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Seismic Performance Assessment and Strengthening of a Residential RC Building Damaged in the 2023 Türkiye Earthquakes: A Case Study

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Abstract: Recent devastating earthquakes have exposed the limitations of conventional seismic design, which primarily ensures life safety but may fall short in preserving post-event functionality and reparability. Particularly in regions with vulnerable building stocks, the socioeconomic consequences of widespread structural damage, including prolonged downtime and reconstruction costs, underscore the urgent need for seismic-resilience-oriented assessment and design strategies. This paper presents a detailed seismic performance assessment of an eight-story reinforced concrete (RC) frame structure damaged during the 6 February 2023 Kahramanmaraş earthquakes. The building's existing structural system and material properties were identified through comprehensive in situ investigations. These included foundation excavation, concrete core sampling, and reinforcement inspections carried out in accordance with relevant standards. Nonlinear performance analyses were then conducted to assess the building's seismic adequacy. The results revealed deficiencies, prompting a retrofitting strategy that adds RC shear walls to improve lateral resistance and achieve resilience-based performance objectives. The study also documents typical damage patterns observed after the earthquakes. In addition to the pushover analysis, nonlinear time-history analyses were conducted to validate the structural response further and provide a comprehensive comparative evaluation. Furthermore, a comparative cost-benefit analysis was conducted to evaluate the financial feasibility of the proposed strengthening strategy against the total reconstruction of the structure. Most notably, it stands as one of the first comprehensive studies conducted after the February 6 Kahramanmaraş earthquakes to propose and implement a detailed retrofitting scheme for a damaged structure, providing valuable insights into strengthening strategies that can guide future engineering practice and policy.

Keywords: RC Building, Performance-based design, Shear wall retrofitting, Structural rehabilitation, Earthquake damage assessment

1. Introduction

The increasing frequency and severity of recent seismic events across the globe have exposed critical limitations in conventional seismic design philosophies, which prioritize life safety while often overlooking long-term functionality and reparability (Pandey et al., 2025). While traditional ductile-based design approaches can prevent collapse, they frequently result in significant damage and residual deformations, rendering buildings uninhabitable or economically irreparable (Takagi, J., & Wada, A., 2019). The socioeconomic consequences of such damage, including extended downtime, reconstruction costs, and disruption to urban systems, are no longer acceptable within the framework of modern societal expectations for resilience and sustainability

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(Sert et al., 2024). These realities underscore the need for an urgent paradigm shift toward seismic design strategies that not only safeguard lives but also ensure rapid post-earthquake recovery (Wen et al.,2024).

The widespread destruction and varying levels of structural damage observed after earthquakes underline that assessing the seismic capacity of existing buildings and making informed decisions for those with insufficient performance constitute a critical step in the development of earthquake-resilient cities (Freddi et al.,2021). This process is a key element of contemporary disaster management measures for existing buildings, ensuring urban planning and the sustainability of social life. Determining the seismic performance of existing structures after devastating earthquakes and making decisions about retrofitting and/or demolition depends on the exhaustive seismic performance. Each study conducted in this context is of vital importance for both academia and practice (Landolfo et al., 2025; Freddi et al., 2025; Imtiaz et al., 2025; Di Sarno and Pugliese, 2020; Çelebi et al., 2013; Yuzbasi, 2025a). By enabling the assessment of structural damage using scientific methods, such studies contribute to the generation of knowledge in the engineering discipline on structural safety, durability analysis, and risk management (Brunesi, Emanuele, et al.,2019; Nascimbene, R., & Bianco, L., 2021). Furthermore, the data obtained and the methods developed will play a critical role in ensuring the safety of the building stock, preventing loss of life, and utilizing resources efficiently. Such studies will also directly contribute to the development of social resilience by increasing the effectiveness of post-disaster recovery and reconstruction processes (Adalier and Aydingun, 2001; Ahmadizadeh and Shakib, 2004; Zhao et al., 2009; Dogan et al., 2021; Lin et al., 2021; Ko et al., 2023; Doğan et al., 2023; Akhlaghi et al., 2021; Wu et al., 2025; Lemnitzer et al., 2014). Similar post-earthquake studies are being carried out in Türkiye, which is located in a geography with high seismic risk.

The February 6, 2023, Kahramanmaraş-centred earthquakes, which impacted a wide region across southeastern Türkiye and northern Syria, resulted in extensive damage and widespread collapse among RC buildings, affecting a substantial share of the urban building stock. The vast destruction and damage to RC structures once again demonstrated that, across a significant portion of this stock, many buildings either lacked proper seismic design, were poorly constructed, or had deteriorated over time, ultimately leading to a marked loss of structural capacity (Yön et al., 2025; İnce, 2024; Vuran et al., 2025; Doğan et al., 2024; Işık et al., 2025; Atmaca et al., 2025; Aras et al., 2025; Işık et al., 2026). In particular, deficiencies in the seismic performance of medium and high-rise RC structures were observed; brittle collapses occurred in the column-beam joint areas, story drifts increased, and serious decreases in horizontal load-carrying capacities occurred (Öztürk et al., 2023; Dedeoğlu et al., 2025; Arslan et al., 2024; Işık et al., 2025a; Yuzbasi, 2024a; Hadzima-Nyarko et al., 2025; Peker et al., 2025). Numerous studies have investigated the damage sustained by RC structures across various provinces and earthquake-prone regions, drawing on both field observations and civil and earthquake engineering principles. The primary causes of damage are generally attributed to design and construction deficiencies, substandard material properties, insufficient transverse and longitudinal reinforcement, and structural irregularities (Erbaş et al., 2025; Işık, 2025; Avcil et al., 2025; Uysal et al., 2025; Aksoylu et al., 2025; Ekici et al., 2025; Aslan et al., 2024; Öztürk et al., 2023; Mercimek et al., 2025). In addition to these studies, numerical analyses have been performed on existing earthquake-affected structures as well as on corresponding structural models. For instance, Çelebi and Kırtel (2025) conducted numerical analyses for an RC structure with ribbed slabs in Gaziantep, one of the provinces affected by the earthquake. Kazaz et al. (2024) evaluated the seismic performance of a heavily damaged RC structure within the scope of structural inspection. Tan et al. (2025) numerically conducted the effect of filled walls on an RC structure exposed to earthquakes. Işık et al. (2025) evaluated the shear force capacity using a numerical structural model they created, considering the reasons for damage in RC columns after earthquakes, such as insufficient transverse reinforcement and low-strength concrete conditions, and compared the results by reinforcing them with fibre polymers.

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Altıok et al. (2024) studied a comparative study of the seismic performance of unreinforced and reinforced school buildings located in an earthquake zone. Bassurucu et al. (2025) conducted a detailed seismic performance analysis of an existing RC structure in Adıyaman province. Atmaca et al. (2025) attempted to identify the main causes of damage through numerical analysis for 400 RC buildings located in the earthquake zone. This study, unlike other studies, is based on determining the earthquake performance of an RC structure exposed to an earthquake by taking into account full-scale field tests and measurements, and strengthening it with RC shear walls.

As a result, the massive destruction caused by the earthquakes centered in Kahramanmaraş represents not only structural devastation but also a macroeconomic shock that has left deep and multifaceted marks on the Turkish economy. The total cost of the earthquake is estimated to exceed 100 billion Euros. An examination of the sectoral distribution of these economic losses reveals that the housing sector, accounting for approximately 55% of the damage, constitutes the largest category, clearly highlighting the financial cost of the fragility of the existing RC building stock. The fact that 86.7% of the buildings in the region have RC structural systems indicates that damage to this building stock is at the heart of the economic loss. In particular, the fact that 80% of the buildings destroyed in the earthquake were constructed before 2000 with inadequate engineering services clearly demonstrates the fragility of the existing RC building stock and the critical need for strengthening works in terms of economic sustainability. The approximately €1.6 billion in compensation paid by the Natural Disaster Insurance Institution (DASK) alone for more than 450,000 independent units illustrates the scale of rehabilitation or reconstruction of moderately and severely damaged RC buildings and the extent of technical intervention in this field (TC SBB, 2023; Gönülcü et al., 2025; Aydın et al., 2025; Aydoğdu and İlkı, 2026).

