

Article

Effectiveness of High-Performance Concrete Jacketing in Improving the Performance of RC Structures

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Abstract

The seismic vulnerability of existing reinforced concrete (RC) buildings that constitute a large portion of the urban building stock has become a growing concern for urban safety. This situation was once again revealed by the massive destruction that occurred in RC structures following the 2023 Kahramanmaraş earthquakes. Particularly in buildings constructed before 1990 and without adequate engineering services, destruction and damage were much greater. In this paper, structural models were created with inadequate transverse reinforcement, low-strength concrete, and inadequate concrete cover thickness, which all play a critical role in the seismic performance of the buildings. Structural analyses were updated for high-performance concrete jacketing models, considering the deformation status obtained for each inadequate parameter. It has been determined that the high-performance concrete can significantly increase structural performance, especially significant increases in shear strength capacities without the need for transverse reinforcement.

Keywords: Kahramanmaraş; earthquake; RC; jacketing; high performance concrete



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1. Introduction

Earthquakes occurring worldwide, particularly in Türkiye, have led to the reliability of existing building stock being questioned in recent years. This again highlights the importance of evaluating existing structures and taking necessary precautions. Post-earthquake damage assessments and pre-earthquake assessments of existing building stock indicate that most buildings have not received the required engineering services and do not meet design requirements. In buildings lacking the required seismic performance, retrofitting can improve the building's performance to the desired level [1–10]. In this context, damage and destruction to RC structures, which constitute a large portion of the urban dominant building stock, play a critical role in the potential loss of life and property [11–15]. Possible damage can be minimized by applying earthquake-resistant design principles to newly constructed buildings and retrofitting existing structures to increase their seismic performance. Decisions regarding demolition and retrofitting, based on detailed seismic performance analysis of the existing building stock, are crucial to reducing the impact of

potential earthquakes. Thus, analyzing the existing building stock can be an essential tool for decision-makers in regions prone to frequent seismic activity [16–22]. The earthquake pair in Türkiye on 6 February 2023 significantly impacted 11 different provinces, causing extensive destruction to the existing reinforced concrete building stock. Incomplete, defective, or complete failure to implement earthquake-resistant structural design principles played a critical role in exacerbating the damage. Concrete and reinforcement deficiencies in reinforced concrete structural elements significantly compromised structural integrity by altering the load transfer mechanisms and accelerating the onset of brittle fracture modes. Poor concrete quality reduced compressive strength, stiffness, and energy dissipation capacity, leading to premature cracking and crushing under seismic or cyclic loading. Similarly, transverse reinforcement deficiencies, such as inadequate transverse reinforcement spacing, insufficient diameter, inadequate hook anchors, and poor material properties, reduced the shear strength, caused longitudinal bar buckling, and facilitated the development of diagonal tensile cracks. The combination of these deficiencies reduces the deformation capacity of RC members and triggers fracture mechanisms that compromise the overall stability of the structural system. Consequently, such deficiencies increase seismic fragility, increasing the likelihood of partial or complete collapse and necessitating targeted strengthening strategies to restore structural integrity and ensure compliance with modern seismic design standards [23–30]. Damage assessment studies, conducted after earthquakes, not only reveal structural weaknesses but also highlight the necessity of taking measures to address these issues in existing structures. The aim of this study was to identify the effects of various variables, such as inadequate transverse reinforcement spacing, low-strength concrete, and inadequate concrete cover thickness, which cause varying degrees of destruction and damage, particularly when the shear capacity of concrete columns is exceeded, on structural performance [31–34]. A further aim of these studies is to determine the extent to which high-strength concrete confinement, under these adverse conditions in existing building stock, affects seismic performance. In particular, the behaviour of columns in existing reinforced concrete structures significantly affects the overall behaviour of the structure. Shear forces in reinforced concrete columns play a critical role in their behaviour under earthquake effects, affecting their strength, stability, and overall structural integrity. Some of the most essential effects of shear forces, considered in the design of RC columns, include concrete shear capacity (since concrete has limited resistance to shear forces), shear reinforcement (stirrups or tie bars), crack control, ductility (the ability to dissipate energy), interaction with axial loads, lateral stability, and the impact on the structure's serviceability. The direct impact of these effects depends on the column's transverse reinforcement spacing, concrete strength, and concrete cover thickness [35–40]. In addition to these studies, studies on unreinforced jacketing have also found a place in the literature. Studies on unreinforced jacketing demonstrate that three critical factors contribute to strengthening: (a) the outer shell effectively compresses the core concrete through the hoop effect, providing increased axial and shear strength; (b) shear transfer compresses the core concrete through interface friction and mechanical interlocking; and (c) mechanical transfer of shear and tensile forces compresses the core concrete through adequate anchorage/dowelling. Furthermore, the combined use of interface bond, the hoop effect, and mechanical anchorage is emphasized as key to strengthened member performance [41–51].

Damage assessment studies on the 2023 Kahramanmaraş earthquakes and field studies conducted by some of the authors clearly revealed that these parameters play a critical role in damage to columns. This and similar studies clearly demonstrate the necessity of taking precautions against these deficiencies and defects in existing RC structures. The unique contribution of this study is the development of a parametric and weighted model set (transverse reinforcement spacing, concrete grade, and concrete cover thickness) based on field

findings in Kahramanmaraş in 2023. The evaluation in this study addresses RC jacketing implemented with high-performance concrete (HPC/UHPC) not only at the element scale but also at the building level. The study goes beyond assessments in the literature, which are often reduced to single-element tests or micro-scale analyses, and reveals the realistic limits and systematic applicability of jacketing with quantitative thresholds. This study provides a demonstration of the suitability of jacketing applications in an academic and practical manner, based on field observations in Kahramanmaraş in 2023. Three main field parameters were considered in the study (transverse reinforcement spacing, concrete compressive strength, and concrete cover thickness) extracted from the 2023 Kahramanmaraş damage data, both individually and in combination, and then transformed into parametric numerical scenarios with realistic values. In this study, the effects of jacketing on both the element and system levels (number of shear exceedances per column, changes in storey stiffness, and period change) are demonstrated on a three-storey regular building model through pushover analyses. The key innovation of this study is the direct conversion of field observations obtained after the 2023 Kahramanmaraş earthquakes into modelling variables and the evaluation of the system-level effectiveness of high-performance concrete (HPC) column jacketing using these data. The study not only validates typical single-element or laboratory-scale jacketing studies in the literature but also presents a new methodological framework with parametric analyses calibrated with field data and proposed decision-making mechanisms. This study also includes numerical analyses on three real parameters, providing a more holistic evaluation compared to traditional single-parameter change-focused modelling in the literature.

2. Advances in RC Strengthening and High-Performance Concrete

Given the importance of understanding how the structural components behave under varying loads, research on the shear strength of reinforced concrete structures is essential. Palanci et al. [52] demonstrate in their study how important it is to consider shear capacities, which are sometimes overlooked, while evaluating a building's seismic performance. According to their research, the accuracy of a building's performance evaluation is greatly impacted by seismic demand estimating techniques and adequate modelling of member shear resistance. Preventing shear failure in reinforced concrete structures is essential since it signifies a quick deterioration of strength and a loss of energy dissipation capability, according to Mwafy and Elnashai's [53] research. The authors suggest a practical method for predicting a shear failure using nonlinear dynamic analysis. Their research demonstrates how crucial it is to include the shear failure as a factor in seismic assessments. Jin et al. [54] conducted an experimental investigation on the size effect in the seismic shear failure of RC cantilever beams. The conclusion of this study is that a member's nominal shear strength and ductility decrease significantly with increasing size, which aligns with Bažant's size effect law. Lima et al. [55] analyzed and compared several theoretical models to evaluate the shear capacity of beam-to-column joints in RC frames. The assessment of the precision and dependability of these models was conducted in this research using a sizable database of experimental results. Li et al. [56] conclude that the selected shear transfer model is crucial for accurate results after extensively evaluating current semi-empirical shear calculation methods. To address the issue of shear-induced building failures, they highlight the need for more robust theoretical foundations. Ali and Saeed [57] experimentally investigated the effects of transverse openings on high-strength concrete beams' stiffness and shear capacity. A negative correlation was revealed between the opening depth and ultimate shear strength, with shear capacity being reduced by up to 53% depending on the size and location of the opening. The scientific literature has delved into machine learning and neural networks, with numerous papers addressing various aspects of these fields. Mansour et al. [58]

employed artificial neural networks (ANNs) to predict the shear strength of reinforced concrete beams. This approach demonstrated greater accuracy and reliability compared to building code predictions. Similarly, Uddin et al. [59] developed machine learning models to estimate the shear capacity of RC beams. The findings of the study demonstrate that they are more objective and accurate than the equations currently adopted in design codes. They concluded that these models predict shear strength with high accuracy. Nguyen et al. [60] proposed an efficient artificial neural network model for predicting the shear strength of RC walls with squat flanges. It was discovered that their model, which was created utilizing 369 test results, could estimate shear capacity more precisely than the empirical equations included in the present design codes. This study also includes the development of a graphical user interface to further facilitate practical application and the suggestion of a predictive formula based on the ANN.

