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Numerical Analysis of Structural Behavior and Damage Mechanisms in Shear-Deficient Reinforced Concrete Columns Retrofitted with RC Jacketing

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Abstract: Designing reinforced concrete columns in accordance with earthquake-resistant design principles and ensuring their proper implementation during construction are among the fundamental factors that determine the seismic performance of reinforced concrete structures. In light of the widespread damage observed in the columns of reinforced concrete buildings during the February 6, 2023, Kahramanmaraş (Türkiye) earthquakes, this study aims to investigate the underlying causes of these failures. Initially, the structural damages are analyzed from earthquake engineering and structural mechanics perspectives. Subsequently, numerical analyses were carried out using a representative reinforced concrete building model to enable a more detailed evaluation. In this context, three different structural models were examined: one reference model and two variations, including different strengthening scenarios. The reference model incorporated C8/10 grade concrete, S220 reinforcement, and transverse reinforcement spacing of 300 mm. For structural elements exceeding their shear force capacity, reinforced concrete jacketing was proposed as the strengthening method. Accordingly, shear-deficient columns were identified, and the jacketing technique was applied incrementally, first to a single column and then to all columns within the structure. When comparing the limit and demand shear forces across the three models, it was observed that strengthening significantly increased the shear strength of the structural elements and offered an effective solution for enhancing seismic performance.

Betonarme Sargılama ile Güçlendirilmiş Kesme Kapasitesi Yetersiz Betonarme Kolonlarda Yapısal Davranış ve Hasar Mekanizmalarının Sayısal Analizi

Anahtar Kelimeler
Deprem,
Enine donatı,
Beton,
Kolon,
Kesme kuvveti,
Sargılama

Öz: Depreme dayanıklı tasarım ilkelerine uygun olarak betonarme kolonların projelendirilmesi ve bu tasarımın inşaat aşamasında eksiksiz şekilde uygulanması, betonarme yapıların sismik performansını belirleyen temel unsurlar arasındadır. 6 Şubat 2023 tarihinde meydana gelen Kahramanmaraş (Türkiye) depremleri sonrasında betonarme binaların kolonlarında gözlemlenen yaygın hasarlar doğrultusunda, bu çalışma söz konusu hasarların temel nedenlerini araştırmayı amaçlamaktadır. Öncelikle, meydana gelen yapısal hasarlar deprem mühendisliği ve yapısal mekanik bakış açılarıyla analiz edilmiştir. Ardından, daha ayrıntılı bir değerlendirme için örnek bir betonarme bina modeli üzerinde sayısal analizler gerçekleştirilmiştir. Bu kapsamda, biri referans model olmak üzere üç farklı yapısal model incelenmiştir; diğer iki model ise çeşitli güçlendirme senaryolarını içermektedir. Referans modelde C8/10 dayanım sınıfında beton, S220 donatı ve 300 mm enine donatı aralığı kullanılmıştır. Kesme kuvveti kapasitesini aşan elemanlar için güçlendirme yöntemi olarak betonarme sargılama önerilmiştir. Bu doğrultuda, kesme dayanımı yetersiz olan kolonlar belirlenmiş ve sargılama işlemi kademeli olarak uygulanmıştır, ilk aşamada tek bir kolona, ikinci aşamada ise yapının tüm kolonlarına müdahale edilmiştir. Üç farklı modelin limit ve hedef kesme kuvvetleri karşılaştırıldığında, güçlendirme yapısal elemanların kesme dayanımını anlamlı ölçüde artırdığı ve sismik performansın iyileştirilmesinde etkili bir yöntem sunduğu görülmüştür.

1. INTRODUCTION

The impact of earthquakes on existing structures and the preventive measures implemented before such events are crucial in mitigating potential loss of life and property. Among natural disasters, earthquakes are responsible for the most severe destruction; however, their effects can be significantly reduced through proactive measures taken before the event. Both pre- and post-earthquake strategies are essential for the construction of safer buildings and the development of seismic design codes, which are instrumental in minimizing the impact on existing structures in high seismic-risk areas [1-3]. Furthermore, such studies provide valuable insights for urban planners and decision-makers, enabling the assessment and enhancement of earthquake resilience in existing infrastructure and guiding the implementation of necessary precautions. Also, some papers developed and applied rapid visual or mobile-based methods to assess seismic vulnerability of buildings in various international contexts [4-6]. Additionally, some authors offered comparative or code-based analyses to refine the structural evaluation of RC buildings under seismic conditions [7-9] and contributed to regional seismic risk analysis by integrating empirical damage data with predictive and AI-based assessment tools [10-12]. These efforts also support the formulation of intervention plans to be executed both before and after a disaster [13-14].