Field investigations and damage analyses conducted after the earthquakes centered in Kahramanmaraş have once again highlighted the need to assess the seismic safety of the existing building stock. Accordingly, improving structures whose seismic performance falls below the levels stipulated in codes through engineering interventions constitutes a critical strategy in constructing disaster-resilient urban spaces. Therefore, strengthening techniques applied to buildings with identified structural defects are considered one of the most effective and sustainable methods for minimizing potential seismic risks by optimizing the dynamic characteristics of existing structures. Strengthening RC structures aims to increase the strength, rigidity, and ductility of the existing structural system under seismic loads, thereby bringing the structure to its targeted performance level. Various strengthening strategies can be employed to enhance structural capacity (Belbachir et al., 2023; Aydoğdu et al., 2025; Narlıtepe et al., 2025; Olabi et al., 2026; Çalım et al., 2026).

Numerous studies collectively examine advanced retrofit techniques utilizing fibre-reinforced polymer (FRP) materials, such as FRP-confined concrete cores, GFRP wrapping, near-surface-mounted GFRP bars combined with engineered cementitious composites, and mechanically pressed CFRP plates, demonstrating their effectiveness in boosting the seismic performance of RC elements (Wang et al., 2022; Qin et al., 2022; Yang et al., 2022; Scalvenzi et al., 2022; Wang et al., 2023; John et al., 2025; Işık et al., 2025b; Wang et al., 2025). In addition, there are also commonly preferred strengthening methods such as steel diagonal members in RC structures, RC jacketing, and adding RC shear walls, etc. Through extensive experimental and analytical studies, they demonstrate significant improvements in axial load capacity, seismic performance, and progressive collapse resistance, while highlighting the importance of design considerations such as column size and practical application methods. (Castro et al., 2017; Karadoğan et al., 2019; Aksoylu and Kara, 2020; TBEC-2018; Saeed et al., 2025; Cheng et al., 2025; Wang et al., 2025; Gao et al., 2025; Xiao et al. 2026; Kap, 2026). The effectiveness of the chosen method directly depends on the existing material quality of the structure and the precision of the technical detailing to be applied (anchors, reinforcement continuity, etc.). The advantages and disadvantages of different engineering

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approaches chosen to improve the seismic performance of existing structures are presented comparatively in Table 1.

Table 1. Comparison of strengthening methods applied in RC structures

Method	Advantages	Disadvantages
RC Jacketting	It significantly increases the cross-sectional capacity and rigidity. It has high fire resistance and can be applied using conventional methods.	It increases the weight (mass) of the structure. The construction time is longer, and it leads to a loss of architectural space.
RC Shear Wall Addition	It significantly improves the horizontal rigidity and seismic performance of the system. It limits relative story displacements.	It adds extra load to the foundation system; foundation reinforcement may be required. It creates significant architectural changes in the building plan.
Steel Crossbars / Frames	It provides rigidity and ductility without adding excessive weight to the structure. It is quick to apply and has a clean working process.	It requires corrosion protection and fire insulation. Connection details with existing RC elements are critical and challenging.
FRP Wrapping	It is very lightweight and thin; it does not alter the architectural dimensions. It has high corrosion resistance and a very high application speed.	It is sensitive to high temperatures (fire). The material cost is high, and its contribution to increased rigidity is limited.
Base Insulation (Seismic Isolator)	It completely isolates the superstructure from earthquake energy and protects the items/sensitive devices inside.	It is very expensive and technically extremely complex to implement in existing buildings.

One strengthening solution is the addition of RC shear walls to existing structures. RC shear walls stand out among strengthening methods due to their increased stiffness and ductility. Among the techniques, RC shear walls are considered one of the most effective methods for enhancing a structure's lateral load-carrying capacity. Strengthening, particularly through shear wall additions, provides a new lateral load-carrying mechanism for the structural system and significantly reduces relative inter-story drift. The FEMA-356 and FEMA-440 guidelines also indicate this method as an effective solution. Similarly, studies have indicated that centrally positioning RC shear walls can minimize torsional irregularities. Therefore, it is crucial to ensure that the shear wall layout is appropriate for the building's geometry and mass distribution (Chandiwala, 2012; Zhang and Mueller, 2017). Studies on RC structures using RC shear walls can be found in the literature. Kaltakcı et al. (2008) discuss a new method for strengthening reinforced concrete buildings, specifically primary schools in Türkiye, using external RC shear walls. Kaltakcı et al. (2010) compare the effectiveness of internal and external shear wall locations on the earthquake behavior of strengthened weak RC frames. Küçükgöncü and Altun (2020) investigate the seismic behavior of exterior RC shear walls when used to strengthen both intact and pre-damaged three-dimensional frames under cyclic loads. Dahesh et al. (2015) explain that shear walls improve the lateral stiffness of RC buildings, which is crucial for controlling story drift against earthquake loading. Kaplan et al. (2011) investigate a new strengthening alternative for RC structures using exterior shear walls, which allows renovation without disturbing occupants or vacating the building. Zad and Melhem (2021) investigate the effects of shear wall location in a typical low-rise building to improve earthquake resistance, modeling a 5-story RC structure both with and without shear walls at different locations. Özkul et al. (2019) investigate the effect of strengthening existing RC frame buildings with shear walls and proper materials by comparing the damage distributions of existing and upgraded structures using nonlinear time history analysis with Van 2011 earthquake data. Altıok et al (2025) explain that strengthening inadequate RC frames with RC shear walls is one of the most traditional methods used for structures lacking sufficient strength, which is vital for earthquake-resistant building stock. Although these elements provide high rigidity, exhibiting the

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expected ductile behavior is only possible with full compliance with the confinement quality, reinforcement ratios, and capacity design principles in critical sections. Therefore, considering that shear walls lacking proper detailing carry a risk of brittle fracture under seismic loads, it can be accepted that ductility is not only a geometric characteristic of the shear wall but also a capacity parameter dependent on the precision of technical application (Kuang and Ho, 2008; Aly et al., 2020; Dindar et al., 2025; Müderrisoğlu et al., 2023; Tura et al., 2025; Yüzbaşı et al., 2026).

1.1 Motivation of the Study

In the aftermath of major earthquakes, the decision to retrofit or demolish existing structures that fail to meet expected seismic performance standards is critically dependent on advanced engineering assessments (Elnashai and Di Sarno 2015). This decision-making process is fundamental to reducing future seismic vulnerability and socio-economic disruption within urban infrastructure systems (Yuzbasi 2025b). Recent catastrophic events, including the 2023 Kahramanmaraş earthquakes, have clearly exposed the substantial disconnect between code-compliant seismic performance objectives and public expectations regarding post-earthquake usability and safety. The prevalence of widespread structural damage and significant residual deformations has frequently rendered buildings either uninhabitable or economically unviable for repair. Consequently, these outcomes impose substantial reconstruction costs and long-term functional downtime, which remain incompatible with contemporary resilience and sustainability objectives. This outcome results in substantial reconstruction costs and prolonged functional downtime, outcomes that fall short of the resilience and sustainability goals of contemporary societies. These challenges highlight the pressing need to transition from traditional life safety-oriented seismic design approaches toward resilience-based strategies that minimize damage, reduce recovery time, and ensure continuity of functionality.