For many years, reinforced concrete column strengthening and seismic retrofitting have been popular study topics. Habib et al. [61] presented a state-of-the-art review on reinforced concrete jacketing, a widely adopted and effective technique for enhancing the stiffness and load-carrying capacity of weak or damaged RC columns, particularly in seismically active regions. Similarly, Raza et al. [62] reviewed strengthening and repair methods for reinforced concrete columns. The paper emphasizes the need for structural sustainability, which involves protecting assets from deterioration caused by extreme events like earthquakes, hurricanes, and ageing. Karayannis et al. [63] conducted an experimental study using a novel thin reinforced concrete jacket to repair earthquake-damaged exterior beam–column joints. A key advantage of this technique is that it does not significantly increase the overall dimensions of the structural elements, thereby minimizing its impact on building size and seismic behaviour. Vadoros and Dritsos [64] experimentally examined the effectiveness of concrete jacketing for strengthening the RC columns. The seismic performance of jacketed columns was compared with that of unstrengthened and monolithic specimens, evaluating parameters such as strength, stiffness, and hysteretic response. They also emphasized the importance of welding jacket stirrup ends to prevent longitudinal bar buckling. Tsonos [65] combined experimental and analytical approaches to assess the effectiveness of two retrofitting techniques, reinforced concrete jacketing and high-strength fibre jackets, for both columns and beam–column joints. The performance of these methods was compared in the study in post-earthquake repair as well as pre-earthquake retrofitting scenarios. Minafò [66] highlighted that reinforced concrete jacketing remains a simple, cost-effective, and widely used technique for enhancing the load-carrying capacity and ductility of existing RC columns, proposing a simplified analytical method for estimating the strength of jacketed columns subjected to axial load and bending moment.

Modern construction increasingly relies on high-performance concrete, valued for its greater compressive strength and long-lasting durability relative to conventional concrete. However, the way this material interacts with reinforcing steel must be carefully considered due to its special mechanical qualities. A comprehensive understanding of reinforcement behaviour within high-performance concrete is crucial for ensuring the civil infrastructure's structural integrity and performance. Ashour [67] conducted experiments to investigate the impact of compressive strength and tensile reinforcement ratio on the flexural behaviour of high-performance concrete beams. A modified method for calculating the effective moment of inertia was proposed in the study, demonstrating that flexural rigidity increases with concrete strength. Akbarzadeh and Maghsoudi [68] conducted both experimental and analytical studies of the flexural behaviour of reinforced high-performance concrete continuous beams, focusing on strengthening them with externally applied carbon- and glass-fibre-reinforced polymer (CFRP and GFRP) sheets. It was discovered in this research that adding CFRP sheets improves ultimate strength and reduces moment redistribution and ductility.

On the other hand, employing the GFRP sheets decreased ductility without appreciably increasing ultimate strength. Cladera and Mari [69] performed an experimental study on the shear failure of high-performance concrete beams. The effect of shear and longitudinal reinforcement was investigated, and a minimum amount of web reinforcement is proposed in the paper, with the results compared to existing shear design approaches. Rashid and Mansur [70] investigated the flexural behaviour of reinforced high-performance concrete beams. It was found that existing code provisions may not adequately address cracking and deflection caused by shrinkage and creep, and it was concluded that reinforcement detailing needs to be reevaluated for improved ductility. Mohammadhassani et al. [71] experimentally examined the failure modes of high-performance concrete beams, highlighting that the higher tensile reinforcement increases the number of cracks while reducing their height and width. Hadi and Li [72] investigated the use of galvanized steel straps and fibre-reinforced polymers for externally reinforcing high-performance concrete columns, demonstrating that this approach effectively enhances column performance under both concentric and eccentric loading.

Ultra-high-performance concrete (UHPC), a class of materials made possible by more recent technological developments, offers noticeably better mechanical qualities, such as much higher compressive strength and ductility. In a review study of ultra-high-performance concrete, Akhnoukh and Buckhalter [73] discussed its mechanical characteristics, uses, and present difficulties. Although UHPC has better qualities than other forms of concrete, the authors point out that the lack of particular design regulations and the requirement for special batching and curing prevent it from being widely used. Goldston et al. [74] experimentally investigated the flexural behaviour of high-performance and ultra-high-performance concrete beams reinforced with glass-fibre-reinforced polymer bars. This investigation revealed the beams' failure modes and discovered that specimens with excessive reinforcement exhibited some "pseudo-ductility." A literature review on the effects of strain rate on ultra-high-performance concrete under tension was conducted by Thomas and Sorensen [75]. The results show that the dynamic increase factors of ordinary concrete are underestimated by current models, indicating the need for better models to anticipate the material's tensile properties. Khaksefidi et al. [76] experimentally examined the bonding behaviour of high-strength steel rebars in both standard performance concrete and ultra-high-performance concrete. According to their research, UHPC significantly reduces the length of the rebar embedment, while increasing the bond strength five times above that of regular-performance concrete. The performance of various surface preparation methods on the interface strength between ultra-high-performance concrete (UHPC) and high-performance concrete (HPC) was examined by Prado et al. [77]. According to their research, flexural testing was the most accurate way to evaluate adhesion, and exposed coarse aggregates gave the best bond performance. Aboukifa and Moustafa [78] carried out an experimental investigation on the seismic behaviour of ultra-high-performance concrete columns reinforced with high-strength steel. The ductility, drift capacity, and seismic performance of the columns were examined, and this yielded important information to guide future design procedures. A novel approach to retrofitting damaged RC beams with ultra-high-performance concrete strips was examined by Murthy et al. [79]. This research effectively showed that damaged beams may be reinforced using this technique without delamination, and the behaviour was correctly predicted by the finite element model that was created. Recent advancements have further improved the remarkable qualities of UHPC by introducing ultra-high-performance fibre concrete (UHPFC). This sophisticated variant stands out for its exceptional strength and durability, as well as the addition of discrete fibres that significantly increase its tensile capacity, crack resistance, and general ductility. Lampropoulos et al. [80] conducted experimental and computational investigations to

evaluate the effectiveness of employing ultra-high-performance fibre concrete layers and jackets for reinforcing RC beams. According to this research, a three-sided UHPFC jacket provided optimum strength, stiffness, and yield performance. The behaviour and strength of ultra-high-performance concrete beams with various kinds of fibre were experimentally examined by Kamal et al. [81]. It was revealed that adding fibres increased the frequency of cracks with smaller widths, increasing the beams' stiffness and maximum load capacity. Al-Osta et al. [82] experimentally examined the efficiency of reinforced concrete beams with ultra-high-performance fibre-reinforced concrete utilizing two distinct jacketing techniques. According to the findings, the flexural performance of the beams was considerably enhanced by both techniques, with particular jacketing configurations offering a superior balance between ductility and strength. The use of ultra-high-performance fibre-reinforced concrete as an effective technique for improving the shear strength of reinforced concrete beams was experimentally investigated by Said et al. [83], who found that this method significantly enhances ultimate shear strength and stiffness while also promoting a ductile failure mode.