The seismic resilience of reinforced concrete (RC) structures is a pressing concern, particularly in regions prone to earthquakes. Given that a significant portion of the built environment consists of these structures, enhancing their capacity to withstand seismic events is critical. Various methodologies have been developed to improve the seismic performance of existing RC buildings, particularly those that do not meet contemporary seismic design standards. This discussion synthesizes recent research findings on retrofitting techniques aimed at bolstering the seismic resilience of these structures. For reinforced concrete buildings exhibiting inadequate seismic performance, several methods can be employed to enhance their seismic capacity to meet the requirements set by earthquake design regulations [15-20]. Strengthening the load-bearing systems of existing reinforced concrete structures, using various techniques applied at the element or system level, is a commonly adopted approach. Particular emphasis is placed on vertical load-bearing elements, as their capacity significantly influences the overall structural performance during seismic events. In addition to increasing the number or size of these vertical elements, the seismic resilience of the structure can be further enhanced through the application of various strengthening methods. Several major earthquakes in Türkiye have provided critical case studies for understanding structural vulnerability and damage patterns. The 1999 Kocaeli, 2003 Bingöl, 2011 Van, and 2020 Elazığ-Sivrice earthquakes revealed common deficiencies in reinforced concrete buildings, such as inadequate detailing, poor construction practices, and insufficient seismic design [21-25].

Over the past two decades in Türkiye, particularly following the devastating Kahramanmaraş earthquakes on February 6, 2023, one of the primary causes of large-scale damage in reinforced concrete (RC) structures has been the failure of vertical load-bearing elements. Structural damage to RC columns, occurring at various levels, is primarily attributed to low-strength concrete and inadequate transverse reinforcement. Studies assessing the damage in RC structures after several earthquakes in Türkiye have highlighted that these two fundamental issues have led to varying degrees of damage in columns, significantly compromising the seismic performance of the structures. As a result, some buildings have experienced partial or total collapse [26-37].

Theoretical and experimental studies in the literature have extensively explored the damage to reinforced concrete (RC) columns and the seismic performance of these load-bearing elements. These studies include evaluations and recommendations on the main causes of damage, increasing the load-bearing capacities of the columns to reduce seismic effects, and improving the regulatory conditions for these elements. Shear force, in particular, is an important factor in determining the durability of structural elements. Proper design of columns and enhancing their resistance to shear forces is critical for the safety of structures. Studies in the literature have provided significant insights into the effects of shear force on columns and have guided design parameters. Paulay and Priestley [38] thoroughly examined the effect of shear forces in reinforced concrete columns and how these forces reflect on the plasticization zones of the column. This study is an important reference for understanding the relationship between shear forces and column durability. Fardis [39] emphasized the need to consider shear forces in the seismic design of columns and the measures to be taken against them. The study presents different design strategies to enhance the durability of reinforced concrete columns. Priestley [40] addressed the relationship between shear forces and plastic deformations in columns and provided important conclusions regarding how shear forces affect the seismic performance of columns. Therefore, it is essential to carefully assess the effects of shear forces on columns during both static and dynamic analyses and incorporate appropriate safety measures into the design process.

Numerous academic studies have explored various strengthening methods for reinforced concrete (RC) columns, comparing the results either experimentally or theoretically [41-48]. One of the primary strategies for enhancing the seismic capacity of existing RC buildings is through the strengthening of vertical load-bearing elements. These elements, such as columns and walls, play a crucial role in the overall structural integrity during seismic events. Methods such as RC jacketing, which involves encasing existing columns with additional concrete and reinforcement, have been shown to improve the ductility and strength of these elements significantly [49-50]. This technique not only increases the load-bearing capacity but also enhances the energy dissipation characteristics of the structure, thereby reducing the likelihood of catastrophic failure during an earthquake [51].

In the eleven provinces affected by the February 6, 2023, Kahramanmaraş earthquake, varying levels of damage and destruction occurred in reinforced concrete structures that constitute a large part of the urban building stock. The structural damages that occurred after this and similar earthquakes reveal the necessity of increasing the earthquake resistance of existing structures. One of the precautions to be taken is to strengthen existing structures on an element or system basis. In this study, structural damages occurring in reinforced concrete columns were first evaluated in light of the February 6, 2023, Kahramanmaraş earthquakes. The main reasons for structural damage in RC columns in such earthquakes are insufficient transverse reinforcement and low-strength concrete. Within this study, a 6-story symmetrical reinforced concrete building model was created, taking into account low-strength concrete and insufficient transverse reinforcement spacing, and structural analyses were carried out. This study distinguishes itself by employing a staged concrete jacketing approach to realistically simulate the retrofitting process and assess the evolution of seismic performance. In contrast to many earlier investigations, this research conducts a comparative analysis of single-column, partial, and full retrofitting strategies within a numerically modeled six-story reinforced concrete building. Columns exhibiting insufficient shear strength were identified, and strengthening was applied initially to a single column, followed by all columns in the structure through concrete wrapping, thereby strengthening them. The limit and demand shear forces were compared for these three different structural models. Additionally, performance ratios for these columns were also compared. The study primarily demonstrates the feasibility of using concrete wrapping in columns with insufficient shear strength.

The flow chart of this study is given in Figure 1.