Rules regarding the evaluation of existing RC structures, as well as their repair and strengthening, were first detailed in Chapter 7 of the 2007 Earthquake Code in Türkiye (Turkish Earthquake Code (TEC), 2007). This code, developed particularly after the 1999 Marmara earthquake, has been a significant development in determining the seismic performance of existing structures and increasing their earthquake resistance (Yüzbaşı and Yerli 2018). Earthquake-resistant structural design has made significant progress over the years, both globally and in Türkiye (Rubini et al., 2025; O'Reilly and Calvi, 2025; Aksoylu et al., 2020; Işık, 2021; Büyüksaraç et al., 2022). As a result, the Turkish Building Earthquake Code was updated in 2018 (TBEC-2018), specifically addressing the evaluation, repair, and strengthening of existing structures, taking into account new construction technologies (TBEC-2018). However, a substantial portion of the existing building stock still fails to meet these updated requirements, making systematic performance assessment and strengthening an urgent national priority.

Therefore, in this study, a comprehensive seismic performance assessment and strengthening scheme were developed for an existing reinforced concrete (RC) building in accordance with Chapter 15 of TBEC-2018. The investigation focuses on an eight-story RC frame structure in Malatya that sustained moderate damage during the 6 February 2023 earthquakes. Through detailed on-site inspections, material testing, and a comparative evaluation of the original design documents, the actual structural configuration and the extent of damage were accurately established. Based on these findings, a retrofitting strategy incorporating strategically placed reinforced concrete shear walls was proposed to enhance the building's lateral load-carrying capacity, improve deformation control, and align its seismic performance with current resilience-oriented design principles. To situate the building-specific investigation within the broader regional context, the study also reviews the typical damage mechanisms observed in RC buildings following the Kahramanmaraş earthquakes, highlighting the recurring weaknesses that contribute to inadequate seismic performance. The primary aim of the paper is to evaluate, in depth, the seismic

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response of the selected RC building before and after retrofitting, and to quantify the improvements achieved through the proposed strengthening solution. To this end, a three-dimensional numerical model of the building was developed using data obtained from field measurements and experimental material characterization. Nonlinear analyses were subsequently performed for both the original and strengthened configurations. By systematically comparing these results, the study demonstrates the effectiveness of the shear-wall-based retrofitting scheme and provides evidence-based insights relevant to post-earthquake rehabilitation of similar RC buildings. Overall, the study distinguishes itself by integrating (i) real-scale post-earthquake damage documentation, (ii) code-compliant structural assessment, (iii) an analytically optimized shear-wall strengthening layout, and (iv) a comparative nonlinear performance evaluation. Together, these components contribute to a more robust framework for assessing and rehabilitating earthquake-damaged RC buildings under contemporary performance- and resilience-driven design philosophies.

In this study, a comprehensive analytical methodology incorporating both static and dynamic approaches was employed to evaluate the seismic performance of the investigated structural system. Initially, nonlinear static pushover analyses were conducted to determine the capacity limits and failure mechanisms of the structure. To further validate these results and capture the dynamic response under seismic excitations, nonlinear time-history analyses were performed using a suite of selected earthquake ground motion records. The comparative assessment of these two methods not only enables the validation of the theoretical capacity curves but also provides a more robust evaluation of the structural performance levels under seismic risk.

In structural strengthening projects, comparing reconstruction and strengthening alternatives in terms of cost is critical for effective resource management and sustainable engineering decisions. This study presents a financial comparison between strengthening and reconstruction scenarios, based on estimated 2026 construction unit costs and current construction items; thus, it analyzes the economic feasibility of different intervention methods.

2. Observed Damage and Spectral Acceleration Assessment in RC Structures during the Kahramanmaraş Earthquakes

Türkiye experienced one of the most devastating seismic events in its historical and instrumental history, beginning with a magnitude 7.7 earthquake centred in the Pazarcık district of Kahramanmaraş province on February 6, 2023, and continuing with a second magnitude 7.6 earthquake centred in Elbistan on the same day. These earthquakes, accompanied by consecutive large aftershocks, caused serious structural destruction and loss of life primarily in Hatay, Adıyaman, and Kahramanmaraş as well as in Malatya, Gaziantep, Şanlıurfa, Adana, Osmaniye, Kilis, Elazığ, and Diyarbakır. The magnitude 6.4 and 5.8 earthquakes that occurred in the Defne and Samandağ districts of Hatay province on February 20, 2023, further exacerbated the damage. These earthquakes, which occurred in regions of Türkiye with very high seismic risk, were felt across a wide geography and were described as the disaster of the century. The classification of buildings located in the earthquake region according to their structural systems is illustrated in Table 2.

Table 2. Distribution of structures in the earthquake region according to structural systems (%) (TC SBB,2023)

Structural system	RC	Steel	Masonry	Precast	Other
Buildings	86.70	2.40	3.50	3.60	3.90
Apartment	95.40	0.40	1.30	0.60	2.30

As can be seen in Table 2, RC structures constitute the predominant building stock in the earthquake area. Structural damage and destruction in these structures played a critical role in the number of fatalities and injuries. In addition to the incomplete, defective, or complete lack of

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implementation of earthquake-resistant design principles in these structures, irregularities within these structures also contributed to the extent of damage. The distribution of damage by city, based on damage investigation studies conducted by the relevant Ministry (TC SBB, 2023) following the disasters, is presented in Table 3.

Table 3. Damage evaluation report by city (Number of residences) (March 6, 2023) (TC SBB, 2023)

City	Slight damage	%	Moderate damage	%	Heavy damage and collapse	%
Kahramanmaraş	161,137	12.59	17,887	13.6	99,326	19.2
Malatya	107,765	8.42	12,801	9.7	71,519	13.8
Hatay	189,317	14.79	25,957	19.7	215,255	41.6
Kilis	27,969	2.19	1,303	1.0	2,514	0.5
Osmaniye	69,466	5.43	4,122	3.1	16,111	3.1
Şanlıurfa	199,401	15.58	6,041	4.6	6,163	1.2
Adana	71,072	5.55	11,768	8.9	2,952	0.6
Adıyaman	72,729	5.68	18,715	14.2	56,256	10.9
Diyarbakır	113,223	8.85	11,209	8.5	8,602	1.7
Elazığ	31,151	2.43	1,522	1.2	10,156	2.0
Gaziantep	236,497	18.48	20,251	15.4	29,155	5.6
Total	1,279,727	100.00	131,576	100.0	518,009	100.0

As can be seen in Table 3, the largest structural losses occurred in Hatay, Kahramanmaraş, Adıyaman, and Malatya. The RC building evaluated in this paper is located in Malatya, one of the four cities with the most serious damage. Figure 1 shows pre- and post-earthquake images of RC structures that have suffered total collapse due to severe damage to their structural system.



Figure 1. Pre- and post-earthquake images of totally collapsed RC structures

Figure 2 highlights the structural damage commonly observed in earthquake-affected regions, reflecting a range of failure mechanisms. Multi-story buildings often experience pancake collapse, where sequential floor slab failures led to sudden vertical collapse, while inadequate foundation–soil interaction caused differential settlements that undermined overall stability. Progressive collapse, in which the failure of a single element triggers a chain reaction of structural failures, was notably observed during the recent Kahramanmaraş earthquake, resulting in extensive damage and emphasizing the need for robust load redistribution (Yuzbasi and Arslan 2025). Poor connections between structural elements led to detachment and partial failures, compromising the continuity of load paths, whereas weak storeys amplified lateral deformations due to reduced stiffness. Torsional effects induced asymmetric rotations, increasing vulnerability in eccentrically loaded buildings, and soft storeys, typically ground floors with open layouts, experienced excessive

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drift. Additional damage arose from pounding effects between adjacent buildings and from heavy overhangs, which imposed local bending and shear demands on supporting members. Collectively, these observations underscore the critical importance of structural redundancy, adequate detailing, and careful consideration of local soil and geometric conditions to mitigate earthquake-induced failures. Common causes of damage observed in the earthquake region are shown in Figure 2.



