. However the main purpose of the Nonlinear Static Method consists of determining the seismic demand concerning maximum displacements and especially concerning maximum plastic displacements under the effect of a given seismic effect, then to compare these demand values with deformation capacities defined for selected performance levels defined for selected performance levels and thus to evaluate its structural performance. Looking from this perspective, the pushover curve does not have a significance beyond showing the nonlinear strength and displacement capacities of the load-bearing system. As a consequence the coordinates of the pushover curve are transformed into modal displacement corresponding to the displacement of the normalized strength of the same system equivalent single degree of freedom system represented by the system's first natural vibration mode and modal pseudo-acceleration coordinates corresponding

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to the normalized strength of the same system. Subsequently, using nonlinear spectral displacement which represents the largest displacement in the equivalent single degree of freedom system under the earthquake effect, the seismic demands indicated above are obtained. Different methods are used to define nonlinear spectral displacement in Displacement Coefficient Method and Capacity Spectrum Method developed as two different versions of the nonlinear static method (Aydınoğlu, 2003).

In this analysis where the nonlinear behaviour at critical sections is modelled with plastic hinge model, the amplitude of the horizontal loads that affect the system is increased step by step according to a distribution that does not change during the analysis or according to distributions that vary at each step and internal strengths, displacements and plastic deformations are calculated at each step.

The Nonlinear Static Method which is briefly summarized above no doubt represents a very important development which can be described as a revolution in earthquake engineering practice and earthquake engineers encouraged by successful applications made on simple systems want to use this method in a more widespread manner. However an important matter which should be stated at this point is the fact that many problems and restrictions concerning Nonlinear Static Method based on static pushover analysis have not been overcome (Krawinkler and Seneviratna, 1998). In fact, the theoretical foundations of the method have not been entirely revealed yet and the development of the model continues to remain intuitive to a great extent (Elnashai, 2002).

2. Static Pushover Analysis

In their studies, to show the effect of torsion irregularity which causes large damages on building systems during an earthquake on the level of damage (Moghadam and Tso, 1995) have emphasized the use of nonlinear analysis methods in no symmetrical structures.

In their study (Kilar and Fajfar, 1997) have presented a simple method for the nonlinear static pushover analysis of no symmetrical structures exposed to uniformly increasing horizontal loads (static pushover analysis). They have said that this method was designed as part of new methods for the valuation of buildings and their seismic designs. They have stated that the structure consists of planar macro elements. In the study, for each planar macro element, a bilinear or multilinear displacement of base shear strength – peak point was assumed. By performing a step-by-step analysis they have calculated the estimated relation between the base shear strength and peak point displacement. In order to reduce certain restrictions of the nonlinear static pushover analysis methods they have developed a new nonlinear static pushover analysis. The methods they have developed, at various levels of the ultra-elastic behaviour of the building, depending on the various rigidities of the elements and the characteristics of the building system, takes into account the variance of the horizontal load distribution and includes higher mode effects.

In order to investigate the conformity of the 3-dimensioned nonlinear static pushover analyses in the seismic analysis of asymmetric structures, the results obtained from nonlinear dynamic analyses were analysed up to the maximum peak displacement and were compared with static incremental pushover analysis results (Faella and Kilar, 1998). In their study (Kalkan and Kunnath, 2007) states the necessity to estimate correctly the seismic demand parameters of critical and basic components in performance based design methods. It was mentioned that nonlinear static procedures were widely used in engineering practices in estimating seismic demands of buildings.

Irtem and Hasgul (2009), in their studies, have aimed to evaluate and compare the structural reaction requests obtained from the capacity spectrum method (CSM) proposed in ATC-40 which is one of the nonlinear static analysis procedures (NSPs) and from displacement coefficients methods (DCM) proposed in FEMA 356. For this purpose, they have studied three dimensionally three multiple storied reinforcement concrete buildings of different characteristics. In order to determine the nonlinear behaviour of buildings under lateral strengths, they obtained base shear strength-peak displacement relations (capacity curves) by a static pushover analysis containing P-delta curves. By taking to account four different seismic risk levels, they determined building performances by using CSM and by using DCM results determined through previous studies. By taking to account multiple-storied reinforcement concrete buildings and comparing structural reaction amounts (such as plastic rotations, storey displacement) they have studied the impacts of different NSP's in the performance evaluation of the buildings.