Within the scope of this study, the leading causes of damage to columns in light of the 2023 Kahramanmaraş earthquakes were examined. Structural analyses were carried out by considering the three most effective parameters in damage, namely insufficient transverse reinforcement spacing, low-strength concrete, and insufficient concrete cover thickness. Since the buildings before 2000 were particularly damaged in the Kahramanmaraş earthquakes, the building model was developed by considering the earthquake regulation of 1975, before this date. Shear force damage states for the considered variables and reference building models were obtained separately for each model. In models where shear force was exceeded, high-performance concrete was used for RC jacketing, and the results were compared. The most crucial distinction of this study from other studies is that it reveals the causes of damage to the columns in light of the 2023 Kahramanmaraş earthquakes and reveals the applicability of strengthening applications for this.

3. Structural Damages in RC Columns in the Light of the 2023 Kahramanmaraş Earthquakes

The 2023 Kahramanmaraş earthquakes devastated a vast area, causing one of the heaviest losses of life and property in Türkiye's recent history. Severe damage was observed, particularly in reinforced concrete and masonry buildings. Factors such as design and construction flaws, inadequate material quality, irregular structural systems, and non-compliance with earthquake regulations exacerbated the damage. Furthermore, collapses due to soft-storey mechanisms, short column effects, and irregularities in reinforced concrete buildings were widely reported, and inadequate detailing and maintenance were also prominent. This situation revealed the seismic resistance deficiency of a large portion of the existing building stock, clearly demonstrating the need for urgent improvements in both engineering practices and urban transformation policies. More damage occurred, particularly in structures constructed before 2000 and in accordance with the 1975 Turkish earthquake code [84–91]. In this study, analyses were conducted using a numerical model created by considering the minimum requirements of this code. To relate these models to the observed damages, insufficient transverse reinforcement, low-strength concrete, and insufficient concrete cover thickness were selected as variable parameters, and numerical analyses were performed. These variables and their effects in the study were examined in the light of the 2023 Kahramanmaraş earthquakes.

Transverse reinforcement in columns plays a critical role in increasing the ductility of the structural system, reducing energy consumption under horizontal loads such as earthquakes, compressing the concrete against buckling to improve its compressive strength, and

preventing buckling of longitudinal reinforcement. Adequate and appropriately spaced transverse reinforcement increases shear capacity in columns, allowing for ductile behaviour rather than brittle fracture. However, inadequate transverse reinforcement can lead to failure mechanisms leading to collapse, such as premature shear failure, concrete bursting, and buckling of longitudinal reinforcement. Such deficiencies, particularly under high seismic demands, significantly undermine the collapse safety of the structure and increase the risk of sudden strength loss and loss of life. Therefore, column transverse reinforcement detailing should be considered a vital design criterion for seismic safety of buildings. Examples of inadequate transverse reinforcement and damage caused by the Kahramanmaraş earthquakes are shown in Figure 1.



Figure 1. Examples of damage caused by inadequate transverse reinforcement.

Concrete strength in columns is a fundamental parameter for the structural system to safely transfer vertical loads and exhibit ductile behaviour under earthquake effects. Concrete with adequate strength increases the rigidity and stability of the column through compressive strength and resistance to crack propagation. Transverse reinforcement provides a more effective confining effect, supporting ductility. However, using low-strength concrete can lead to critical problems such as premature collapse, uncontrolled crack expansion, and loss of bearing capacity. This can lead to sudden collapses, shear failures, and a weakening of the structure's overall stability, particularly in columns carrying high axial loads. Therefore, inadequate concrete strength in columns directly negatively impacts the structure's seismic performance, reducing collapse safety and significantly increasing the risk of loss of life. Examples of damage caused by the low-strength concrete in the Kahramanmaraş earthquake are shown in Figure 2.



Figure 2. Examples of damage by low-strength concrete.

Concrete cover thickness in columns plays a critical role both in protecting reinforcement against corrosion and fire and in ensuring the concrete–reinforcement bond. Adequate cover thickness prevents rust by delaying the penetration of harmful ions (e.g., chloride and sulphate) from external factors into the reinforcement. It also maintains structural integrity

by preserving the reinforcement's thermal resistance under fire. Inadequate cover thickness accelerates reinforcement corrosion, weakens bonding, and increases crack formation, significantly reducing cross-sectional rigidity and load-bearing capacity. Such deterioration can lead to strength losses and ductility in columns, leading to the development of fracture mechanisms that can collapse under dynamic conditions such as earthquakes. Therefore, the adequacy of concrete cover thickness in columns should be considered an essential design criterion for long-term durability and structural safety. Examples of inadequate concrete cover thickness and resulting damage during the Kahramanmaraş earthquakes are shown in Figure 3.



Figure 3. Examples of damage caused by insufficient concrete cover.

In RC columns, shear forces can significantly affect not only the intra-section stress distribution but also the out-of-plane stability of the member. In columns with insufficient transverse reinforcement, high shear demands can accelerate crack formation, leading to loss of rigidity and the development of out-of-plane failure mechanisms. Especially under earthquake loads, increased out-of-plane movement weakens structural integrity and compromises the overall stability of the structural system. Such out-of-plane column failures are illustrated in Figure 4.

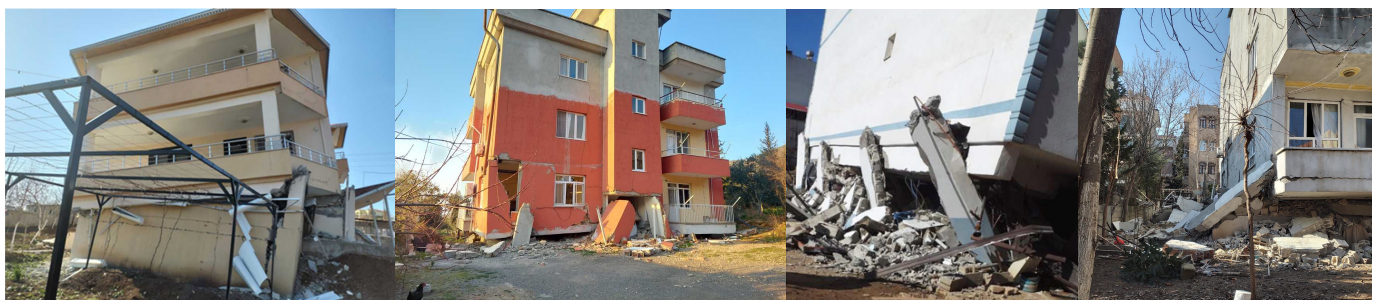


Figure 4. Out-of-plane failure of RC columns.

4. Numerical Analysis

Seismic events in Türkiye have historically caused serious damage to RC structures, resulting in significant loss of life and property. Major earthquakes such as the 1992 Erzincan, 1995 Dinar, 1998 Adana/Ceyhan, 1999 Kocaeli, 1999 Düzce, 2003 Bingöl, 2011 Van, 2020 Elazığ, 2020 İzmir, and 2023 Kahramanmaraş earthquakes have revealed the inadequate seismic resistance of RC structures [92–99]. Türkiye has made changes and in-

novations in earthquake-resistant structural design principles over time, following the devastating earthquakes it has experienced. After the 1939 Erzincan earthquake, seismic design codes officially came into force and were used with changes over time [100–103]. The current Turkish Building Earthquake Code (TBEC-2018) is much more comprehensive and detailed than the previous codes. The 1999 earthquakes (Marmara and Düzce) significantly raised awareness of the seismic safety of buildings in Türkiye, demonstrating their significance. Therefore, the second category encompasses buildings constructed after 2000. Nearly all buildings built before 1998 have insufficient ductility. This deficiency stems primarily from the insufficient emphasis on ductility in the relevant codes during those years [104]. This situation is shown in Figure 5.