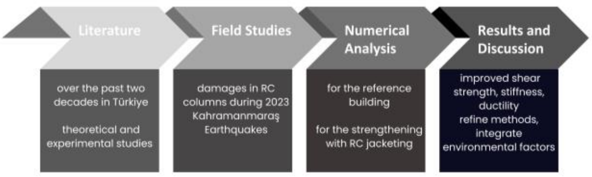

Figure 1. The flow chart of this study

2. MATERIAL AND METHOD

2.1. Damages in Columns Due to the Kahramanmaraş Earthquakes

Türkiye, a country highly vulnerable to seismic risks, faced a major disaster as a result of the Kahramanmaraş earthquakes that occurred on February 6, 2023. These two powerful earthquakes, with epicenters in the Pazarcık and Elbistan districts of Kahramanmaraş province, caused widespread destruction and significant loss of life across 11 provinces. The earthquakes, with magnitudes of Mw=7.7 and Mw=7.6, struck on the same day within the same region, and aftershocks further worsened the severity of the damage, complicating rescue efforts. The most severe damage occurred in the provinces of Hatay, Kahramanmaraş, and Adıyaman, while Malatya, Elazığ, Adana, Gaziantep, Osmaniye, Şanlıurfa, Kilis, and Diyarbakır were also significantly affected. In the aftermath of the earthquakes, thousands of buildings were damaged or collapsed to varying degrees. The region's infrastructure, including transportation, communication, and other essential services, also suffered extensive damage. More than 50,000 lives were lost, and thousands were injured. Tens of thousands of buildings experienced various levels of damage, with many completely collapsing. It was found that most of these buildings were aged structures that had not received adequate engineering attention, with many suffering extensive damage due to poor seismic performance. Weak construction practices, particularly the inadequacy of column and beam systems, were identified as key factors contributing to the widespread destruction. Examples of completely collapsed reinforced concrete buildings are shown in Figure 2.

Figure 2. Examples of reinforced concrete buildings that have collapsed completely (Photos taken by authors)

In some reinforced concrete structures, partial collapses have occurred due to structural irregularities and/or deficiencies. Examples of such damage are illustrated in Figure 3.

Figure 3. Examples of partial collapses due to various irregularities and deficiencies (Photos taken by authors).

Field observations have shown that the use of insufficient transverse reinforcement in columns is one of the main causes of damage. In order to reduce the brittle nature of concrete, the excessive spacing of transverse reinforcement that surrounds the core concrete has resulted in a decrease in the strength and ductility capacity of the concrete. The use of transverse reinforcement well beyond the spacing limits defined in earthquake-resistant design principles has caused an increase in the buckling lengths of longitudinal reinforcements, leading to buckling damage in the longitudinal reinforcement even under smaller critical load values. Poor workmanship, insufficient anchorage, the application of transverse reinforcement to longitudinal reinforcements with 90º hooks instead of 135º hooks, and inadequate concrete cover thickness have resulted in many of the expected functions of transverse reinforcement not being achieved. Insufficient transverse reinforcement and low-strength concrete have directly negatively affected the shear strength capacities of columns, causing damage at varying levels. Particularly, columns on the ground floor have caused the structural system to collapse through a failure mechanism in the columns on the lower floors, due to shear force-induced out-of-plane displacement. Moreover, the lack of transverse reinforcement tightening in the lower and upper confinement zones of the columns has led to the formation of plastic hinges in these areas. Additionally, various utility elements passing through the columns reduce the concrete cross-section, which can lead to a decrease in the load-bearing capacity of the element. Apart from all these factors, the degradation of core concrete, improper mix ratios, inadequate compaction, excessive loading, and chemical and other influences can also contribute to the damage. Furthermore, insufficient transverse reinforcement used to reduce the brittle nature of the core concrete may also lead to this issue. Another cause of damage observed in the field was the use of either only plain reinforcement or both plain and ribbed reinforcement together. The formation of short columns, whose shear capacity is lower than their bending capacity, is another reason for the damage. In buildings constructed in close proximity to one another, the hammering effect generates additional shear forces in the load-bearing elements of adjacent structures, making it easier to exceed the limit of shear forces. Examples of damage resulting from these combined factors are shown in Figure 4.

Numerical analyses were carried out for a medium-height regular reinforced concrete structure in order to reveal the effects of the causes of damage at different levels in the columns as a result of field observations on the structural analyses**.** A reference structural model was created by taking into account the main causes of damages frequently encountered in columns as a result of field investigations in damaged reinforced concrete structures, which are the dominant urban building stock in the earthquake region, such as low strength concrete (C8/10), insufficient transverse reinforcement spacing (ϕ8/300) and the use of plain reinforcement (S220).

Figure 4. Examples of damage in columns caused by various factors (Photos taken by authors)

In order to represent these structures, a 6-story building without any irregularities was modeled. Afterwards, the rate at which the capacity of the structure changed was determined by using reinforced concrete wrapping. Pushover analysis was preferred in the structural models considered. This type of analysis is widely used to calculate how structures will behave under earthquake effects. Pushover analysis is a nonlinear static analysis method used to understand how structures will behave under dynamic loads such as earthquakes. In addition, it requires fewer calculations than nonlinear time history analyses, which makes it preferred in engineering applications. The reason for choosing this approach, which is particularly preferred as a numerical analysis method, is that it can represent the earthquake behavior of the structures in question as close to reality as possible and contribute to the understanding of existing damages. The structures analyzed in the study are limited to mid-rise reinforced concrete buildings with a certain type of load-bearing system. Therefore, the analysis method is valid for this group of structures and may not give the same accurate results in different systems, such as steel structures or mixed systems.