Figure 2. Structural damage widely encountered in the earthquake zone: a) pancake collapse, b) inadequate foundation-soil interaction, c) progressive collapse, d) inadequate connection between structural elements, e) weak storey, f) torsion effect, g) soft storey, h) pounding effect, i) heavy overhang

The spectral acceleration records obtained from accelerometer stations during the Kahramanmaraş earthquakes were analyzed and compared with the site-specific design spectra developed for the location of the structure, considering the DD-2 earthquake level and ZC soil class in accordance with the 2007 and 2018 Turkish Earthquake Codes. Data from the five stations with the highest recorded values in Malatya were considered. The design spectra were created based on the DD-2 earthquake ground motion level and ZC soil class. For the Pazarcık earthquake (M_w=7.7),

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the results in the N-S and E-W directions are shown in Figure 3. At some stations, small increases were observed in the short-period range, but in general, spectral accelerations at all stations remained below the design spectra and did not exceed the code-based curves. In contrast, records from the Elbistan earthquake (M_w=7.6) are given in Figure 4 for N-S and E-W directions. At station 4406, especially in the short-period range, spectral accelerations clearly exceeded both design spectra. At other stations, spectral values were mostly below the design spectra in both directions, but in some medium-period ranges they approached the code curves. These results show that in some stations and directions, design spectra can be exceeded. This suggests that current seismic codes may not always fully represent real earthquake demands. As a result, structures in some areas may be exposed to higher-than-expected accelerations, which can increase the risk of damage.

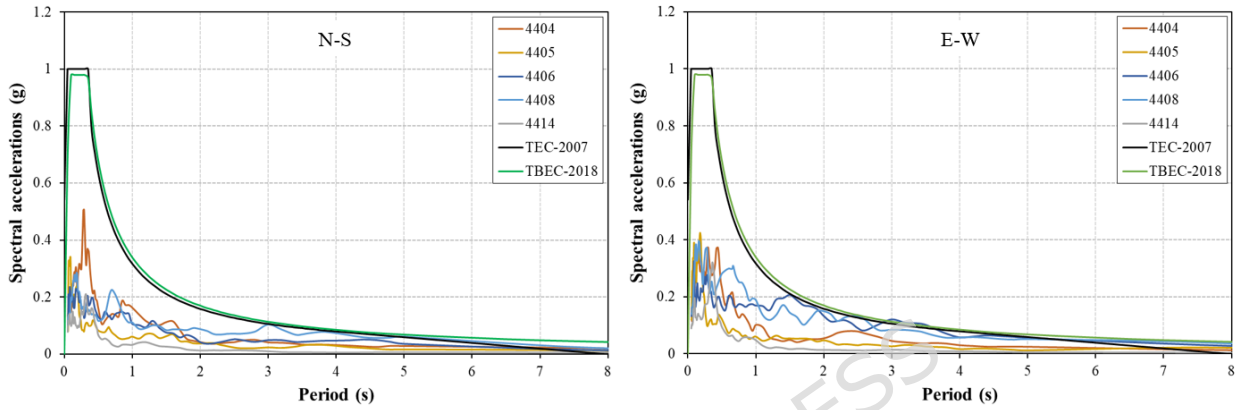


Figure 3. Comparison of recorded and design spectral accelerations in N-S and E-W directions for Malatya stations during the Pazarcık earthquake (M_w=7.7)

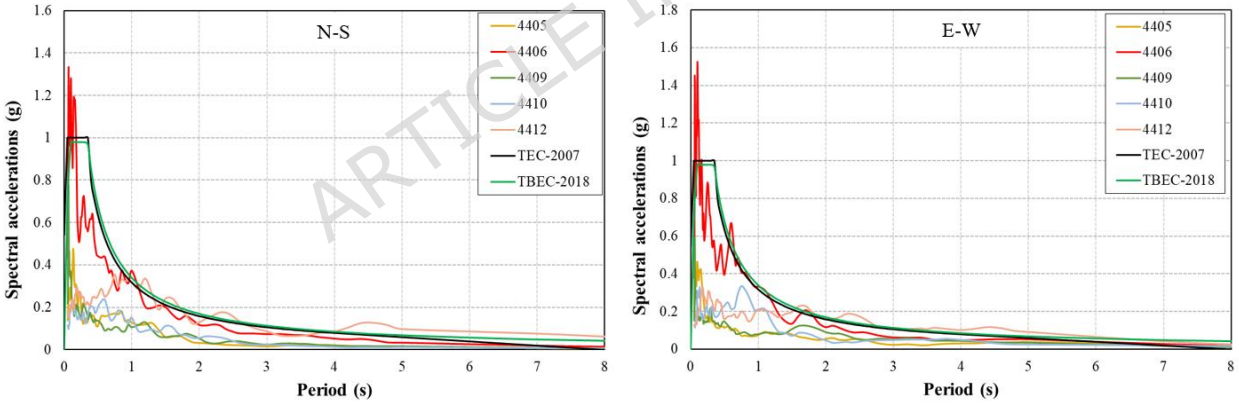


Figure 4. Comparison of recorded and design spectral accelerations in N-S and E-W directions for Malatya stations during the Elbistan earthquake (M_w=7.6)

To clarify the spatial relationship between the recorded ground motions and the study area, Figure 5 presents the locations of the selected strong-motion stations together with the investigated building.

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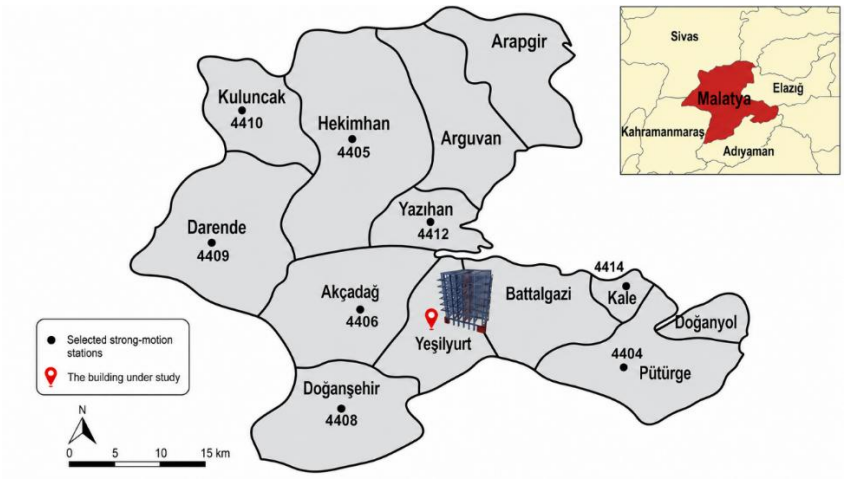


Figure 5. Location distribution of seismic stations and the study area.

3. Description of the Current RC Structure and Damage Status

The seismic performance assessment of the existing RC structure considered within the scope of the study was carried out according to the procedure specified in Chapter 15 of the TBEC-2018, which was revised in 2018 and entered into force in 2019. According to this chapter, the earthquake performance and decision-making process of any structure is carried out according to the process steps in Figure 6.



