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The Effect of Different Steel Brace Types on Reinforced Concrete Frame System Retrofit

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Interstory drift.

Abstract: One of the common methods used as an alternative to shear walls in the retrofit of reinforced concrete (RC) structures is steel braces. The use of steel braces is preferred because of its rapid application as well as the increase in stiffness and strength. By using different types of braces in reinforced concrete frames, displacements can be reduced and properties such as structural performance, shear capacity, ductility, stiffness and strength can be increased. If the behavior characteristics of the hybrid system are known, the structural performance of the reinforced building can be predicted after the retrofit. In this study, the effect of different types of steel braces recommended in the Turkey Building Earthquake Code 2018 (TBEC-2018) on reinforced concrete building retrofit, was investigated. For this purpose, a 9-storey RC frame system was retrofitted using diagonal, X, inverted V, V and K type bracings. Considering the strength and stiffness results, an answer was searched for the question of which brace type had the best result in retrofit. The results obtained from the analyzes show that the X and K type bracings stand out in terms of strength and stiffness.

Farklı Çelik Çapraz Türlerinin Betonarme Çerçeve Sistem Güçlendirmesine Etkisi

Anahtar Kelimeler
Çelik çaprazlar,
Güçlendirme,
İtme analizi,
Göreli kat ötelemesi

Öz: Betonarme yapıların güçlendirmesinde perde yapımına alternatif olarak kullanılan yaygın yöntemlerden birisi de çelik çaprazlardır. Çelik çapraz kullanımı rijitlik ve mukavemet artışının yanı sıra hızlı uygulanabilmesi nedeniyle de dikkatleri çekmektedir. Betonarme çerçevelere farklı türden çaprazlar eklenerek yer değiştirmeler azaltılıp, yapısal performans, kesme kapasitesi, süneklik, rijitlik, mukavemet gibi özellikler iyileştirilebilir. Bir binayı güçlendirme sonrasında yeniden tasarlama, ancak yeni hibrit sistemin davranış özellikleri biliniyorsa mümkündür. Yapılan bu çalışmada Türkiye Bina Deprem Yönetmeliği 2018'de önerilen çelik çapraz türlerinin betonarme bina güçlendirmesi üzerindeki etkisi araştırılmıştır. Tasarlanan bir betonarme çerçeve sistem diyagonal, X, ters V, V ve K tipi çelik çaprazlar kullanılarak güçlendirilmiştir. Dayanım ve rijitlik sonuçları göz önünde bulundurularak güçlendirmede en iyi sonuç hangi çapraz türünde edilmiştir sorusuna cevap aranmıştır. Yapılan karşılaştırmalarda X ve K tipi çaprazların dayanım ve rijitlik açısından ön plana çıktığını göstermektedir.

1. INTRODUCTION

According to the principle of earthquake resistant building design, it is expected that the buildings will have adequate strength and stiffness to prevent them from collapsing and to increase the life safety for the inhabitants, under the influence of severe earthquakes. Steel braced frames are widely used to control the seismic performance of structures and improve lateral stiffness under severe horizontal forces such as earthquakes. In braced frames, proper bracing arrangements will increase lateral resistance and reduce internal forces, particularly bending moments in columns and beams [1-8]. Braced steel frames are divided into two, as central and eccentrically braced steel frames, depending on the arrangement of the braces [9]. Central braced frames are widely used for traditional structures due to their practical and economic advantages. The idea of using steel bracings in reinforced concrete structures has attracted more and more attention in recent years. When the previous studies are examined, it is seen that the studies focused on either the external bracing of reinforced concrete frames or the internal bracing through intermediate steel frames [10-11].