3. RESULTS

3.1. Numerical Analysis

In this section, a reinforced concrete building model has been developed to illustrate the effects of confinement-based strengthening methods on the shear force of columns. The model incorporates low-strength concrete and reinforcement conditions as the materials used. Specifically, C8/10 concrete and S220 plain reinforced concrete bars were selected. For the transverse reinforcement in the columns, ϕ8/300 mm spacing was applied throughout the entire column length. All other structural characteristics in this model have been considered fixed, establishing this model as the reference building for evaluation. The numerical model was analyzed using a pushover analysis performed in the Seismostruct software [52].

In the modelling of all structural samples, force-based plastic hinge frame elements (in-frmFBPH) were employed for both columns and beams. These elements simulate the distribution of inelastic behavior along a defined length by applying force-based plasticity, thereby confining nonlinearity to a finite region. To accurately capture the stress–strain distribution, a total of 100 fibers were assigned to the cross-sections, which is considered sufficient for this modelling approach. The plastic hinge length (L_p/L) was set to 16.67%, based on relevant structural analysis and design guidelines. This ratio indicates the portion of the column or beam length where plastic deformations are expected to concentrate under seismic loading, allowing the structure to dissipate energy effectively while maintaining its stability. The selected value aligns with widely accepted engineering practice for estimating plastic hinge lengths in components exhibiting inelastic behaviour. Uniform load distributions were taken into account in all structural analyses.

Pushover analysis is a method used to determine the seismic behavior of structures, especially under horizontal loads. This approach is integral in evaluating the seismic performance of buildings, providing critical insights into the safety and functionality of a structure. The results of static pushover analysis are essential for identifying areas where excessive deformation or material strength limits may be exceeded, signaling the need for design modifications. Furthermore, these analyses are valuable for optimizing designs and reducing costs throughout the design process. At the same time, these types of analyses are also used to determine the potential performance of existing structures in the event of an earthquake. As a structural analysis technique, push-over analysis is used to explore the non-linear behavior of buildings, especially in the context of earthquake engineering and seismic evaluation. It offers a more comprehensive understanding of a structure's response to dynamic loads, such as those induced by earthquakes, by accounting for non-linear deformations beyond the elastic limit [53-60]. The flow chart for this type of analysis is shown in Figure 5.

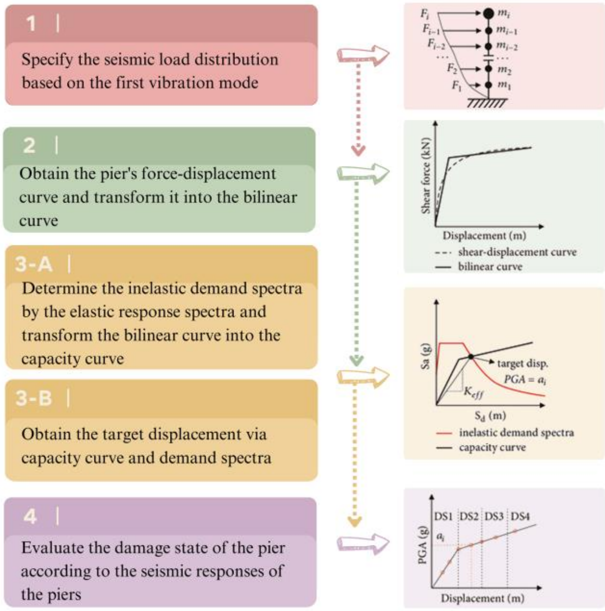

Figure 5. Flowchart of pushover analysis modified from Guo et al. [61]

The reinforced concrete building model used in the pushover analysis is symmetrical and comprises four equal spans of 4.50 m in both the X and Y directions. The numerical model represents a six-story structure, with each floor having a height of 3 m, resulting in a total structural height of 18 m. The floor plan and the designation of the columns for the numerical analyses are provided in Figure 6.

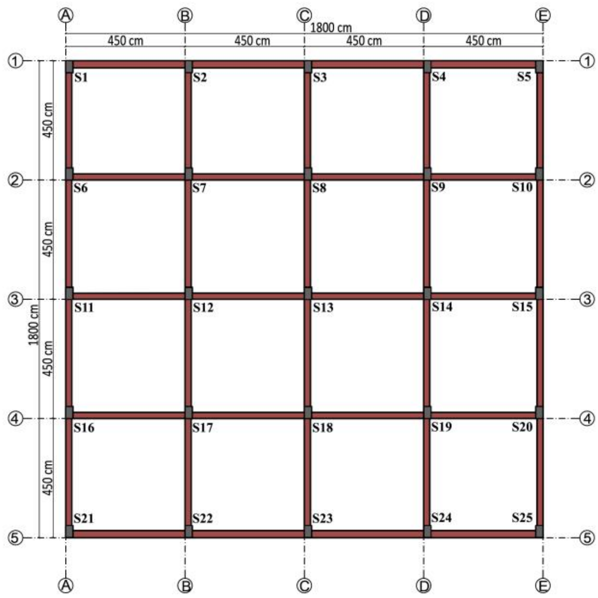

Figure 6. Floor plan and column names of the sample building.