Figure 6. Flow chart for earthquake performance analysis, repair, and strengthening of the existing buildings

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The structure under study is located in Malatya and was constructed in 2012. It was designed in accordance with the 2007 earthquake regulations in effect at the time of construction. The building consists of a total of eight storeys: a basement, a ground storey, and six standard storeys. Commercial businesses occupy the ground storeys, while all of the upper floors are used for residential purposes. The RC structural system of the building measures 25.30 m x 29.60 m in plan, with a height of approximately 27 m. The building has an appropriate width-length-height ratio. Structural elements are arranged regularly in plan. The long edges of the columns and shear walls are distributed appropriately along the X and Y directions of the structure (40%-50%). This design approach coincided with the centres of mass and rigidity, and the structure did not experience additional effects such as torsion as a result of the 2023 Türkiye earthquake. Pre-earthquake images of the structure are shown in Figure 7.



Figure 7. Pre-earthquake images of different facades of the examined building

The damage caused by the Kahramanmaraş disasters and the subsequent failure of structural elements are illustrated in Figure 8.

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Figure 8. Post-earthquake damages in the building: a) non-structural damage, b) moderate damage to the beam, c) spalling of the column, d) damage to the column, e) reinforcement buckling due to missing neck stirrups in the column, f) spalling of the elevator shear wall

Considering the criteria specified in the current earthquake code (Special Rules for the Assessment and Reinforcement Design of Existing Building Systems Under Earthquake Effects), the design, analysis, and evaluation of the examined building will be conducted to determine whether any reinforcement is required. Accordingly, assuming the building has a limited knowledge base, a survey study was conducted to determine its geometry. Core drilling and stripping were performed in accordance with the "Limited Knowledge Base on RC Buildings" criteria to determine material properties and structural member details. The structure was modelled in the ETABS program based on material information, member details, and building geometry. The structure was analysed using nonlinear calculations. The damage status of the structure was determined according to the TBEC-2018 code criteria, and the need for reinforcement was determined. A survey was conducted to assess the damage to the structure following the Kahramanmaraş earthquakes and to identify and implement potential repair and/or reinforcement requirements. The standard storey plan based on the survey is shown in Figure 9.

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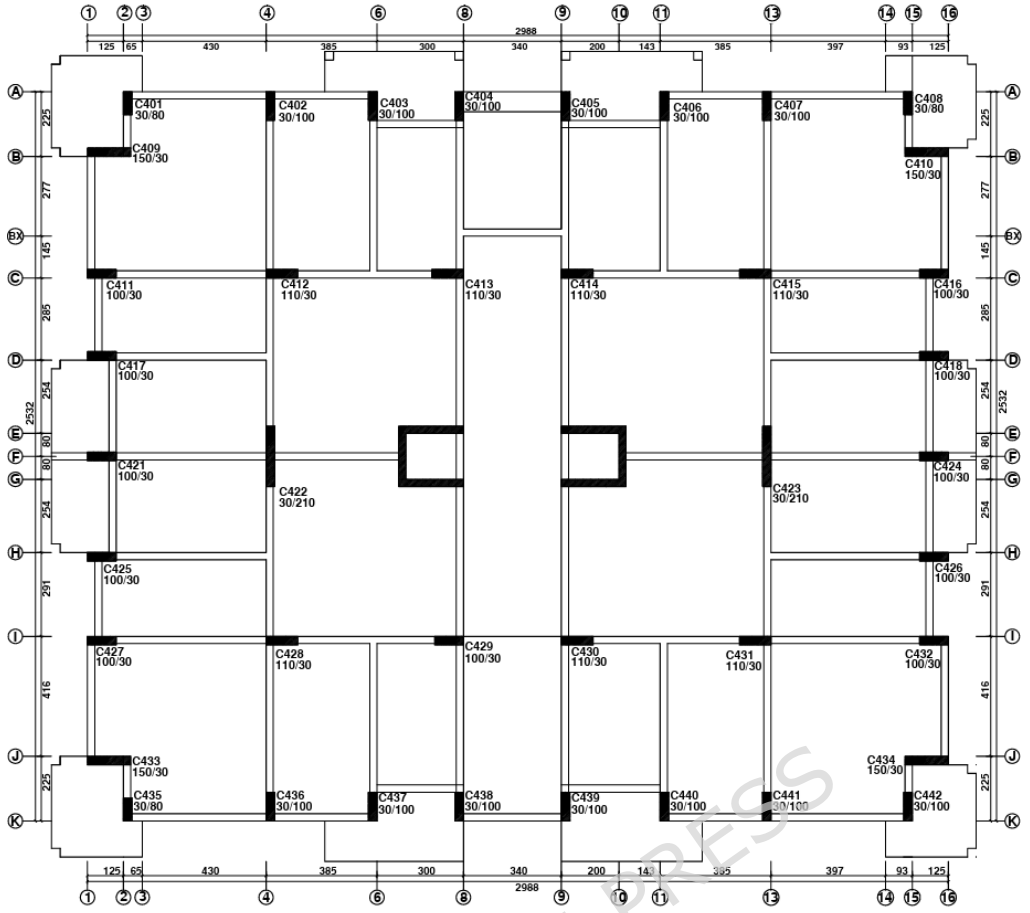


Figure 9. Storey plan of the examined building (current situation, before the earthquake)

A comparison of the approved architectural and structural plans with the survey project revealed some structural changes to the columns, beams, and shear walls. While the approved structural plan designed the basement storey as a perimeter earthquake curtain on all four sides, the survey found that three sides were designed as curtains to suit the basement's intended use (garage entrance). Furthermore, the approved structural plan showed that the structural elements, designed as two 30x210 cm curtain walls throughout the building, were implemented as T-columns on the basement and ground floors and as 40x210 cm columns on the standard floors. The 30x100 cm columns designated S02 and S07 in the structural plan were designated 30x110 cm in the survey, while the columns designated S12, S15, S26, and S29 were designated 40x110 cm in the survey. Beam dimensions vary across the basement, ground, and standard storeys. According to the survey project, the K03 beam, measuring 25x60 cm, was used in the basement and ground storeys, while the beam, measuring 70x25 cm, was used in the standard storeys. However, according to the approved structural project, the same beam is 25x60 cm on all storeys. According to the approved structural project, there are no beams connecting the elevator bulkheads to the T-columns or the 40x210 column. In contrast, the survey project features four 25x45 cm beams at either end of the columns and bulkheads. One of these beams is 40x45 cm in size on the basement, ground, and first standard storeys, and 25x45 cm on the other standard storeys. The building utilizes 40 columns with varying cross-sectional properties, along with beam elements of 25x45 cm, 40x45 cm, 25x60 cm, and 70x25 cm. There are no shear elements in the building. The structural elements are symmetrical along both axes in the building plan. After determining the building's geometric properties, taking into account its geographical location, local soil class, and exceedance probability, seismic parameters were obtained using the Türkiye Earthquake Hazard Maps Interactive Web Earthquake Application. These values are shown in Table 4.

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Table 4. Seismic parameters used for the structure

Parameter	Value
Earthquake ground motion level	DD-2
Local soil class	ZC
Horizontal elastic design acceleration spectrum corner period (s) (TA)	0.069
Horizontal elastic design acceleration spectrum corner period (s) (TB)	0.346
Short period map spectral acceleration coefficient (S_S)	0.816
Map spectral acceleration coefficient for 1.0 second period (S_1)	0.226
Short period design spectral acceleration coefficient (S_{Ds})	0.979
Design spectral acceleration coefficient for 1.0 second period (S_{D1})	0.339
Vertical elastic design acceleration spectrum corner period (T_{AD})	0.023
Vertical elastic design acceleration spectrum corner period (T_{BD})	0.115

Based on the assessments provided in TBEC-2018, the existing structure is targeted to achieve the Controlled Damage (CD) performance level for a DD-2 earthquake level, with a 10% probability of exceeding spectral magnitudes in 50 years and a recurrence period of 475 years. A deformation-based assessment and design approach was used as the assessment/design approach. The design parameters of the examined structure are given in Table 5. The parameters presented in Table 5 are derived from two different sources: (i) direct field observations and measurements obtained through on-site investigations, including geometric properties, material characteristics, and structural details; and (ii) code-based parameters defined according to TBEC-2018 provisions, such as behaviour factor (R), importance coefficient (I), and load participation coefficients. This distinction is explicitly considered to ensure consistency between measured data and analytical modelling assumptions.