2.1. Capacity spectrum method

Two methods can be implemented for the existing reinforcement concrete buildings, linear and nonlinear analysis. In the linear analysis method, only the material's behaviour within linear limits is taken into account. As the nonlinear behaviour of the material is not taken to account additional capacity cannot be used in the elements. The linear analysis includes processes that use static horizontal strength, dynamic horizontal strength and demand-capacity ratios. There are several methods in the nonlinear analysis. These methods are, in the general sense, based on "Time History" analysis. However, as this analysis method is competed method which cannot be widely used, simplified nonlinear analysis methods are used. In the "Capacity Spectrum Method" which is one of the simplified linear analysis methods, in order to find the maximum displacement the intersection point between the capacity (pushover) curve and the reduced demand spectrum curve is found and nonlinear analysis is performed (Kesim, 2005).

The Capacity Spectrum Method is based on the principle that the maximum displacements which may occur in the building due to a certain seismic movement and the building's horizontal load bearing capacity are interconnected. Inelastic deformations occur on a building which is subject to increased seismic loads and these deformations increase the damping of the building which in turn decreases the building's displacement demand with the increased damping. Capacity Spectrum method consists of finding especially the performance point that is the point where the capacity spectrum (produced from the capacity curve) and the elastically reduced demand spectrum (corrected by taking to account the nonlinear behaviour) (Özdaş, 2006).

The first phase of the nonlinear incremental pushover analysis is to obtain the building's capacity curve. In order to obtain the capacity curve of the building, the building is observed until it reaches the limit situation under the fixed vertical loads and horizontal equivalent seismic loads (F) increasing from the ground by calculating according to the incremental pushover analysis where the effect of geometrical changes on the equation of equilibrium are taken to account. As a result of these changes, it is the capacity curve obtained by uniting geometrically the intersection points ($\delta ç$) of the total base shear strengths (Vt) which are reaction strengths for each load value in the vertical direction and the roof (peak) displacements in the horizontal directions. This curve is called the pushover curve (Özdaş, 2006).

By using the exiting relation between the base shear strength (Vt) which impacts a building a building and the top floor i.e. the roof displacement ($\delta ç$) it is transformed to a spectrum curve at the spectral acceleration (Sa) and spectral displacement (Sd) plane.

In order to determine the seismic effect, a seismic demand spectrum with 5% damping is created by using the C_A and C_V seismic coefficients. C_A represents the effective maximum acceleration coefficient, C_V, the spectrum value of the 5% damped system which has a period of 1 sec. The seismic coefficients of C_A and C_V are determined according to the seismic region where the building is located, to its distance to a known seismic source, the type of earthquake which is to be used in the calculations and the soil classification. The N_A and N_V coefficients which represent the distance to the earthquake source are found in the Table 1, according to the building's distance to the earthquake source and the type of earthquake which shall be created by the source.

Table 1. Near source factors (ATC–40, 1996).

Seismic source type	Closest distance to known seismic source							
	≤ 2 km		5 km		10 km		≥ 15 km	
	N_A	N_V	N_A	N_V	N_A	N_V	N_A	N_V
A: Faults that are capable of producing large magnitute events	1.50	2.00	1.20	1.60	1.00	1.20	1.00	1.00
B: All faults other than types A and C	1.30	1.60	1.00	1.20	1.00	1.00	1.00	1.00
C: Faults that are not capable of producing large magnitute events	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

In order to compare S_a and the traditional demand spectrum given in period format with the capacity spectrum which is in the spectral acceleration – spectral displacement format it has to be transformed to the ADRS format. The period and spectral acceleration which is on any point on the traditional demand spectrum is turned into spectral acceleration-spectral displacement.