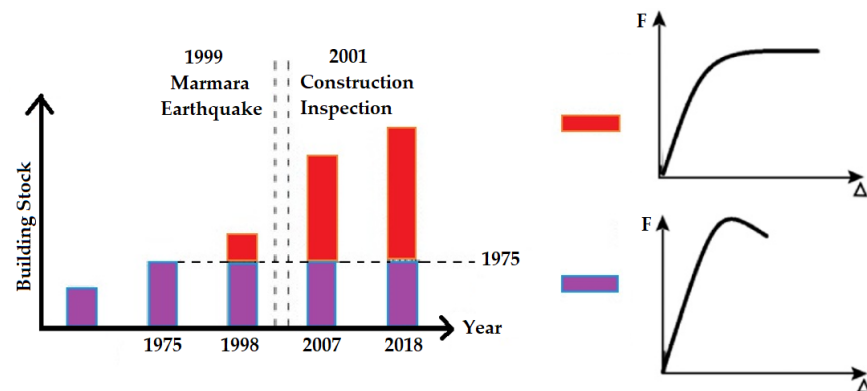


Figure 5. The change in building stock with the evolution of earthquake codes in Türkiye.

Consequently, the pressing need to assess the resilience of existing structures and implement effective mitigation strategies to reduce the potential impacts of future earthquakes has become increasingly apparent. A significant proportion of the buildings that collapsed or sustained severe damage during the Kahramanmaraş earthquakes were reinforced concrete structures constructed before the year 2000. This study used numerical analyses to represent these buildings, considering the minimum requirements stipulated in the 1975 seismic design code that governed their construction [105]. The minimum conditions included in the 1975 code and used in the reference building model within the scope of this study are shown in Table 1.

Table 1. Structural characteristics considered in the study.

Parameter	1975
Concrete Grade	C14
Reinforcement Grade	S220
Columns Dimensions (mm)	250 × 250
Beams Dimensions (mm)	200 × 300
Beam Lower Reinforcement	2 ϕ 12
Beam Upper Reinforcement	2 ϕ 12
Longitudinal Reinforcement (column)	4 ϕ 14
Transversal reinforcement (mm)	ϕ 8
Concrete cover (mm)	25
Spacing of Transversal reinforcement (mm)	200

The column and beam cross-sections considered in the numerical modelling for the reference building are shown in Figure 6.

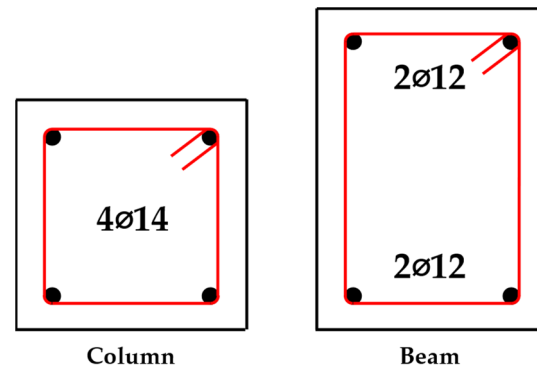


Figure 6. Cross-sections of columns and beams.

In addition to these features, a regular mid-rise RC structure was modelled. For this purpose, a three-storey building with a height of 3 m per storey was modelled. The ZC, which can be called the average soil class in the TBEC-2018 [106], was selected as the local soil class. The damping ratio in the building is considered to be 5%. Using Seismostruct v2024 software [107], the structure consisting of three openings, each 5.50 m in both directions, was modelled.

The storey plan and markings of the columns of the reference structural model are given in Figure 7. The structural systems were considered as the frame type, and RC columns, beams, and slabs were defined in accordance with the 1975 seismic design code.

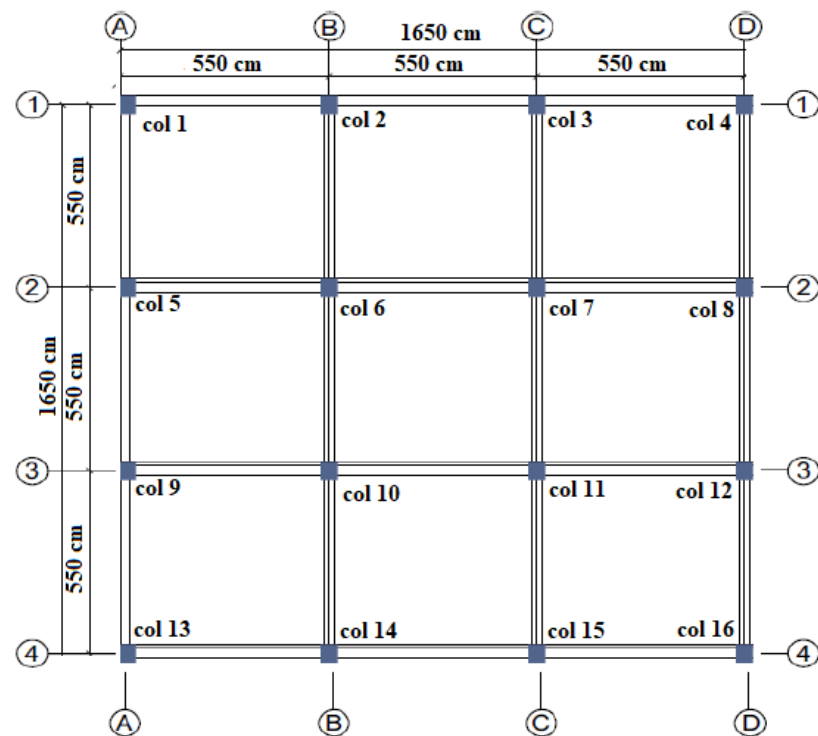


Figure 7. The blueprint of the reference building model.

The 2D and 3D models for the reference building model are shown in Figure 8.

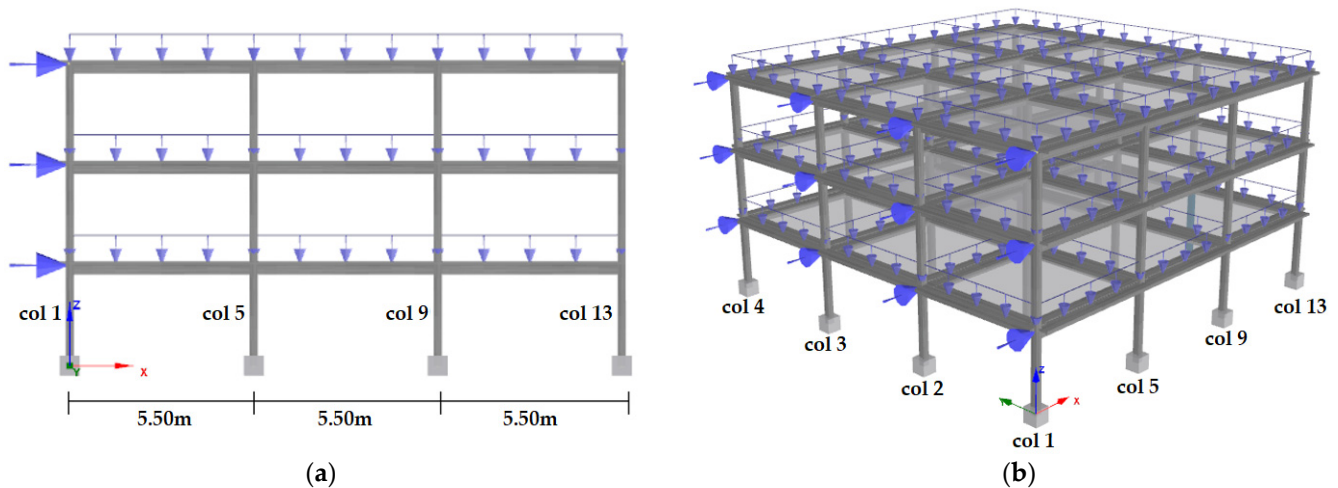


Figure 8. The 2D (a) and 3D (b) models of the reference building model.