Table 5. Design parameters obtained for the examined structure

Number of storeys	Basement + Ground + 6 Normal (8-storey)
Height of storey	Basement: 3.1m, Ground: 5m, Normal storey: 3.05m
Height of slab	25 cm (ground storey), 15 cm (normal storey)
Type of slab	Beam slab flooring
Live loads participation coefficient	0.3
Structure usage class (BKS)	3
Structure importance coefficient (I)	1
Earthquake design class (DTS)	1
Structure height class (BYS)	5 (H=26.4m)
Structural system behaviour coefficient (R)	4
Over strength coefficient (D)	2.5
Concrete grade	C15
Reinforcement grade	S420
Level of knowledge	Limited
Type of usage	Residential

In assessing the existing structure, static loads were calculated separately for dead loads, additional dead loads, live loads, snow loads, and wall loads, and applied to the structure. These static load values are given in Table 6. The interior walls of the structure are constructed of 8.5 cm-thick brick, and the exterior walls are constructed of 20 cm-thick aerated concrete. The load values were obtained by taking into account the TS-498 and TS EN 1991-1-3 standards currently used in Türkiye to determine the loads acting on structures.

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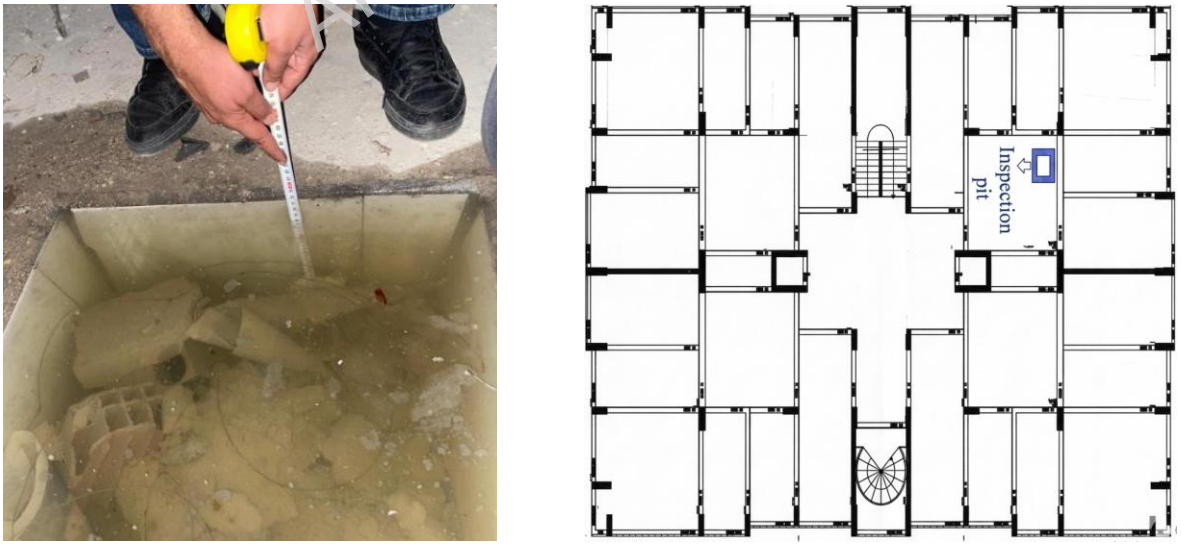
Table 6. Static load values considered in the structure

Type of loads	Values
Weight of roof covering, screed, plaster, and insulation materials	2.42 kN/m^2
Other storeys' coating, screed, plaster, and insulation material weight	2.15kN/m^2
Live load (in rooms, corridors)	2 kN/m^2
Live loads (stairs)	3.5 kN/m^2
Live loads (balconies)	5 kN/m^2
Snow loads	0.972 kN/m^2

In this study, the interaction of non-structural infill walls, which have a critical effect on the dynamic and static behavior of the structural frame, with the beams was analytically simulated within the framework of the equivalent distributed load model. In this context, in line with common assumptions in the literature and unit weight calculations, the linearly distributed vertical load value transferred to the beams per unit length by standard brick infill walls with a thickness of 8.5 cm was determined as 5.18 kN/m, and for aerated concrete walls with a thickness of 20 cm, this value was determined as 6.87 kN/m and directly integrated into the structural system. The direct modeling of these loads as distributed loads is based on the theoretical assumption that infill walls transfer gravity loads homogeneously to the structural system before exhibiting compression strut behavior. This approach is a fundamental requirement, especially in linear elastic analyses where the stiffness and mass distribution are accurately modeled, in order to realistically reflect the initial period and dynamic behavior of the structure.

3.1. Determination of the Foundation System

After determining these values, the structure's foundation system was determined through excavations. An inspection pit was dug at a location within the building to determine the foundation system. Observations and examination revealed that the structure's foundation system was an 80 cm thick raft foundation. The inspection pit and the structure's foundation plan are illustrated in Figure 10.



(a) **(b)**

Figure 10. Determination of the foundation system of the building, (a) examination and excavation for determination of the foundation system, (b) location of the inspection pit

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3.2. Determination of Material Properties

The existing material strengths to be used in calculating the capacity of the structural members were defined in accordance with the provisions of the TBEC-2018. To determine the concrete material characteristics of the RC building, which is the subject of the study, core specimens were taken from 12 columns and tested according to the TS EN 12504-1 standard by a laboratory authorized by the Ministry of Environment, Urbanization, and Climate Change within the framework of the regulation principles. The approach used in the evaluation of core samples in the TBEC-2018 was taken into account in determining the concrete compressive strength. The mean and standard deviation values of the samples were calculated, and as a result of statistical calculations, the concrete compressive strength was calculated as 15 MPa. To determine the reinforcement status, a sufficient number of destructive/stripping and non-destructive/X-ray examinations were conducted on the beams, columns, and shear walls of the structure. As a result of the examination, it was determined that the diameters, spacing, and numbers of vertical and horizontal reinforcement were compatible with the static project, and no corrosion was observed. For the stripped and X-rayed structural elements, the reinforcement realization coefficient was determined to be 100%, and the reinforcement quality was defined to be S420. Images from the determination of concrete and reinforcement properties are shown in Figure 11.