Different methods are used to retrofit reinforced concrete structures [12-14]. When the studies in the literature are examined; In the retrofit of reinforced concrete structures, it has been tried to determine whether the best reinforcement method is a reinforced concrete shear wall or steel bracing by taking into account the interstory drift [15] .In steel buildings with regular and irregular geometry, the diagonal central steel bracing system has been found to have more energy absorption capacity than the inverted V central steel cross curtain system [16]. It has also been shown that when the beams of a steel braced frame with weak short columns are replaced, the inelastic behavior of the frame can be improved [10]. It has been tried to determine which is the best retrofitting method by using different bracing types related to the reinforcement of reinforced concrete structures [17]. When the mega braced configurations are examined, it is seen that the amount of steel for the structural elements and connections is lower. As a result, the reduction in construction cost makes mega braced frames attractive for use in seismic reinforcement applications [18]. Only tension braced frames (TOBFs) have poor seismic energy dissipation capacity and a compressed hysteresis behavior due to premature buckling of slender bracing members. The main concern in using the TOBF system is the determination of appropriate performance factors for seismic design. For this purpose, a series of predicted ground motions are applied and the safe design factor is obtained [5]. There are also studies examining the behavior of structures reinforced with both conventional central and composite steel bracing systems [19]. It has been found that the retrofit of low-rise reinforced concrete frames with steel X braces is beneficial to the performance of the frame columns in terms of many parameters. However, for medium and high-rise frames, the adverse effects of retrofit especially on the columns connected to the bracing system should be considered, and local retrofit of the columns should be done locally if necessary [20]. In the seismic performance of medium-height reinforced concrete buildings, a formula for fatigue has been developed considering the results of retrofit with different types of decentralized steel braces [21]. When looking at the experimental studies investigating the effect of adding different types of steel braces on the behavior of reinforced concrete moment-frames, strength, stiffness, crack expansion, ductility, energy loss and strength reduction factor of all frames were evaluated. Considering the ductility and strength reduction factor parameters, the results show that the decentralized brace has a better performance than the other specimens. However, when the hardness, strength and crack control parameters are evaluated, it is concluded that the behavior of the X brace is better [22].

In this study, it is aimed to determine which of the centric steel braces type, recommended in TBDY 2018 Section 9.5, gives the best results in retrofit of reinforced concrete frame. In the first stage of the study, a reference reinforced concrete frame with 9 floors and 3 spans was designed considering the TS500 and TBEC 2018 criteria. The necessity of retrofit the reference frame under the effect of a design earthquake is discussed. Performance analysis was performed by applying a single-mode pushover analysis at the decision stage. By using 6 different types of braces, the most suitable one in reinforced concrete frame retrofit was decided.

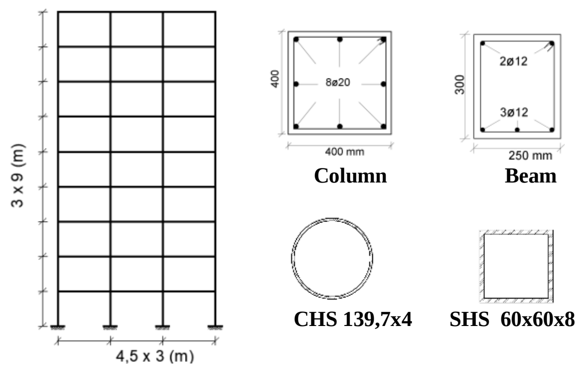
2. NUMERICAL STUDIES

In the study, the central steel bracing types recommended in TBDY 2018 Chapter 9, were used to retrofit a reinforced concrete frame. The reinforced concrete frame system has 9 floors and the building usage class is 3, the frame does not have any structural irregularities.

Analytical modeling of the framework and analyzes were performed in SAP2000 computer software [23]. The reinforced concrete frame system is retrofitted by using different steel brace types and cross sections. Modal and pushover analyzes were performed in Sap 2000 program. By comparing the analysis results, the answer to the question of which brace type is the most suitable for retrofitting was sought.