The 2D and 3D models created in the software program, the applied loads, and the depiction of some columns are shown in Figure 7.

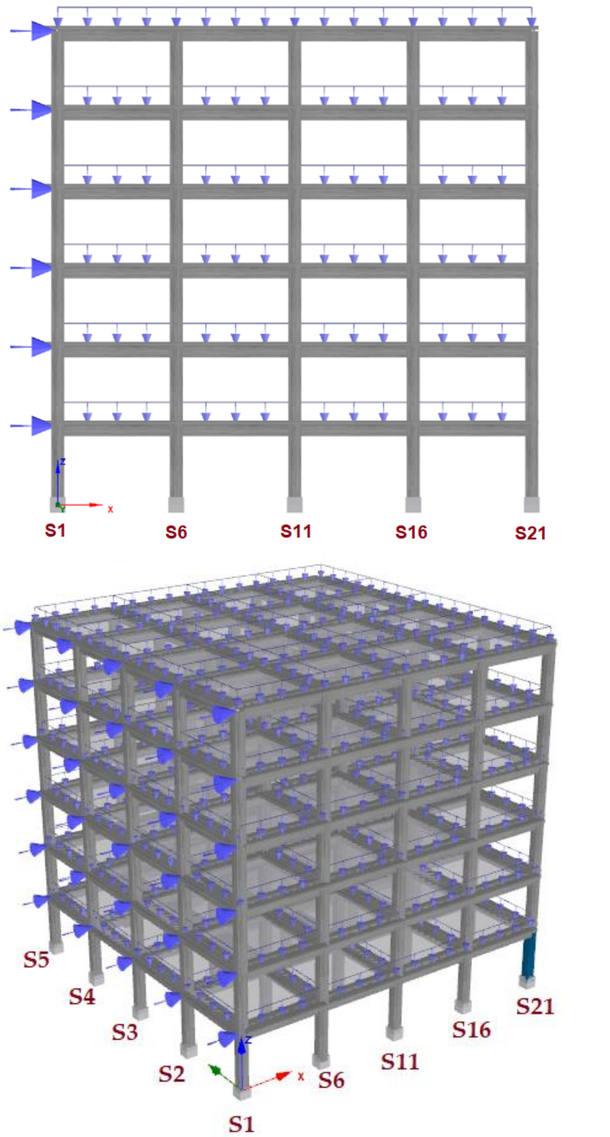

Figure 7. 2D and 3D structural models and representation of some columns

The structural parameters and dimensions of the structural elements considered in the reference RC building model are shown in Table 1.

Table 1. The RC building parameters considered in the study

Parameters		Values	Parameters	Values
Concrete Class		C8/10	Column Stirrup	Φ8/300
Reinforcement Class		S220	Beam Stirrup	Φ8/200
Beam dimensions (mm)		250x600	Concrete Cover (mm)	25
Slab height (mm)		120	Material model for Concrete	Non-linear (Mander et al)
Story height (m)		3	Material model for Steel	Menegotto/ Pinto
Columns (mm)		400*500	Type of constraint	Rigid diaphragm
Longitudinal bars (columns)	Corners	4Φ20	Local Soil Class	ZA
	Top bottom side	4Φ16	Damping ratio	5%
	Left right side	4Φ16	Importance class	II

When selecting the reinforced concrete structures for the structural analyses, the more widely used Eurocode 8 [62] was taken into consideration. The selected reinforced concrete building was considered for residential purposes and was selected as building importance class II (Ordinary buildings; not belonging to the other categories). The characteristics of the local soil class considered in the study are given in Table 2.

Table 2. Local soil class and its characteristics (Eurocode-8)

Soil class	Description of Stratigraphic Profile	V_{s30} (m/s)	N_{SPT} (blows/30cm)	C_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	>800	---	---

This study focuses on determining whether the shear forces are exceeded in reinforced concrete columns and applying the confinement method for strengthening in columns where shear forces are exceeded. For all columns where the confinement method was applied, a confinement thickness of 100 mm, which is the minimum confinement thickness specified in the Turkish Building Earthquake Code (TBEC-2018), was considered. The column cross-sections before and after confinement are shown in Figure 8.