Figure 11. Determination of concrete and reinforcement properties

It should be emphasized that the material properties used in the analytical model were not arbitrarily assumed but were primarily based on field investigations. The concrete compressive strength value was obtained through statistical evaluation of core test results in accordance with TS EN 12504-1 and TBEC-2018 provisions. Therefore, this value represents an experimentally supported characteristic strength rather than a purely assumed parameter. Similarly, the reinforcement grade was identified through a combination of destructive stripping and non-destructive X-ray investigations, which confirmed compatibility with the original design specifications. Accordingly, the reinforcement was classified as S420 in line with code definitions. These procedures ensure that the adopted material properties reflect actual in-situ conditions while remaining consistent with standardized code-based classifications. Unlike many previous studies relying solely on assumed material properties, this study integrates experimentally obtained data from field testing into the structural modelling process, thereby enhancing the reliability of the

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seismic performance assessment. For modelling and strengthening purposes, C30 concrete and S420 reinforcement were adopted as representative material classes for RC construction. According to TBEC-2018, concrete grades ranging from C25 to C80 and reinforcement grades such as B420C/S420 are permitted for structural applications. Furthermore, recent studies on seismic assessment and retrofitting of RC buildings in Türkiye commonly employ C30 concrete and 420 MPa reinforcement for newly added or strengthened elements, reflecting current engineering practice. The material safety factors used in this study are based on limit state design principles. The partial safety factor for reinforcement (γ_s=1.15) and for concrete (γ_c=1.50) are adopted to account for uncertainties in material strength, construction quality, and modelling assumptions. These values are consistent with international standards such as Eurocode 2 and are compatible with Turkish design practice. The use of partial safety factors ensures that the design strengths (f_{cd}, f_{yd}) are derived from characteristic material properties (f_{ck}, f_{yk}) by incorporating reliability-based reductions, thereby providing a consistent safety margin in structural analysis and performance assessment. Design strength values are obtained using equations $f_{cd}=f_{ck}/\gamma_c$ and $f_{yd}= f_{yk}/\gamma_{s,}$ taking into account strength and material safety values (TS500, 2000).

3.3. Structural System Modelling and Performance Evaluation of the Existing Structure

After determining the material properties, loads, and soil properties in accordance with the existing structural design, a 3-dimensional digital model of the examined structure was formed in the ETABS program, taking into account the design criteria in the TBEC-2018. 3-D views of the structure are shown in Figure 12, and storey plans are shown in Figure 13.

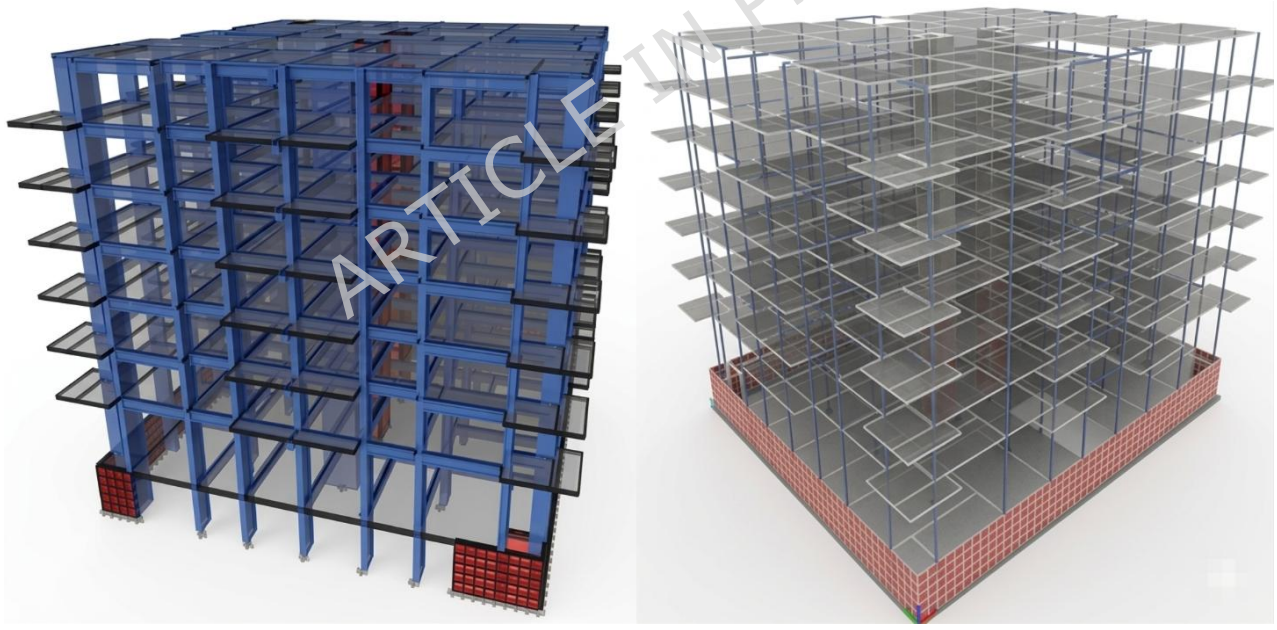
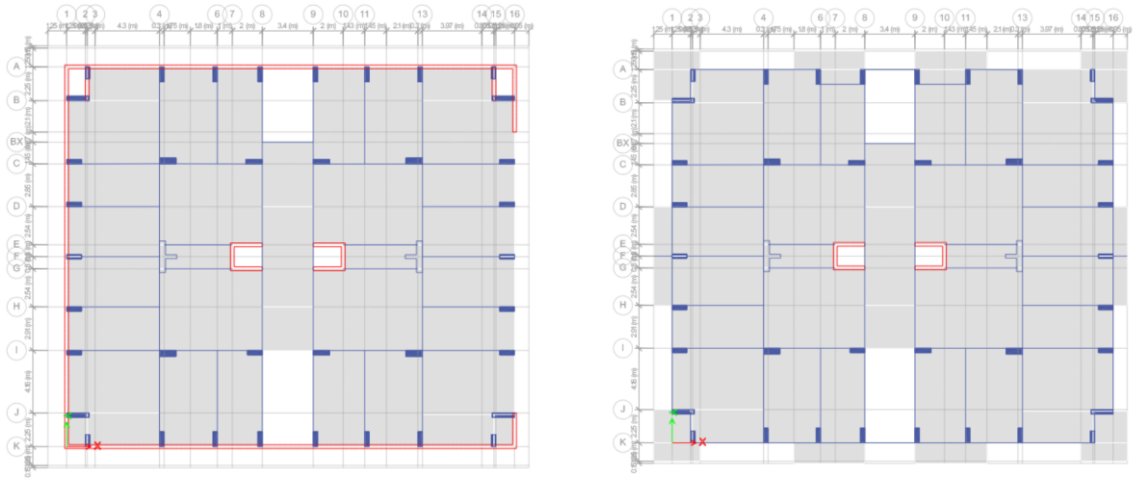


Figure 12. 3-D views of the model

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Basement storey plan

Normal storey plan

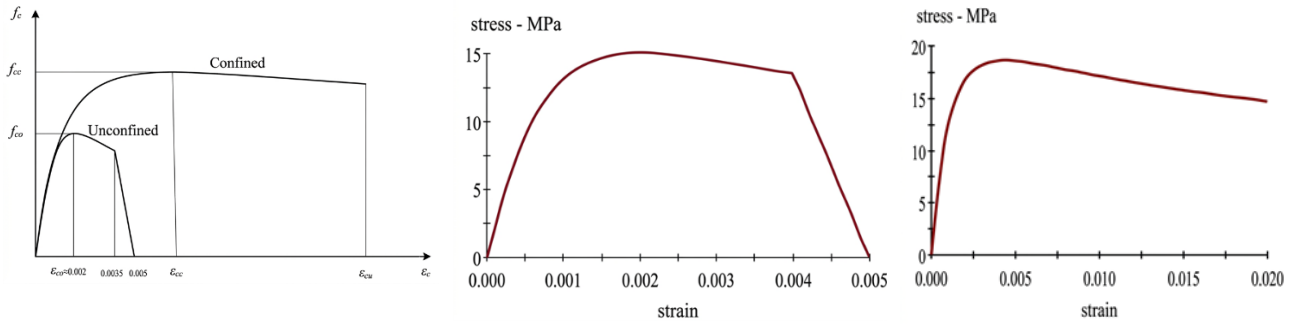
Figure 13. Storey plan (pre-earthquake current system)

The seismic performance assessment of the structure was based on the rules for evaluating existing building systems under earthquake impact specified in Chapter 15 of TBEC-2018. In accordance with the existing rules and calculation principles, the seismic performance assessment of the 8-story RC structure, including the basement, was conducted using the nonlinear pushover analysis method, a nonlinear analysis method.