2.1. Numerical Model of RC Frame

The reinforced concrete frame used in the analyzes has 3 spans with a length of 4.5m. Story height is equal and 3m on all stories. S420 steel grade and C25 concrete grade were used in the design of the bearing elements. The effective section stiffnesses of columns and beams were applied as specified in TBEC 2018 Chapter 4. Column sections are 40x40cm and beam sections are 25x30cm (Figure 1). In the design of the frame, Turkey Building Earthquake Code 2018 [24] and TS500 Requirements for Design and Construction of Reinforced Concrete Structures [25] were taken into account. Controlled damage performance level (CD) has been achieved as stated in the TBEC 2018. Lumped plastic hinges are used in the analytical model.



(a) (b)

Figure 1. Reinforced concrete frame (a) numerical model (b) column, beam and braces cross-section details

Lumped plastic hinges are used in the analytical model. In this plastic hinge approach, it is accepted that the nonlinear behavior of column and beam elements occurs in the most stressed end regions of the element under the influence of earthquake, and linear elastic behavior occurs outside of this. In column elements, plastic hinges are defined by the axial load and biaxial moment interaction, and in beam elements by the moment curvature relationship. In earthquake resistant building design, the ground motion at the location of the building and the earthquake loads acting on the building are calculated by using the elastic acceleration spectrum of the relevant location from the Turkey Earthquake Risk Map. It has been accepted that the earthquake level affecting the frame is Earthquake Ground Motion Level-2 (DD-2), and it is located in Sakarya University of Applied Sciences, Technology Faculty. The earthquake parameters used in the study are given in Table 1.

Table 1. Horizontal elastic response spectrum parameters of the frame

Earthquake Parameters	
Soil classification	ZB
Building usage class (BKS)	3
Building height class (BYS)	5
Seismic design category	1
Targe Building Performance Level	CD
S_{DS}	1.527
S_{D1}	0.372

2.2. Determination of Seismic Performance of Reinforced Concrete

It has been determined whether the RC frame provides the performance level specified in TBEC 2018. At this stage of the study, it is aimed to determine whether the frame meets the performance target, which is the design condition, and to reveal the contribution of steel braces to the frame behavior. Buildings with a building height class of more than 2 must meet the controlled damage (CD) performance level according to TBEC 2018. At this performance level, the main goal is to avoid loss of life, so it is aimed to limit the damage to the bearing elements. In order to determine the performance level of the frame, Single-Mode Pushover Analysis was performed. One of the conditions for using unimodal pushover analysis is that the BYS must be greater than 5 and this condition is met. Another condition is that the ratio of the effective mass of the base shear force belonging to the dominant vibration mode of the building to the total mass of the building is at least 70%. Modal analysis was performed and it was determined that this condition was also met (Table 2). Finally, the condition that the torsional irregularity coefficient of the building is $\eta bi<1.4$ is also met.

Table 2. Modal analysis results of the reference frame

	Period (s)	Mass Participation (%)
Reference	1.160	77

The pushover curve of the frame (Base shear force-Displacement) was obtained by single-mode pushover analysis. The modal capacity diagram of the frame was obtained by applying the transformation equations, specified in TBEC 2018 Chapter 5, to the pushover curve (Figure 5). By superimposing this diagram with the demand spectrum, the maximum modal displacement of the dominant mode, that is, the modal displacement demand of the frame, was found to be 0.27 m in the direction of the earthquake considered (Figure 2).