If the horizontal coordinates of the intersection between the capacity spectrum and the reduced demand spectrum is not different than the spectral displacement value with an interval of ±5% the performance point which is found can be accepted as the real performance point. If the horizontal coordinates of the intersection between the capacity spectrum and the reduced demand spectrum is not within the above indicated interval, a new point is determined and the iteration is continued. The performance point is defined as the maximum value of displacement which may occur in the building in the face of the ground motion.

3. Pushover Analysis Details

The 6-storey reinforcement concrete building with frame system examined in the study has been dimensioned adequately regarding geometry and materials to ensure ductility requirements. The building's concrete group is between C14–C30, the concrete steel rebar group was selected as S420. The characteristics of the reinforcement concrete six-storey building with frame system are shown in Table 2. The section of the reinforcement concrete six-storey building with frame system are shown Fig. 1. Static pushover analyses are performed in the SAP2000 V14 program.

In the study, static pushover analyses of a 6-storey reinforcement concrete building with frame system were made according to 5 different concrete classes. In this study, plastic hinge hypothesis has been used to take into account the nonlinear behaviour. According to that, it is assumed that the plastic deformations are assumed to occur at regions named as plastic hinge and acted with linear elasticity at other sections. In order to determine the seismic performance of buildings, the limit rotation values belonging to different performance levels were used for columns and beams indicated in ATC 40.

Table 2. Characteristics of six-storey reinforcement concrete structure.

Earthquake zone	2
Effective ground acceleration coefficient	0.30
Earthquake zone coefficient	0.30
Soil group	Z2
Building importance coefficient	1
Earthquake type	Design earthquake
Spectrum characteristic periods	T_A: 0.15 T_B: 0.40
Conveyor system behavior coefficient	8
Concrete group	C14, C16, C20, C25, C30
Steel rebar group	S420 – S220

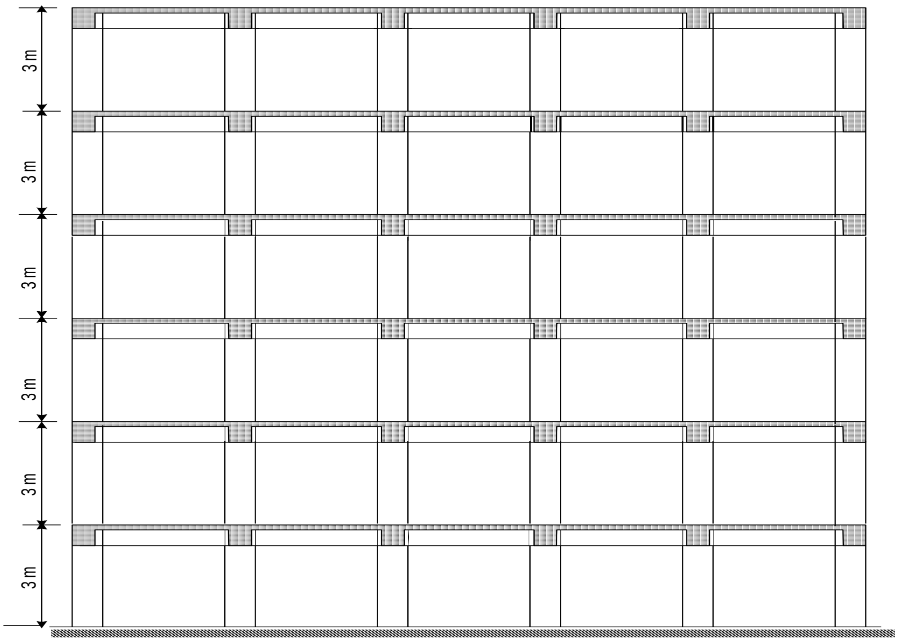

Fig. 1. Section of six-storey reinforcement concrete structure.

As a result of the static pushover analysis the base shear strength in the case of the building's failure and the peak displacement were found. In the analysis made for the C30 concrete class, the relation between the base shear strength and displacement is shown in Fig. 2. The failure load of the building is 14,443 kN. The peak displacement corresponding to this failure load is 0.304 m. As a result of the static pushover analysis 333 plastic hinges at immediate use performance level (B–IO), 361 of them at the controllable damage interval (IO–LS), 47 of them at limited safety interval (LS–CP) have occurred and the building has reached the state of failure.