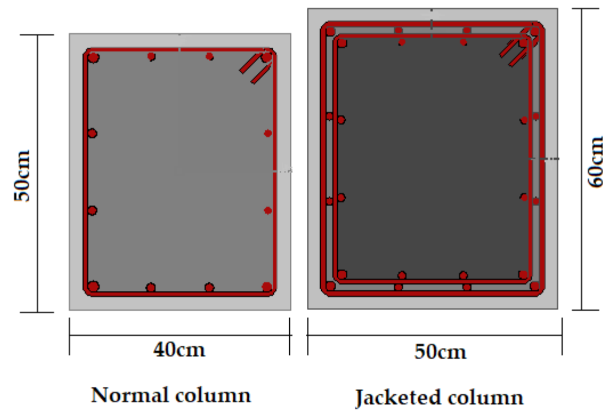

Figure 8. Column cross-sections before and after jacketing

The material and dimensional properties of the cross-sections before and after jacketing are shown in Table 3; examples of the application are provided in Figure 9.

Table 3. The material and dimensions of the cross-sections before and after jacketing

Section Material (s)		Section Dimensions	
External Longitudinal reinforcement	S420	External height	60 cm
Internal Longitudinal/transverse reinforcement	S220	Internal height	50 cm
External transverse reinforcement	S420	External width	50 cm
Concrete Jacket	C25/30	Internal width	40 cm
Concrete core	C8/10	Cover thickness	2.5 cm

Figure 9. Example of the structural member strengthening with the jacketing method (Photos taken by authors)

For the element strengthening using the jacketing method, structural analyses were first performed on the reference building model. Following this, the jacketing method was applied to columns where the shear force capacity was exceeded. Initially, the jacketing method was applied to a single column that exceeded its shear force capacity, referred to as Model I, which represented a minimal intervention scenario, serving as a baseline for evaluating the incremental impact of jacketing. In Model II, the jacketing method was applied to all columns of the structure. The 2D and 3D building drawings for Model I are presented in Figure 10.

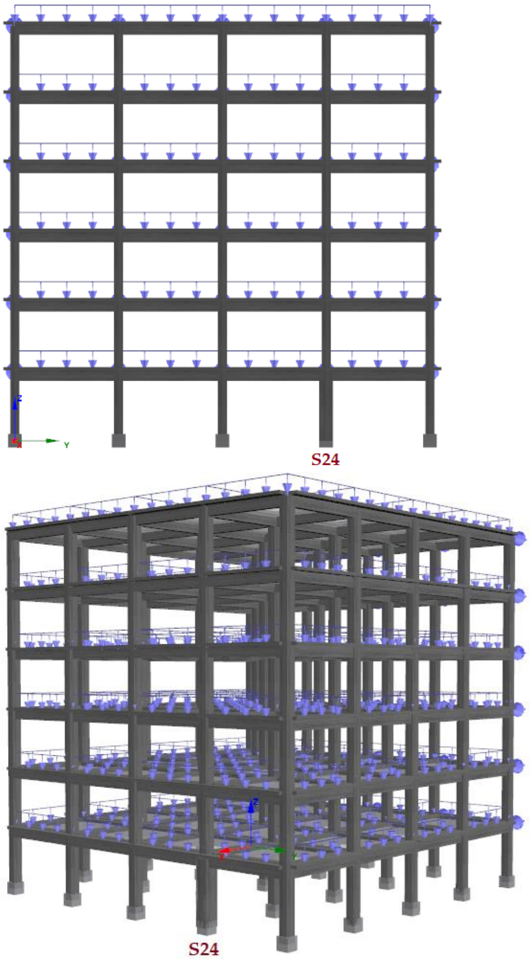

Figure 10. 2D and 3D structural drawings of Model I

The 2D and 3D structural drawings of Model II, created similarly, are shown in Figure 11.

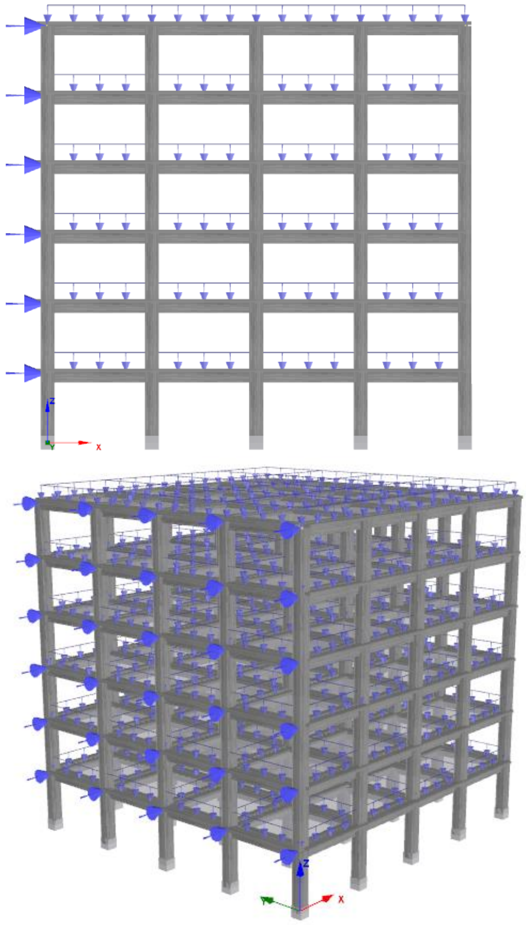

Figure 11. 2D and 3D structural drawings of Model II

The main objective of performance-based earthquake engineering is to determine the performance of structures under different limit states. For all the models considered in the study, the period, base shear force, as well as elastic and effective stiffness values, have been obtained. Additionally, the target displacements specified in Eurocode-8, which is widely used worldwide, including damage limitation (DL), significant damage (SD), and near collapse (NC), have been separately obtained. All these values are shown on the pushover curve in Figure 12.