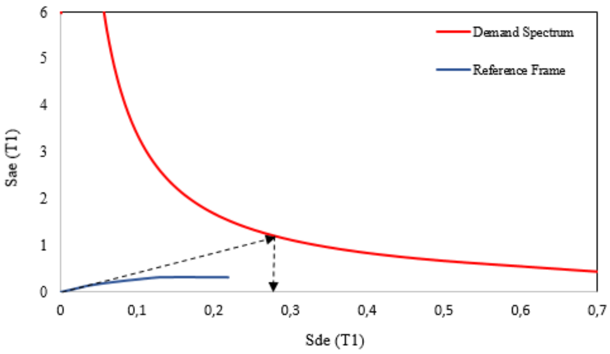


Figure 2. Modal capacity diagram of the reference frame

The calculated displacement demand was applied by the pushover analysis to the frame, and the plastic rotation values formed in the bearing system elements were obtained. While determining the performance level of the frame, it is necessary to determine the plastic rotation limits of the bearing elements and to check whether the rotation amounts in the sections as a result of the pushover analysis exceed these limits. According to TBEC 2018, the plastic rotation limits allowed for controlled damage (CD) and collapse prevention (GÖ) performance levels were calculated by using the yield and collapse prevention curvature values of the bearing elements (Figure 3).

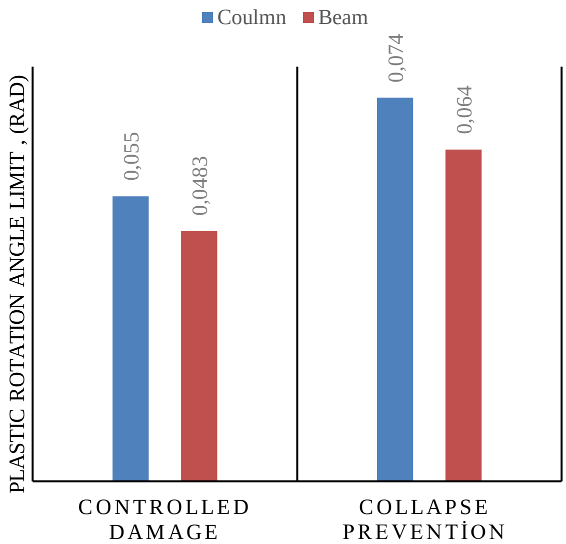


Figure 3. Plastic rotation angle limits of performance levels

The target displacement was applied to the frame by pushover analysis, and as a result, no hinges were formed in the columns, but plastic hinges were formed at the ends of some beams. When the plastic hinges rotation values were examined, it was determined that the CD performance level met the limit values. The rotation values of the 3 hinges with the highest rotation angles in the beams are given in Table 3.

Table 3. Highest plastic rotation angles in beams

	Rotation Angle (Rad)	Controlled Damage (ϴp, rad)	Collapse Prevention (ϴp, rad)	Situation
Beam	0.0175	0.0483	0.064	Provides
Beam	0.0173	0.0483	0.064	Provides
Beam	0.0173	0.0483	0.064	Provides

In the performance evaluation, it was determined that the plastic rotation values provided the CP performance level. After the performance evaluation, it was checked whether the interstory drift and second order effects meet the limits specified in TBEC 2018. It was determined that the effective relative interstory drift values for all stories exceeded the limit value. In the control of the second order effects, it was determined that the limit values given in the TBEC 2018 were exceeded, except for the first two floors.

2.3. Retrofit of The RC Frame With Centric Steel Braces

Although the designed RC frame provides the performance level required by the TBEC 2018, the relative interstory drift and second order effects have exceeded the limits. In order to limit the relative interstory drifts and second order effects, the frame is retrofit with centric steel braces. Diagonal, X, inverted V, V and K central diagonal braces given in TBDY 2018 were used for retrofit. S235 steel circular (CHS139.7x4) and square hollow section (Tube 60x60x8) are used diagonally, whose cross-sectional areas are very close to each other (Table 4).

Table 4. Properties of sections used in steel braces

	Cross-section area (cm^2)	Moment of inertia (cm^4)
Circular hollow section	16,96	$7{,}68 \times 10^{-3}$
Square hollow section	17,05	$3{,}93 \times 10^{-2}$

It is possible to retrofit reinforced concrete buildings with different types of steel braces. However, using the most suitable type of steel braces is important in terms of earthquake resistance and design cost. From this stage on, retrofit was made by using 5 different types of steel braces in order to determine the most suitable type of steel brace for retrofit (Figure 4). In the analytical modeling, nonlinear behavior is taken into account with the moment hinges defined at both ends of the steel braces. By taking the analysis results of the unretrofitted frame as a reference, the models were compared considering the performance levels of the frames and the results of the effective relative interstory drift.