In all the structural models, force-based plastic hinge frame elements (infrmFBPH) were employed to represent both columns and beams. This element formulation allows for the distribution of inelastic behaviour over a predefined region through force-based plasticity, thereby confining nonlinear responses within a finite segment. To achieve an accurate representation of stress–strain distributions, each cross-section was discretized into 100 fibres, a resolution deemed sufficient for the required level of modeling accuracy. The plastic hinge length ratio (L_p/L) was specified as 16.67%, in accordance with established analytical and design provisions. This parameter identifies the critical region of a structural member where the plastic deformations are expected to concentrate under seismic loading, thus facilitating energy dissipation while preserving overall structural stability. The adopted value aligns with widely accepted engineering practices for estimating hinge lengths in inelastic structural components. In addition, uniformly distributed loads were incorporated into all structural analyses.

It is a fact that the behaviour of building materials under load can be determined using some mathematical models, which is vital in building design and evaluation [108]. The nonlinear concrete model [46] and steel model [109] were used for concrete and steel material. The stress–strain relationship of the material models considered for these models is demonstrated in Figure 9.

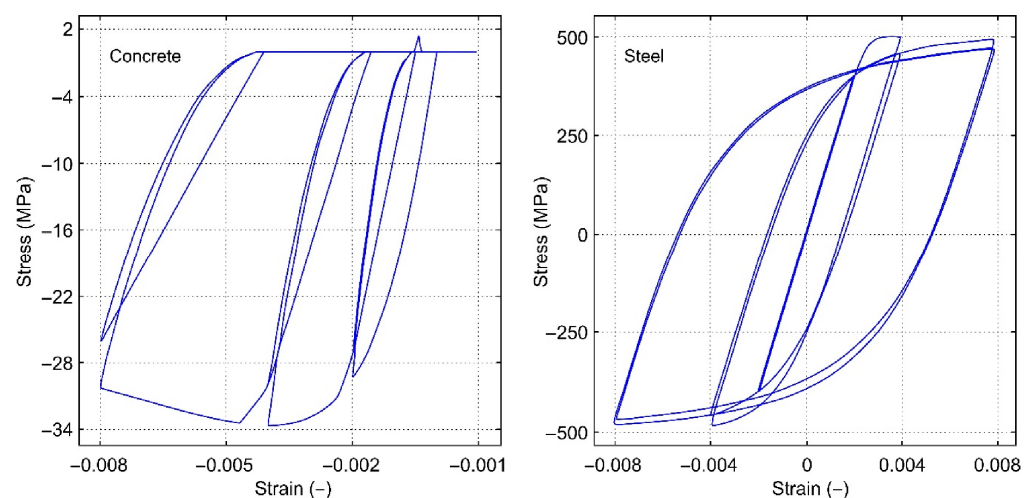


Figure 9. Material models for concrete and steel considered in the study.

Pushover analysis was applied to all structural models to examine deformation capacity and structural response under specified loading. This method accounts for both elastic and inelastic behaviour and is widely used in earthquake engineering to estimate seismic performance. It offers a more comprehensive understanding of a structure's response to dynamic loads, such as those induced by earthquakes, by accounting for nonlinear deformations beyond the elastic limit [110–115]. The corresponding flow chart is presented in Figure 10. The numerical models were developed in Seismostruct [107] using a three-dimensional frame representation of the structural system. The base supports were modelled as fixed, while the slabs were assumed to behave as rigid diaphragms in-plane, ensuring uniform load transfer to the columns. Gravity loads were applied before the lateral pushover analysis, in which the lateral forces were distributed uniformly along the building height.

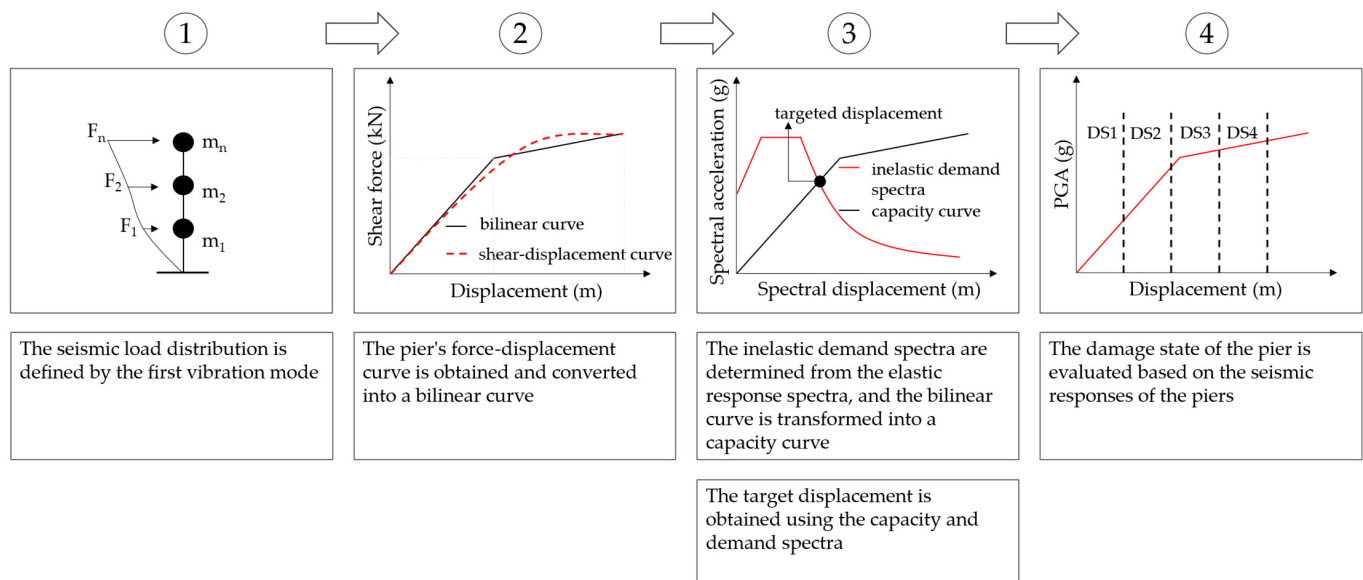


Figure 10. Flowchart of pushover analysis.

The shear force damage state obtained for the reference building model is shown in Figure 11.

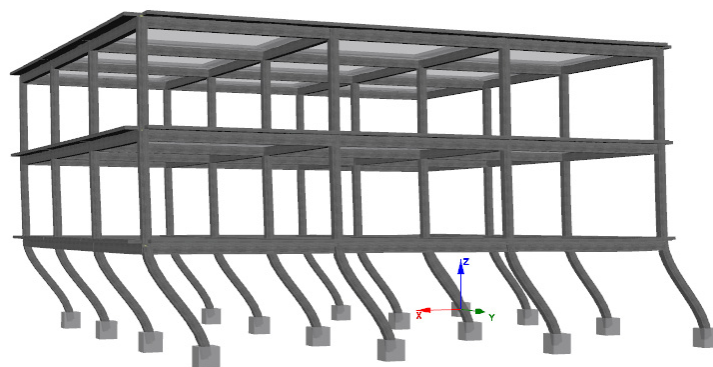


Figure 11. Shear damage status of the reference building.

As can be seen in Figure 10, there is no shear force exceedance in the reference building model. Furthermore, the 50 steps selected in the structural analysis have been fully completed. As stated in the previous section, necessary changes were made to the reference building model for the situations frequently encountered in damaged columns, and structural analyses were performed for the variables. The descriptions of the structural

models created for the variables considered are shown in Table 2. All other structural features remained the same, and no changes were made.

Table 2. Structural models created for different variables.

Model No.	Description
Model I	Insufficient Transverse Reinforcement: Transverse reinforcement spacing in columns has been increased to 400 mm. ($\phi 8/400$)
Model II	Low-Strength Concrete: Concrete that is below the intended strength (C8/10)
Model III	Insufficient Transverse Reinforcement ($\phi 8/400$) + Low-Strength Concrete (C8/10)
Model IV	Inadequate Concrete Cover (0.10 cm)

The shear force damage states obtained for the Model I and Model II are shown in Figure 12. Red colored columns show columns where the shear force is exceeded.