In the analyses made for the concrete groups of C25, C20, C16 and C14, the relation between base shear strength and displacement were shown in the Figs. 3, 4, 5 and 6.

Static pushover analysis was made above for five different concrete classes and the results that are obtained are shown in Fig. 7. When the results of the capacity curves are evaluated, depending on the increase of concrete quality, an increase occurs in the base shear strength compensate by the building.

Base shear strength and displacements according to the different concrete and S420 reinforcement classes are shown in Table 3. When the table is observed, it is seen a decrease of 8.46% is observed in the base shear strength when the concrete class is reduced from C30 to C14. Whereas in the peak displacements a decrease of 11.84% occurs.

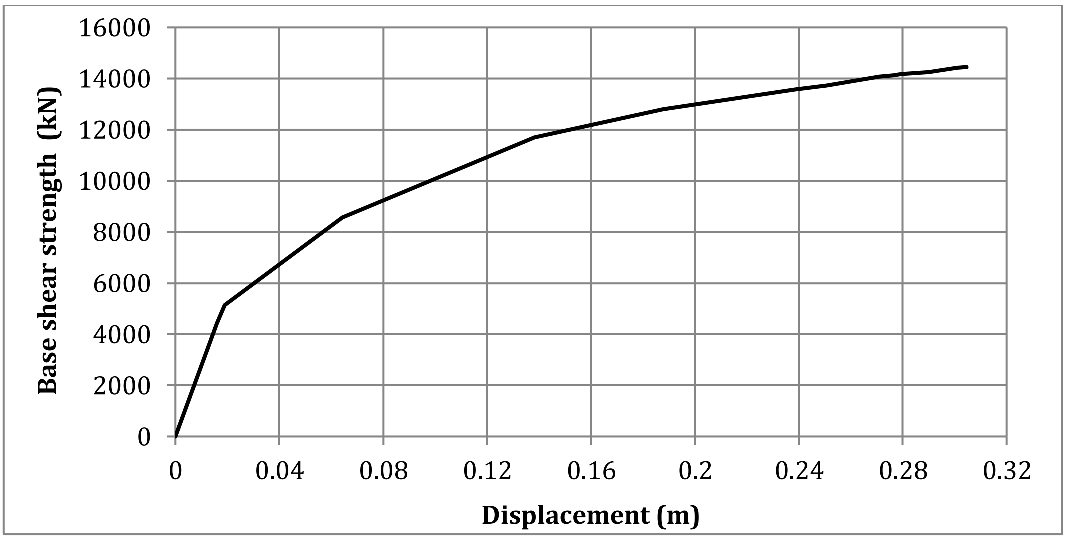

Fig. 2. Capacity curve for C30 concrete group.