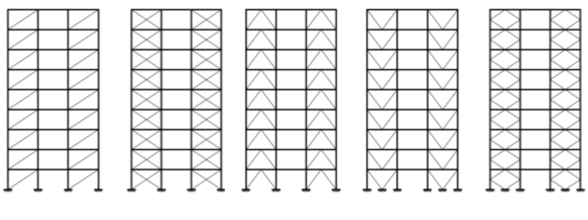


Figure 4. Steel braces used in reinforcement

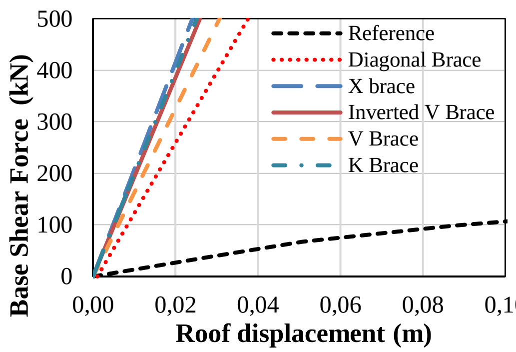
3. ANALYSIS RESULTS

Numerical models of all reinforcement types were created in the Sap2000 computer package program and modal analysis was performed. As a result of the analysis, the mass participation in all retrofit models shows almost 100% agreement with each other in circular and square hollow sections. Since the mass participation rate of the 1st mode was more than 70%, the performance evaluation was continued with the single-mode pushover analysis method. Modal analysis results showed that X and K braces contribute more to structural stiffness than other brace types. It was determined that the results of the circular and square hollow section models were compatible with each other (Table 5).

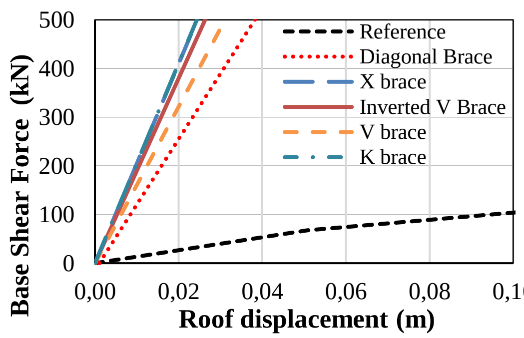
Table 5. Modal analysis results of retrofitted frames

Model	Circular hollow sections period (s)	Mass participation (%)	Square hollow sections period (s)	Mass participation (%)
Diagonal Brace	0,37	78,5	0338	78,5
X brace	0,30	75,5	0,30	75,6
Inverted V Brace	0,32	77,0	0,32	77,0
V Brace	0,34	77,0	0,34	77,0
K Brace	0,31	74,6	0,30	74,3

After the modal analysis, static pushover curves were obtained for all models with pushover analysis and the curves were compared (Figure 5). When the curves are examined, it is possible to say that the appropriate retrofit process will increase the capacity of the structure.



(a) Circular hollow section pushover curve



(b) Square hollow section pushover curve

Figure 5. Comparison of pushover curves (a) circular hollow sections (b) Square hollow sections

The displacement demands of all models were calculated by overlaying the modal capacity diagrams, obtained by the conversion of the static pushover curves, with the demand spectrum. The displacement demands of the circular and square hollow section models are the same except for the K braces. When the braces were compared among themselves, the two lowest displacement demands were obtained in the K and X braces (Figure 6).