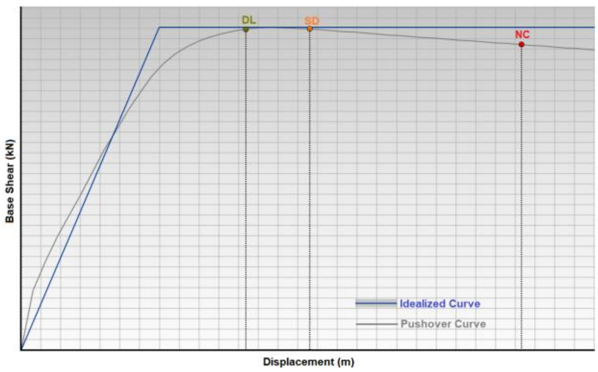

Figure 12. Typical pushover and idealized capacity curves

Table 4 shows comprehensive explanations for the limit state values considered in this study.

Table 4. Limit states in Eurocode-8

Limit State	Description	Return Period (Year)	Probability of Exceedance (in 50 Years)
Damage limitation (DL)	Only lightly damaged; damage to non-structural components is economically repairable	225	0.20
Significant damage (SD)	Significantly damaged; some residual strength and stiffness; non-structural components damaged; uneconomic to repair	475	0.10
Near-collapse (NC)	Heavily damaged; very low residual strength and stiffness; large permanent drift, but still standing	2475	0.02

All the result values for all models considered in the study are presented in Table 5.

Table 5. Results obtained for structural models

Model	Period (s)	Base Shear (kN)	K-elas (kN/m)	K-eff (kN/m)	Target Displacement (m)		
					DL	SD	NC
Reference	0.61	3910.89	141810.23	87579.85	0.0392	0.0503	0.0873
Model I	0.60	4266.82	143842.78	83955.93	0.0417	0.0535	0.0928
Model II	0.45	10296.89	202400.94	111922.93	0.0357	0.0458	0.0794

The results demonstrate that the jacketing method has increased the rigidity of the structure, leading to a reduction in the period value. In turn, the target displacements for earthquake safety have also been reduced in the more rigid structures. The deformation states obtained for the shear force capacities of the structural models considered in the study are shown in Figure 13.

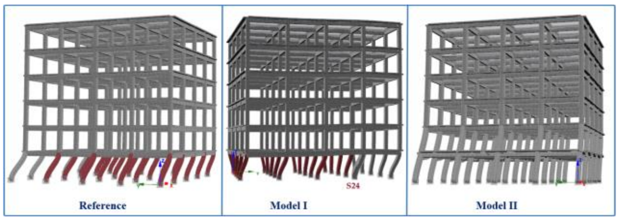

Figure 13. Deformations obtained for shear force capacities.

The structural analyses conducted for the reference model revealed that shear forces were exceeded in a total of 20 columns on the ground floor. In Model I, only the S24 column on the ground floor was strengthened using the jacketing method. In Model II, where element strengthening was applied to all columns in the structure, additional analyses were carried out. A comparison of the demand, limit, and performance ratio (PR) values for the columns on the ground floor across all models is presented in Table 6.

Table 6. Comparison of performance ratios for shear forces in structural models

	Reference			Model I			Model II		
	Demand	Limit	PR	Demand	Limit	PR	Demand	Limit	PR
S1	111.56	73.65	1.51	105.93	70.19	1.51	280.89	465.67	0.60
S2	108.65	71.31	1.52	107.44	71.92	1.49	290.60	464.59	0.63
S3	107.04	71.34	1.50	110.11	73.25	1.50	291.00	463.84	0.63
S4	109.16	71.22	1.53	113.83	73.33	1.55	289.72	464.10	0.62
S5	No exceed			No exceed			No exceed		
S6	97.53	77.57	1.26	90.32	70.85	1.27	330.23	514.05	0.64
S7	92.78	75.06	1.24	92.23	72.56	1.27	351.63	535.94	0.66
S8	90.83	73.86	1.23	96.50	76.33	1.26	335.71	523.95	0.64
S9	95.03	73.75	1.29	104.58	79.89	1.31	335.49	523.30	0.64
S10	No exceed			No exceed			No exceed		
S11	88.72	72.37	1.23	77.82	69.88	1.11	333.55	523.98	0.64
S12	83.97	68.20	1.23	82.12	68.20	1.20	339.03	531.11	0.64
S13	83.33	68.20	1.22	88.62	70.67	1.25	338.28	532.49	0.64
S14	84.31	68.20	1.24	98.96	76.15	1.30	337.88	531.13	0.64
S15	No exceed			No exceed			No exceed		
S16	83.23	68.20	1.22	72.82	67.47	1.08	340.72	532.69	0.64
S17	78.30	66.53	1.18	78.45	67.47	1.16	346.33	541.18	0.64
S18	76.24	66.53	1.15	91.84	74.30	1.24	347.63	543.54	0.64
S19	78.35	66.53	1.18	107.02	79.50	1.35	346.60	541.42	0.64
S20	No exceed			No exceed			No exceed		
S21	72.55	65.02	1.12	66.51	64.94	1.02	347.81	558.38	0.62
S22	66.92	64.62	1.04	71.95	64.67	1.11	346.09	559,45	0,62
S23	66.89	64.62	1.04	92.97	75.79	1.23	344.95	559,86	0,62
S24	66.98	64.62	1.04	No exceed			345.78	559.32	0.62
S25	No exceed			No exceed			No exceed		