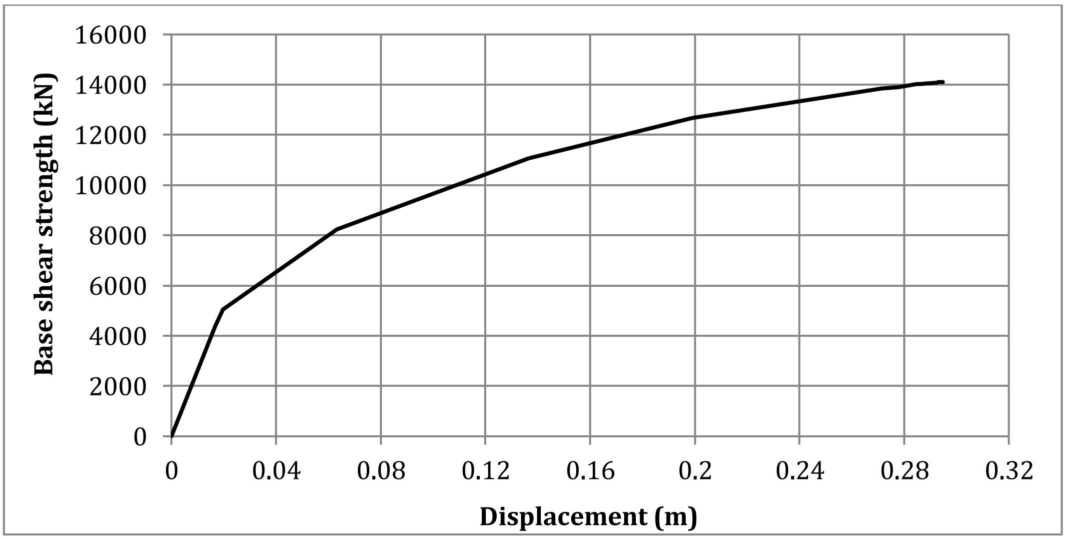

Fig. 3. Capacity curve for C25 concrete group.

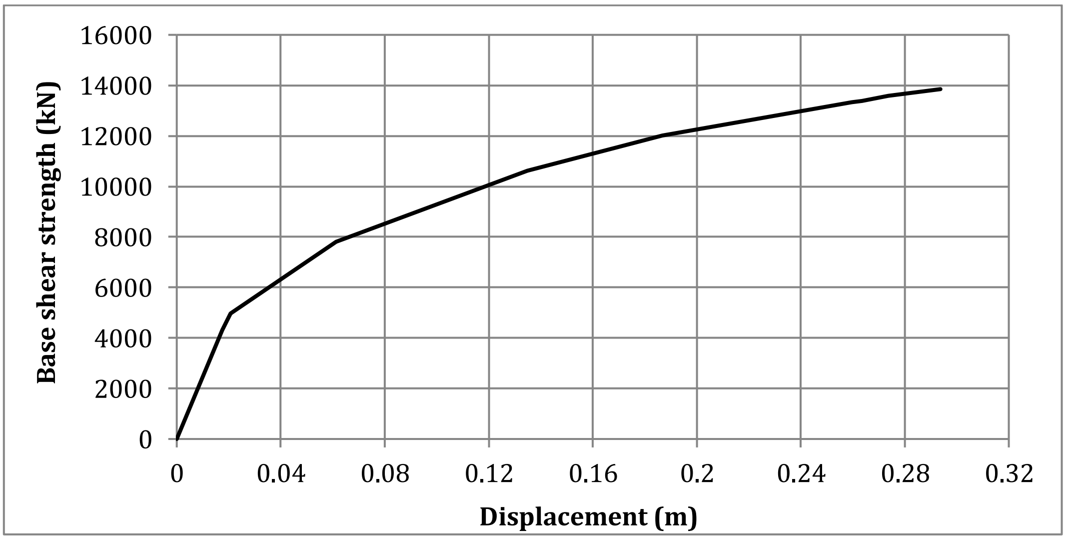

Fig. 4. Capacity curve for C20 concrete group.