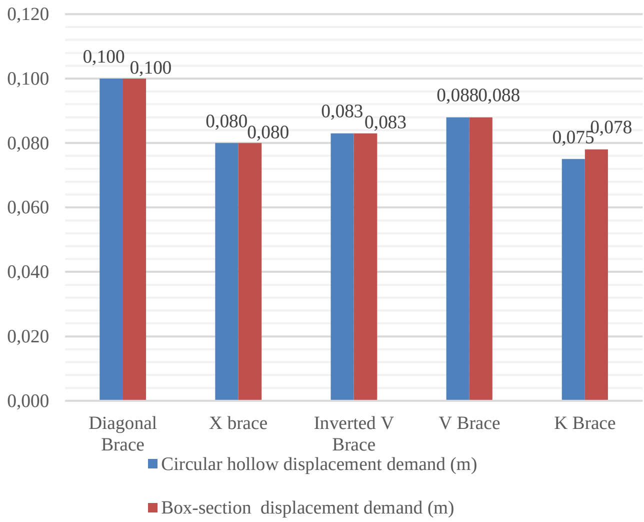


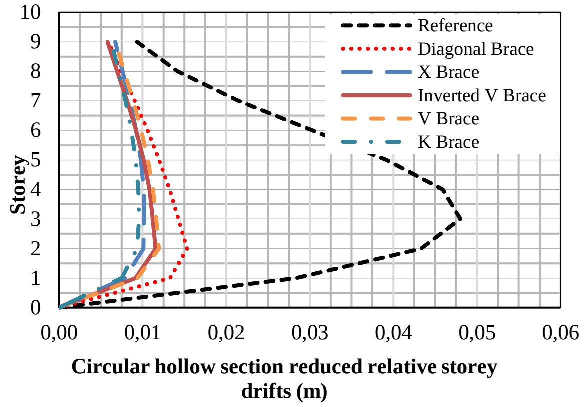
Figure 6. Target displacements of models

The displacement demands were applied to the all retrofitted models by pushover analysis and the plastic hinge rotation angles of the bearing elements were determined. When the results were examined, it was determined that the hinges were formed at the beam ends in all models. The maximum rotation angle values in the models are presented in Table 6. In the comparison, it was determined that the CP performance level was provided in all models and the result obtained was deemed appropriate in terms of design.

Table 6. Maximum plastic rotation angles in models as a result of pushover analysis

Model	Circular hollow section hinge rotation (Rad)	Square hollow section hinge rotation (Rad)	Controlled damage rotation limit (Rad)	Situation
Diagonal Brace	0.0045	0.0047	0.0483	Provides
X brace	0.0033	0.0031	0.0483	Provides
Inverted V Brace	0.0031	0.0030	0.0483	Provides
V Brace	0.0036	0.0036	0.0483	Provides
K Brace	0.0028	0.0030	0.0483	Provides

After the performance evaluation, it was determined that the main purpose of retrofit the frames was to limit the relative interstory drifts. For this reason, it has been checked whether the relative interstory drift values exceed the TBEC 2018 limit values. The reduced relative interstory drifts of all models were calculated and the maximum effective interstory drift values were obtained by using these values (Figure 7, Table 7-8). Maximum effective relative interstory drifts are limited to 0.008 in the TBEC 2018.



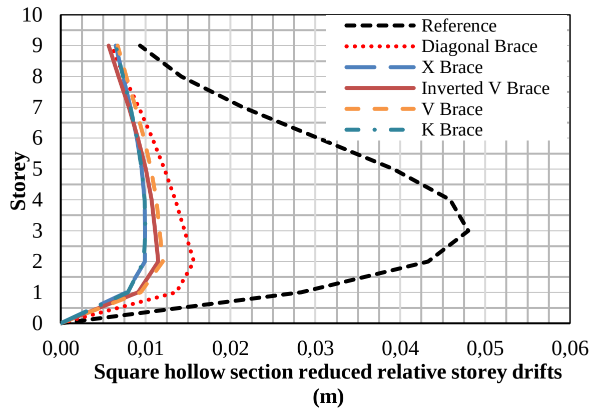


Figure 7. Reduced relative interstory drift values of all retrofit models

Relative interstory drift expresses, the ratio of the drift demands occurring at different stories in the case of horizontal drift. The effective relative interstorey drifts of the models provided the upper limit value, (0.008) given in TBDY 2018, for circular hollow section X and K braces. In circular hollow section models, there are drift values exceeding the limit value in X and K braces. In square hollowsection models, on the other hand, the relative interstory drift condition is satisfied only in the Inverted V braced model.