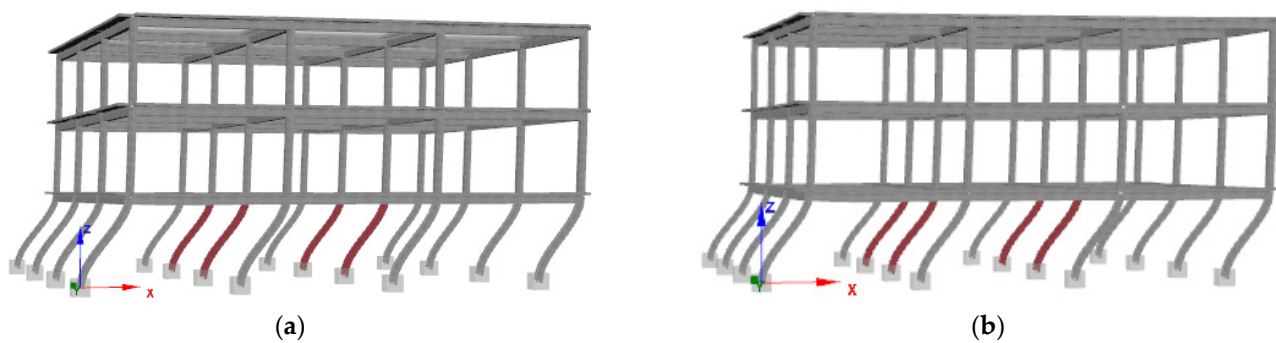


Figure 12. Shear damage status for: (a) Model I and (b) Model II.

In Model I, only insufficient transverse was selected as a variable, while in Model II, only the low-strength concrete was chosen as a variable. In both models, the shear force capacity was exceeded in four columns on the first storey, and these columns are shown in Figure 13.

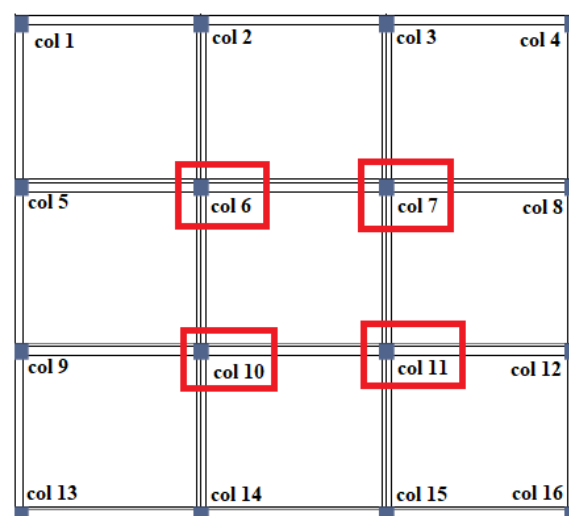


Figure 13. Columns with shear force capacity exceeded for Model I and Model II.

In Model III, the variables in Models I and II were considered. The shear damage condition obtained for Model III, where inadequate transverse reinforcement spacing and low-strength concrete were replaced together, is shown in Figure 14.

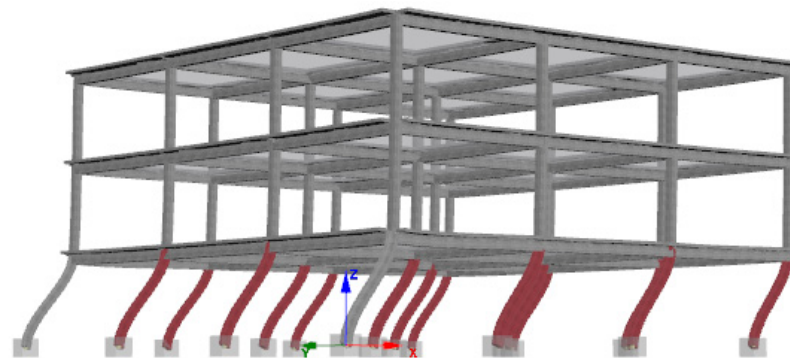


Figure 14. Shear damage status for Model III.

In the case of insufficient transverse reinforcement and low-strength concrete, which play the most critical role in the shear force capacity of columns, the number of columns exceeding the shear force capacity increased dramatically. The first-storey columns whose shear force capacity is exceeded for Model III are shown in Figure 15.

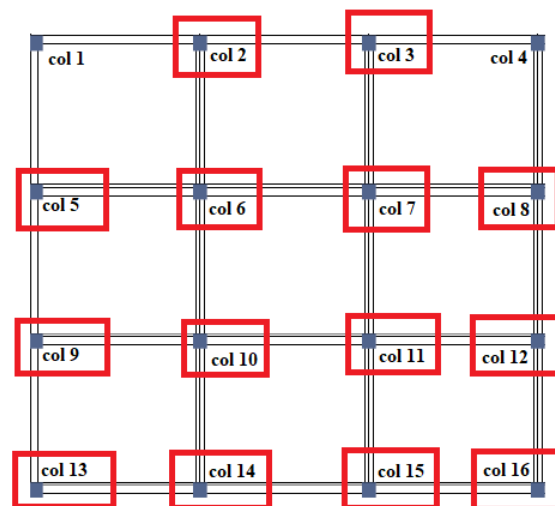


Figure 15. Columns with shear force capacity exceeded for Model III.

To compare the high-performance concrete jacketing to normal-strength concretes, the analysis was renewed in Model III by taking the concrete jacketing as C20. The shear force damage status in Model II, when all the structural characteristics are kept constant and only the concrete jacketing is made of standard strength concrete (C20), is shown in Figure 16.

Before the reinforcement, the number of columns exceeding the shear capacity in Model II was 14. No columns exceeded the shear capacity with the high-strength concrete jacketing. However, although the number of columns exceeding the shear capacity decreased with the normal-strength concrete jacketing, the number of columns exceeding the shear capacity remained high at 10.

Another variable considered in the study was insufficient concrete cover thickness. Model IV was created by considering the minimum concrete cover thickness (1,0 mm) allowed by the software for col 6 in the reference building model. The shear force damage state obtained for this model is shown in Figure 17.

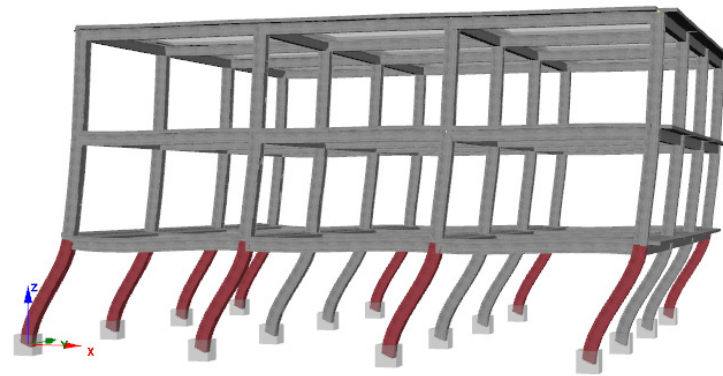


Figure 16. Shear damage status for Model III with regular-strength concrete.

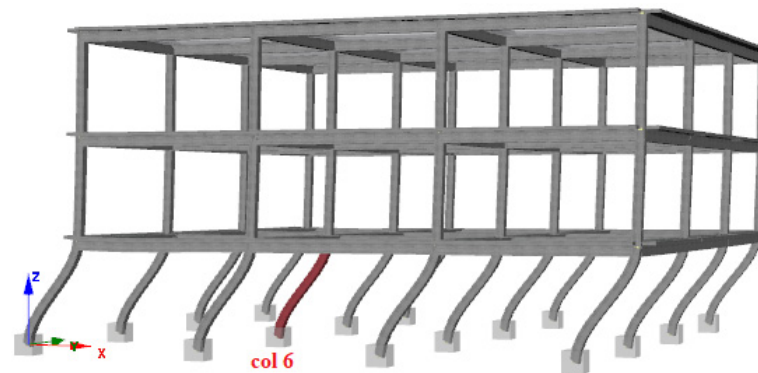


Figure 17. Shear damage status for Model IV.