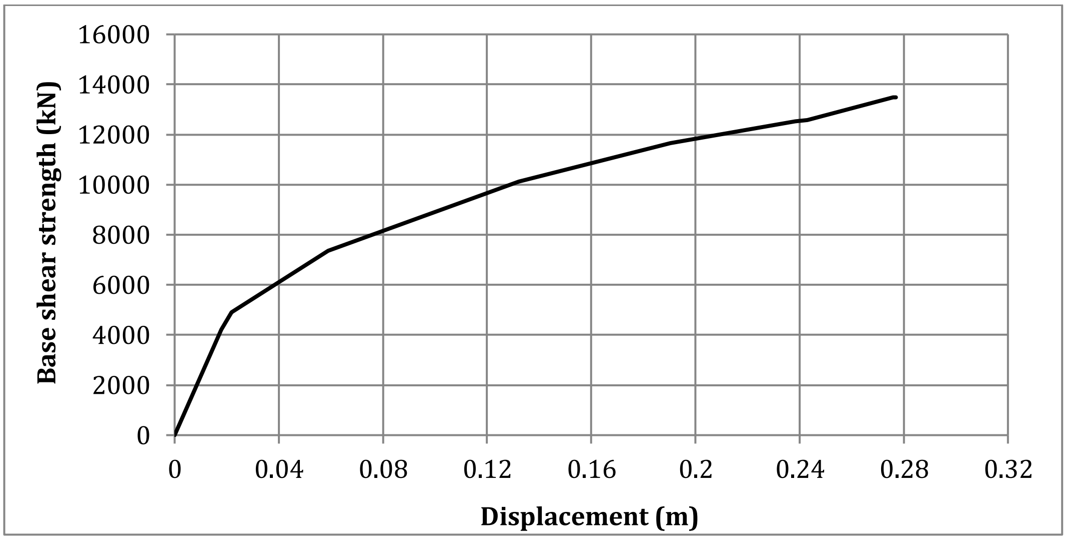

Fig. 5. Capacity curve for C16 concrete group.

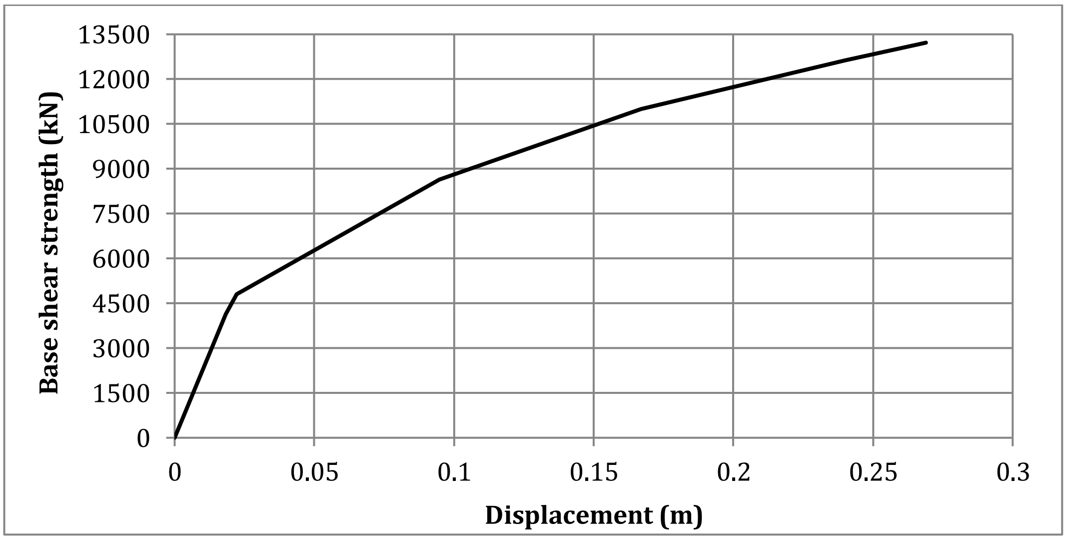

Fig. 6. Capacity curve for C14 concrete group.