Table 7. Effective relative interstory drifts of circular hollow sections (m)

Storey	Diagonal brace	X brace	Inverted V brace	V brace	K brace
1	0.011	0.007	0.008	0.008	0.006
2	0.014	0.008	0.010	0.010	0.008
3	0.013	0.008	0.009	0.010	0.008
4	0.012	0.008	0.009	0.009	0.008
5	0.011	0.008	0.008	0.009	0.008
6	0.010	0.008	0.008	0.008	0.007
7	0.008	0.007	0.007	0.007	0.007
8	0.007	0.006	0.006	0.007	0.006
9	0.005	0.006	0.005	0.006	0.005

Table 8. Effective relative interstory drifts of square hollow sections (m)

Storey	Diagonal brace	X brace	Inverted V brace	V brace	K brace
1	0.027	0.011	0.006	0.008	0.008
2	0.041	0.014	0.008	0.010	0.010
3	0.046	0.013	0.008	0.009	0.010
4	0.044	0.012	0.008	0.009	0.009
5	0.037	0.011	0.008	0.008	0.009
6	0.029	0.010	0.007	0.008	0.008
7	0.020	0.008	0.007	0.007	0.007
8	0.014	0.007	0.006	0.006	0.006
9	0.009	0.006	0.005	0.005	0.006

4. RESULTS AND DISCUSSIONS

As a result of the performance analysis, it was determined that the plastic hinge rotations in the bearing elements did not exceed the CD limit given in TBEC 2018. After the performance analysis, the effective relative interstory drift values, which were required to be checked in TBEC 2018, were obtained. In the control, it was determined that the relative interstory drift limit value given in the earthquake code was exceeded at all floors in the reference model. In the next step, it is aimed to limit the relative interstory drift values of the reference frame. For this purpose, the reference frame was retrofit by using different types of centric steel braces (diagonal, X, inverted V, V and K braces). Circular and square hollow sections with close cross-sectional areas were used for retrofit.

While looking for an answer to the question of which brace retrofit is better, modal analysis results, displacement demands and effective relative interstory drift results are taken into account. When the modal analysis results are compared, it is an expected result that the highest period value will appear in the reference building (Table 6). Among the retrofit models, the results for both cross-section types almost overlap with each other. Among the steel braces, the period values of the models with X and K braces was lower than the other braces (Table 7). From this result, it was concluded that X and K brace types make the structure more rigid. From this result, it was concluded that X and K brace types make the structure more rigid.

When the displacement demands obtained under the effect of the design earthquake are examined, in the section type comparison, the results in circular hollow section models in K braces are 4% lower than in square sections. When bracing types were compared, it was determined that the lowest displacement demand was obtained in circular section K braced models, followed by the X braced model with a 6.7% higher value (Table 8).

The final comparison was made over the relative interstory drift values. As a result of the retrofit, it was determined that the relative interstory drift values decreased in all models. In the section type comparison, it was determined that lower relative interstory drift values were obtained in circular hollow section models in all brace types (Table 9). When bracing types were compared, it was concluded that the relative interstory drift values in the K braced models were lower than the other models, followed by the X model. Among the brace types, the best results were obtained in the K braced models, followed by the X braced models.

When the obtained results are evaluated in a general framework, it is concluded that the circular hollow section with the same area gives better results than the square section. Depending on the architectural features of the application, one of the K and X cross types can be preferred.

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