All the structural models considered were created by considering the causes of damage observed due to field observations. The presence of features that negatively affect the structure's seismic performance increases the damage level. Especially in RC structures, the transverse reinforcement spacing and concrete strength below the predicted values play a critical role in the shear force capacity. This disrupts the structural integrity and makes the stability of the structure risky. This problem exists especially in existing buildings built before 2000. Different strengthening methods can be used to increase the seismic performance of existing structures. Concrete jacketing of columns is one of these methods, and within the scope of this study, concrete jacketing was performed using the high-performance concrete. This study examines whether the shear demand in RC columns surpasses their capacity and implements confinement as a strengthening strategy when exceedance is observed. Concrete jacketing was selected due to its effectiveness in enhancing shear resistance and ductility, thereby improving overall seismic performance. A jacketing thickness of 100 mm was employed for all strengthened columns, corresponding to the minimum requirement specified by the Turkish Building Earthquake Code (TBEC-2018). The column cross-sections after jacketing are shown in Figure 18. For the high-performance concrete, C60 was selected, and jacketing was performed.

Concrete jacketing was made only on the columns where the shear capacity was exceeded.

The material and dimensional properties of the cross-sections before and after the jacketing are shown in Table 3; examples of the application are provided in Figure 8.

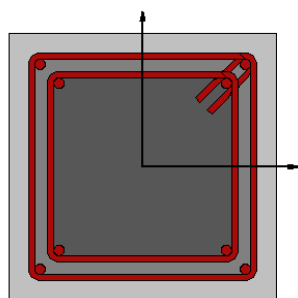


Figure 18. Column cross-sections after jacketing.

Table 3. Structural models created for different variables.

Section Material (s)		Section Dimensions	
External Longitudinal/transverse reinforcement	S420	External height	350 mm
Internal Longitudinal/transverse reinforcement	S220	Internal height	250 mm
External longitudinal reinforcement	4 ϕ 14	External width	350 mm
Concrete Jacketing	C60	Internal width	250 mm
Concrete core	C14	Cover thickness	25 mm

All element controls (element rotation capacity and shear capacity) were determined in accordance with EN1998-3:2005-Annex A, in accordance with the definitions in EN1998-1:2004, 4.2.2 (1) P, (2) and (3). In calculating the deformation capacities of jacketed elements, the assumptions specified in EN 1998-3:2005 are used: (i) the behaviour of jacketed elements is monolithic; (ii) the axial load acts on the entire cross-section of the strengthened element, not only on the first column as before; and (iii) the concrete properties of the jacket element are valid for the entire cross-section [110]. Shear capacity checks of the jacketed elements were carried out according to EN1998-3:2005.

The shear force damage status obtained after the RC jacketing for Model I is shown in Figure 19.

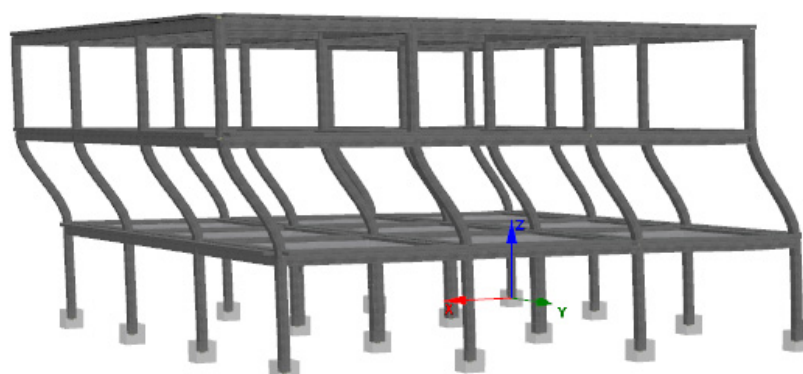


Figure 19. Shear damage status for RC jacketing in Model I.

The shear force damage status obtained after the RC jacketing for Model II is shown in Figure 20.

The shear force damage status obtained after the RC jacketing for Model III is shown in Figure 21. The RC jacketing was performed only for columns whose shear force capacity was exceeded.

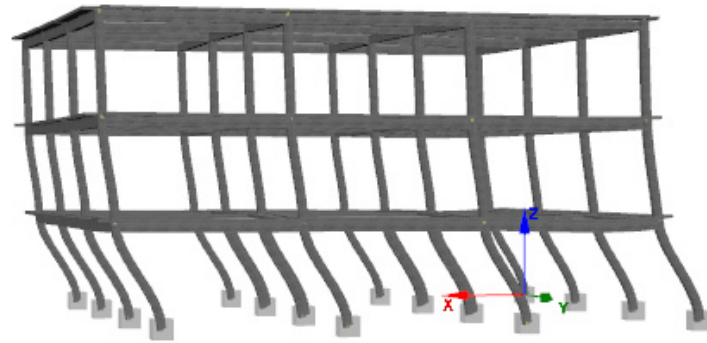


Figure 20. Shear damage status for RC jacketing in Model II.

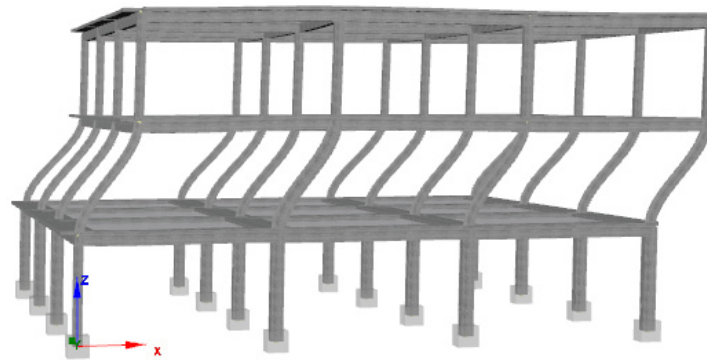


Figure 21. Shear damage status for RC jacketing in Model III for exceeded columns.

Since there is a stiffness change between stories, the RC jacketing was used on all columns for Model III. The shear force damage status for this model is shown in Figure 22.

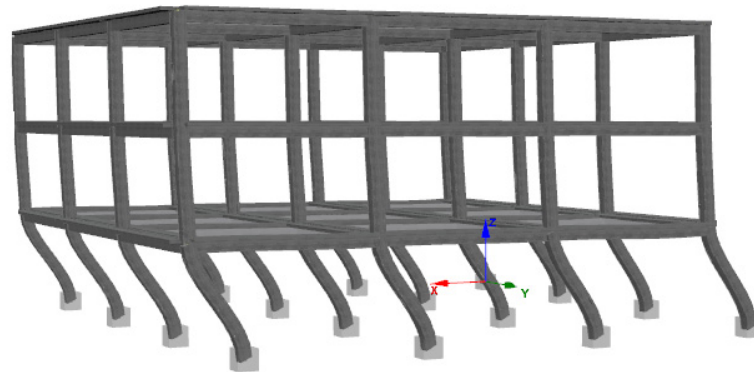


Figure 22. Shear damage status for RC jacketing in Model III for all columns.

Model III, the most unfavorable model considered in the study, was analyzed by applying only the high-performance concrete (C120) jacketing. No transverse or longitudinal reinforcement was used. As in other structural models with reinforcement in both directions, jacketing was selected as 100 mm and new column dimensions were taken as 350×350 mm. In this case, the new column cross-section obtained is shown in Figure 23. Concrete jacketing was applied only to columns whose shear force capacity was exceeded.

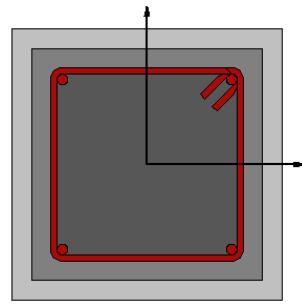


Figure 23. Cross-section of RC columns after the jacketing.

The shear force damage state obtained for this model is shown in Figure 24.