With the applied jacketing method, the shear force capacity was not exceeded in all columns. In Model I, where the jacketing method was applied to a single column, the shear force was still exceeded in the other columns. However, no exceedance occurred in Model II, where jacketing was applied to all columns. This clearly demonstrates the applicability of the jacketing method in increasing the shear force capacity. It should be noted that this condition can only be achieved if the rules provided in TBEC-2018 regarding this method are followed. The ratios of columns where the shear force is exceeded for all structural models are given in Table 7.

Table 7. Number of columns where the shear force has been exceeded

Model	Total number of columns on the 1st floor	Total number of columns	Exceeded the number of columns	%
Reference	25	150	20	13.33
Model I	25	150	19	12.66
Model II	25	150	0	0

In column strengthening using jacketing methods, increasing the shear and compressive strength to enhance the ductility of the columns can help address the weaknesses associated with lap splices. However, these methods cannot increase the bending capacity of the columns (TBEC-2018).

4. DISCUSSION AND CONCLUSION

Improving the performance of the load-bearing system under earthquake effects is of critical importance in terms of ensuring the safety of existing structures. In this context, strengthening reinforced concrete columns is a common engineering practice, especially in terms of increasing ductility, strength, and energy absorption capacity. Jacketing, which is one of these strengthening methods, aims to increase the load-bearing capacity by externally jacketing the column section with various materials.

This study investigated the seismic vulnerability of shear-deficient reinforced concrete columns and the effectiveness of concrete jacketing as a strengthening method, using lessons learned from the 2023 Kahramanmaraş earthquakes and numerical analyses of representative structural models. Observations from the earthquake highlighted that low-strength concrete and inadequate transverse reinforcement are primary contributors to structural damage. Numerical analysis confirmed that these deficiencies lead to a significant reduction in the seismic capacity of columns, necessitating effective retrofitting strategies.

Through the implementation of concrete jacketing, this study demonstrated a marked improvement in the shear force capacity and overall seismic performance of reinforced concrete columns. Incremental jacketing application, starting with single-column strengthening and extending to all columns, resulted in enhanced rigidity, reduced structural period, and lower target displacements. The findings highlight the ability of the jacketing technique to mitigate brittle failure mechanisms and increase column ductility when applied in accordance with code provisions.

This study underscores the importance of addressing shear deficiencies in seismic retrofitting practices. By effectively applying techniques like concrete jacketing, engineers can improve the resilience of aging infrastructure in seismically active regions. The results also contribute to the growing body of knowledge on seismic strengthening methods, providing practical insights for enhancing the safety and durability of existing structures.

In the context of this study, the observed reduction in structural period was considered a favorable outcome, as it signifies enhanced stiffness and improved seismic performance, particularly for mid-rise, regular reinforced concrete buildings. The target displacement in the pushover curve represents the anticipated maximum displacement under seismic loading, and its reduction generally signifies improved performance. This is accompanied by an increase in horizontal force-resisting capacity, as demonstrated in Model II, where the strengthened columns exhibited higher base shear values and reduced displacements. The results of this study are primarily relevant to mid-rise, regular reinforced concrete buildings with shear-deficient columns.

In conclusion, the enhancement of seismic resilience in existing RC structures is a multifaceted challenge that requires a combination of innovative techniques and technologies. From traditional methods like RC jacketing to modern solutions involving advanced materials and digital technologies, a wide array of options exists for improving the seismic performance of these buildings. As the frequency and intensity of seismic events continue to rise globally, the urgency for effective retrofitting strategies becomes increasingly apparent. Future research should focus on refining these techniques, exploring new materials, and developing comprehensive frameworks that integrate economic, environmental, and social considerations into the retrofitting process.

Before applying jacketing to reinforced concrete columns, technical and structural factors such as the current damage status, material compatibility, reinforcement and geometry information, their effect on the general behavior of the structure, and application conditions should be taken into consideration. Achieving the purpose of reinforcement depends on the sensitivity with which it is implemented. Otherwise, it will not be possible to provide the functions expected from the reinforcement.

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