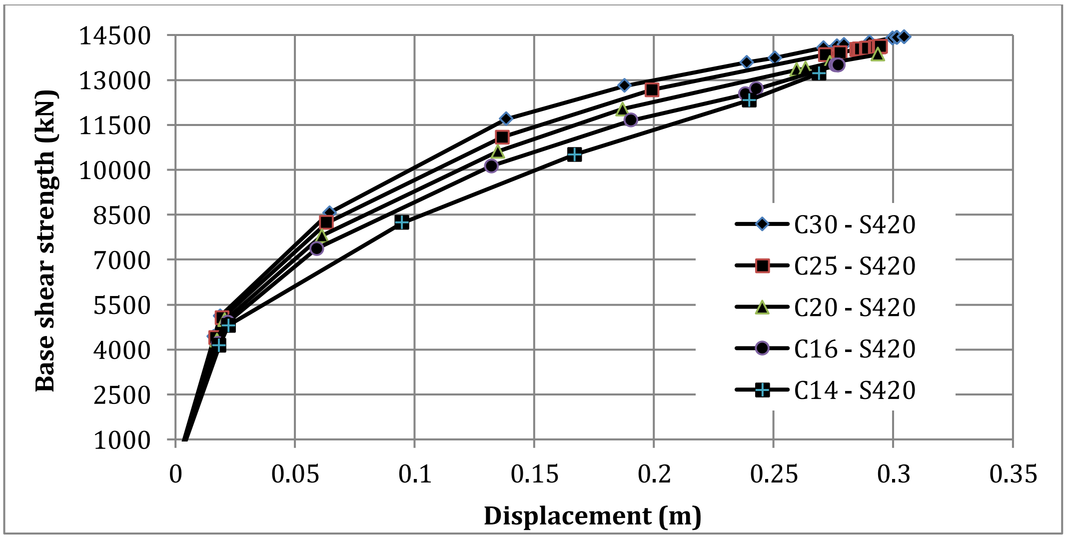

Fig. 7. Capacity curve for concrete group (S420).

Table 3. Base shear strength and displacement according to the concrete and reinforcement classes.

Concrete and steel rebar group	*V* (kN)	*D* (m)	Reduction ratios of base shear strength according to C30 concrete group (%)	Reduction ratios of peak displacements relative to C30 concrete group (%)
C30–S420	14,443	0.304	-	-
C25–S420	14,108	0.297	2.32	3.29
C20–S420	13,850	0.291	4.11	4.28
C16–S420	13,486	0.276	6.63	9.21
C14–S420	13,220	0.268	8.46	11.84

An increase in the concrete quality, by increasing the number of plastic hinges ensures that it carries heavier loads. This situation is shown in the Table 4.

The reinforcement group is taken as S220, the capacity curves obtained for different concrete classes have also been shown on a single graph Fig. 8. When the figure is studied, an increase in the base shear strength is observed depending on the increased concrete quality.

Base shear strength and displacements according to the different concrete and S220 reinforcement classes are shown in Table 5. When the table is observed, it is seen a decrease of 12.58% is observed in the base shear strength when the concrete class is reduced from C30 to C14. Whereas in the peak displacements a decrease of 19.56% occurs. As a result, base shear strength and displacements according to the different concrete and S220-S420 reinforcement classes are shown in Fig. 9.

Table 4. Distribution of plastic sections according to the concrete and reinforcement classes.

Concrete group	B - IO	IO - LS	LS - CP
C30	333	361	47
C25	325	385	22
C20	320	393	19
C16	310	409	13
C14	298	428	7

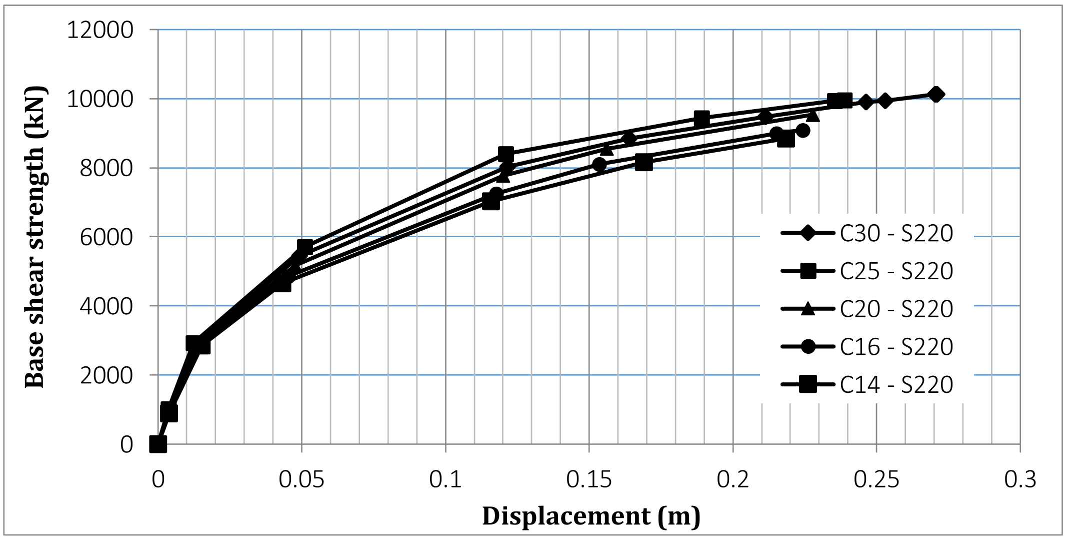

Fig. 8. Capacity curve for concrete group (S220).