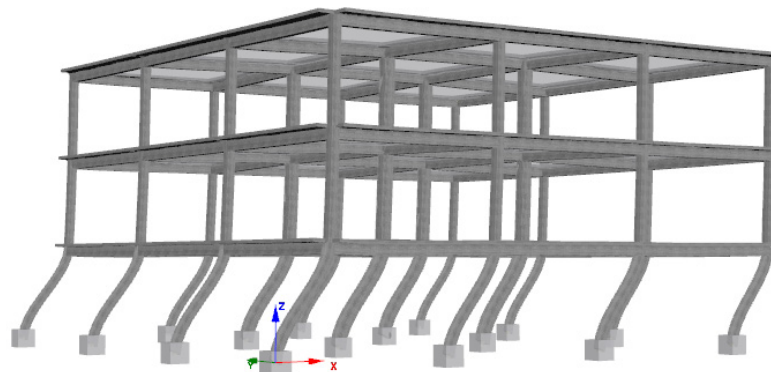


Figure 24. Shear damage status for concrete (C120) jacketing in Model III.

With the jacketing made using the high-performance concrete (C120), there are no columns whose shear force capacity is exceeded. The shear force damage status obtained after the RC jacketing for Model IV is shown in Figure 25. The RC jacketing was performed only for columns whose shear force capacity was exceeded.

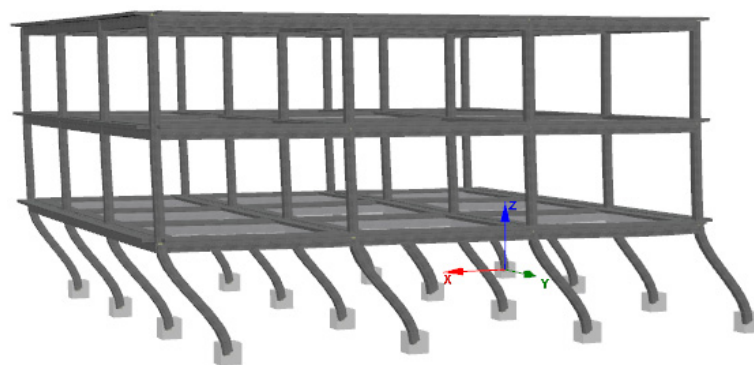


Figure 25. Shear damage status for RC jacketing in Model IV for the exceeded column.

Shear force capacity is a fundamental parameter governing the performance of structural elements when subjected to horizontal actions, and it plays a decisive role in ensuring overall structural safety, particularly under dynamic excitations such as earthquakes. Exceeding this capacity often leads to sudden and brittle failures, which not only compromise the integrity of individual members but also pose a serious threat to the global stability of the entire structural system, potentially resulting in abrupt collapse. Unlike the flexural deficiencies, which may allow for some redistribution of stresses, inadequate shear resistance prevents structural elements from developing the desired ductile response. As a consequence, seismic energy cannot be effectively dissipated, leading to rapid propagation of damage throughout the structure. This issue is of particular importance in reinforced

concrete systems, where the shear failures are typically more catastrophic and less predictable than flexural failures. Therefore, accurate evaluation and enhancement of shear capacity are essential steps in the seismic design and retrofitting of structural members to ensure both resilience and safety.

5. Conclusions

The 2023 Kahramanmaraş earthquakes once again highlighted the urgent need to strengthen existing RC structures, many of which were constructed before the enforcement of modern seismic codes. Field observations and post-earthquake assessments revealed that a significant proportion of structural damage and collapse originated from deficiencies in shear capacity, particularly in columns. As primary vertical load-bearing elements, columns play a critical role in maintaining overall stability; however, when their shear strength is inadequate, they are highly vulnerable to brittle and sudden failures under seismic loading. Such shear failures are especially detrimental, as they prevent the development of ductile behavior, hinder energy dissipation, and accelerate progressive damage propagation throughout the structure. The observed collapses in the Kahramanmaraş earthquakes clearly demonstrated that insufficient column shear capacity undermines the seismic resilience of individual buildings and poses a serious threat to life safety. Consequently, assessing and enhancing the shear resistance of existing columns should be prioritized in retrofitting strategies to ensure the structural integrity and mitigate the risks of catastrophic collapse in future seismic events.

Structural analyses were carried out for three variables affecting columns' shear force capacity: insufficient transverse reinforcement, low-strength concrete, and insufficient concrete cover. Analyses performed on the reference building model, considering these variables, clearly revealed that these three factors play a critical role in shear force capacity. The results obtained in this context are entirely consistent with field observations. With the combination of too many negative parameters, the number of columns whose shear force capacity was exceeded also increased. These defects observed in existing RC structures would play a critical role in their seismic performance. To this end, models were developed that utilize the high-performance concrete consolidation methods to strengthen these structures. After the reinforcement, there were no columns whose shear force capacity was exceeded. However, for such reinforcement practices to gain meaning, they must be implemented sensitively.

In the context of seismic retrofitting, the concrete jacketing (RC jacketing) is widely recognized as an effective technique for enhancing the load-bearing capacity, ductility, and overall seismic resilience of deficient reinforced concrete members. However, the efficiency of this method is highly dependent on several critical factors that must be carefully considered during design and application. One of the most important aspects is the bond quality between the existing member and the newly added jacket. Inadequate surface preparation, insufficient roughening of the concrete substrate, or improper use of bonding agents may result in weak interface behaviour, leading to premature de-bonding and reduced retrofit effectiveness. Another essential consideration is the continuity and detailing of reinforcement within the jacket. Proper anchorage, overlap lengths, and transverse reinforcement spacing are necessary to ensure composite action and to prevent premature shear or confinement failures.

In addition, the jacket's thickness must be selected according to both code provisions and structural requirements, balancing the need for sufficient confinement and strength enhancement with potential issues such as increased member dimensions and added dead load. Confinement effectiveness is strongly influenced by the ratio and arrangement of transverse reinforcement; inadequate confinement detailing may compromise ductility

and energy dissipation, especially under cyclic seismic loading. Furthermore, construction quality control plays a decisive role: poor workmanship, inadequate compaction of newly placed concrete, or insufficient curing can significantly reduce the intended strengthening benefits. From a structural performance perspective, jacketing should be evaluated at the member scale and within the global structural system. For instance, strengthening individual columns without addressing deficiencies in beams, joints, or foundations may lead to undesirable stiffness irregularities and redistribution of seismic demands. Therefore, a holistic assessment is required to ensure that the retrofitting strategy does not inadvertently introduce new vulnerabilities. Finally, compliance with relevant seismic codes and guidelines, such as TBEC-2018, is essential to guarantee that the retrofitting intervention meets minimum safety and performance requirements. In addition to all these, after the RC jacketing is performed, the stiffness/strength differences between the floors must be controlled.

In this study, pushover analysis was used for a three-storey reinforced concrete structure model to determine the stiffness reduction under increasing lateral load and the collapse mechanism. This study, which goes beyond single-element analyses and provides an integrated assessment at the building scale, considers three critical factors from the 2023 Kahramanmaraş earthquake. While existing reinforcement layouts are usually maintained in experimental or analytical studies, this study analyzed only the HPC sheathing scenario without reinforcement, thus isolating the independent contribution of the HPC. The results were directly compared with field damage observations. In these respects, the study not only confirms previous jacketing research but also provides a methodological model to guide practice. In the study, no shear capacity exceedance was observed as a result of the jacketing constructed with C120 high-performance concrete (HPC) without additional longitudinal or transverse reinforcement; however, this does not directly imply that the interface shear strength, confinement effect, and buckling restraint mechanisms required by design regulations were achieved. In real-life applications, sufficient bonding between the existing column core and the new jacketing concrete requires surface roughening, mechanical connections using shear dowels or anchor rods, and circumferential consolidation and buckling control using hoop steel along the jacketing. In this context, it can be assumed that the unreinforced HPC shells in the study provide a limited passive consolidation effect on the core concrete due to their high compressive strength and low crack opening; however, this effect may not completely prevent permanent bond loss or interface slippage under cyclic loading. Therefore, it is recommended that in future applications, the interface roughness and dowel details should be included in the design, and the shear transfer capacity and circumferential tightening effect of the HPC shell should be verified experimentally and analytically in comparison with the reinforcement added systems. This study theoretically evaluates the system-scale effects of HPC cladding. Experimental verification of interface behaviour and long-term bond performance is recommended for future research. Furthermore, validating the proposed decision framework for different building types (irregular-plan, high-rise) will increase the generalizability of the method.

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