Table 5. Base shear strength and displacement according to the concrete and reinforcement classes.

Concrete and steel rebar group	*V* (kN)	*D* (m)	Reduction ratios of base shear strength according to C30 concrete group (%)	Reduction ratios of peak displacements relative to C30 concrete group (%)
C30–S220	10,122	0.271	-	-
C25–S220	9,957	0.238	1.63	12.18
C20–S220	9,538	0.227	5.77	16.24
C16–S220	9,095	0.224	10.15	17,.34
C14–S220	8,849	0.218	12.58	19.56

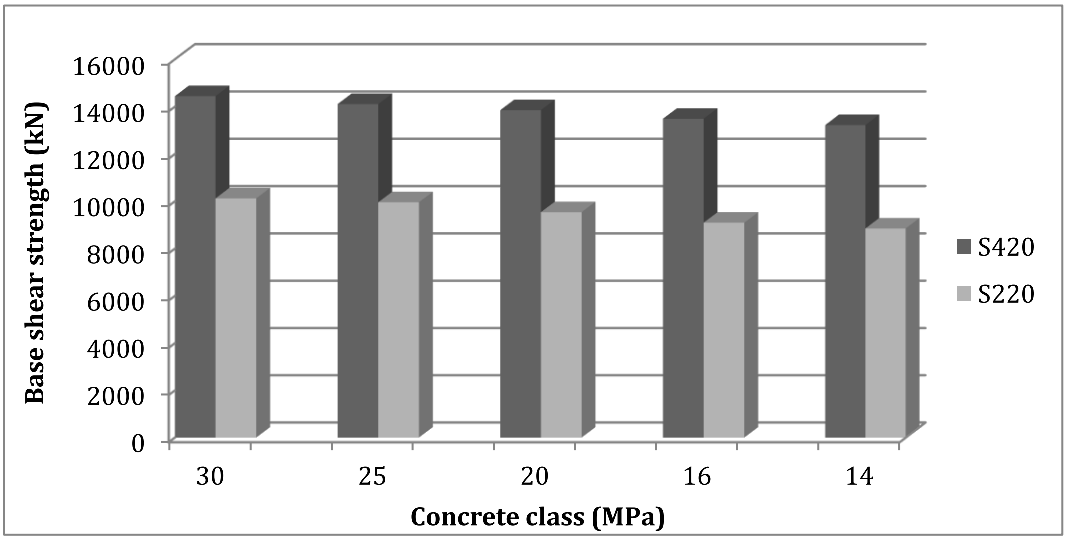

Fig. 9. Base shear strength and displacements according to the different concrete and S220-420 reinforcement classes.

4. Conclusions

In the study, the six-storey building with concrete frame system has been designed to provide high ductility requirements. The results obtained in the scope of this study are indicated below.

When the results of the capacity curves are evaluated, depending on the increase of concrete quality, an increase occurs in the base shear strength compensate by the building. In the event of using concrete class C30 instead of C14, an increase of 8.46% occurred in the base shear strength. There is an increase of 11.84% in peak displacement.

According to the result obtained in this study, while 7 plastic hinges occur at the limited safety interval (LS – CP) for concrete class C14, this value becomes 47 for the concrete class C30. The increase in the quality of concrete results in an increase in the number of plastic hinges causing it to carry more loads.

As a result of the analyses which have been made, in the event of the reinforcement strength being S220 instead of S420, the base shear strength compensate by the C30 concrete class has decreased by 30%.

When the capacity curves are evaluated, depending on the increase in the concrete quality it is seen that the building requires more horizontal loads for the same displacement value. When the demand base shear strengths at the performance point of the building which examined in the study in the event of considering a concrete class of C30 instead of C14 the base shear strength was observed to increase by 8% in utilization earthquake, by 11% in design earthquake, by 14% in the maximum earthquake. For all studied concrete classes performance levels are in Immediate Use state.

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