3.3.1. Defining Material Models

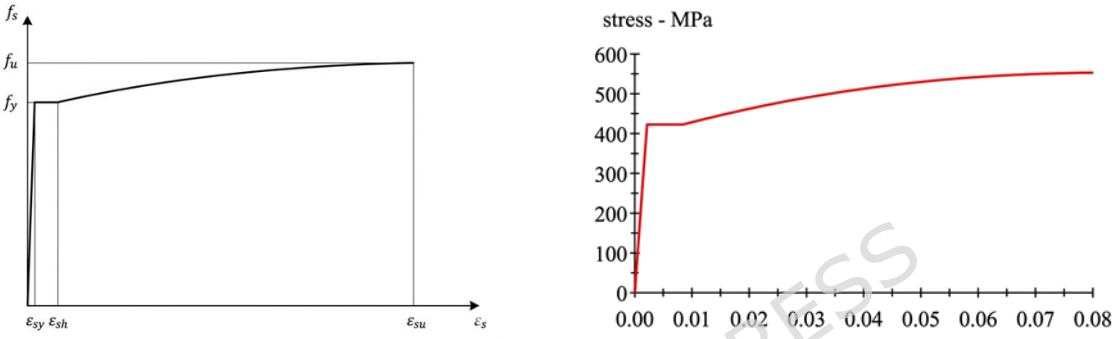
The material models adopted in this study were defined using experimentally obtained material properties combined with code-based constitutive relationships. The concrete compressive strength used in the model was derived from core test results, while reinforcement properties were determined through in-situ inspections. These experimentally obtained parameters were directly incorporated into the material model definitions. It should be noted that, although advanced constitutive models such as the Mander model for confined concrete and the Menegotto–Pinto model for reinforcement are frequently used in the literature, the material models employed in this study are based on the formulations recommended by TBEC-2018. This choice ensures consistency with the code-based performance assessment framework and the nonlinear analysis procedures implemented in ETABS. The primary objective of this study is to evaluate the seismic performance of an existing structure within a code-compliant assessment framework rather than to develop or compare advanced material constitutive models. Therefore, the use of standardized material models is considered appropriate and sufficient for the scope of this study. Nevertheless, the influence of different material models on the global structural response is acknowledged, and future studies may explore the sensitivity of the results to alternative constitutive formulations. Code-based material models are widely preferred in performance assessment studies of existing buildings due to their robustness, simplicity, and compatibility with engineering practice. The first step in determining the performance of a structure is to define nonlinear materials. Material models were defined based on data obtained from core drilling, X-rays, and stripping results using the nonlinear material models included in TBEC-2018. The material models considered are detailed in Figure 14 for concrete and Figure 15 for steel.

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(a) (b) (c)

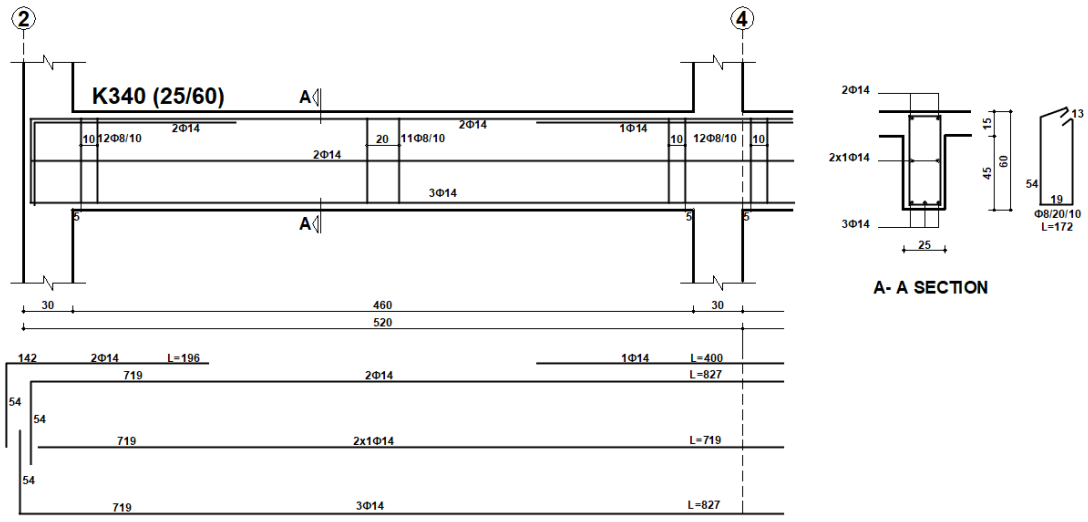
Figure 14. Material models for concrete, (a) confined and unconfined concrete model (TBEC-2018), (b) unconfined concrete model for C15 concrete (XTRACT), (c) confined concrete model for C15 concrete (XTRACT)



(a) (b)

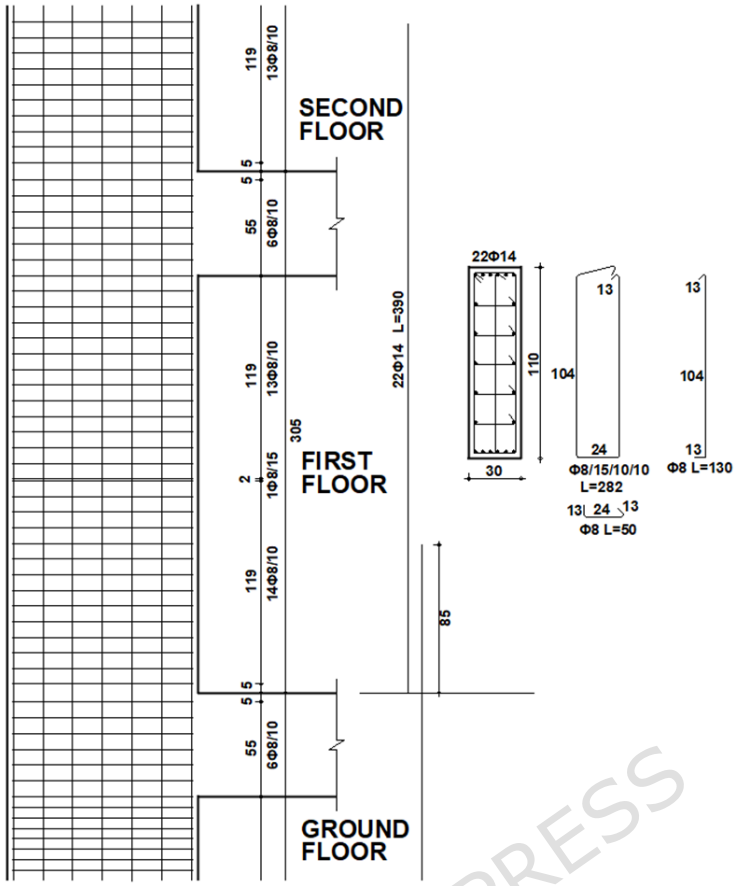
Figure 15. Material model for reinforcement steel, (a) reinforcement steel model (TBEC-2018), (b) material model for S420 type reinforcement steel (XTRACT)

The material models of the existing RC building were defined in ETABS, a structural analysis program that performs analysis based on data obtained from core drilling and stripping results. XTRACT was used to determine the moment-curvature relationships of the beams, the yield surfaces of the elevator bulkheads and columns, and the moment-curvature relationships. This data, obtained from XTRACT, which will be used in the performance analysis of the structure, was transferred to ETABS for use in the modelling phase. The cross-sectional properties of a 25x60 beam, a 30x110 column, and a 30x200 elevator bulkhead are shown in Figure 16.

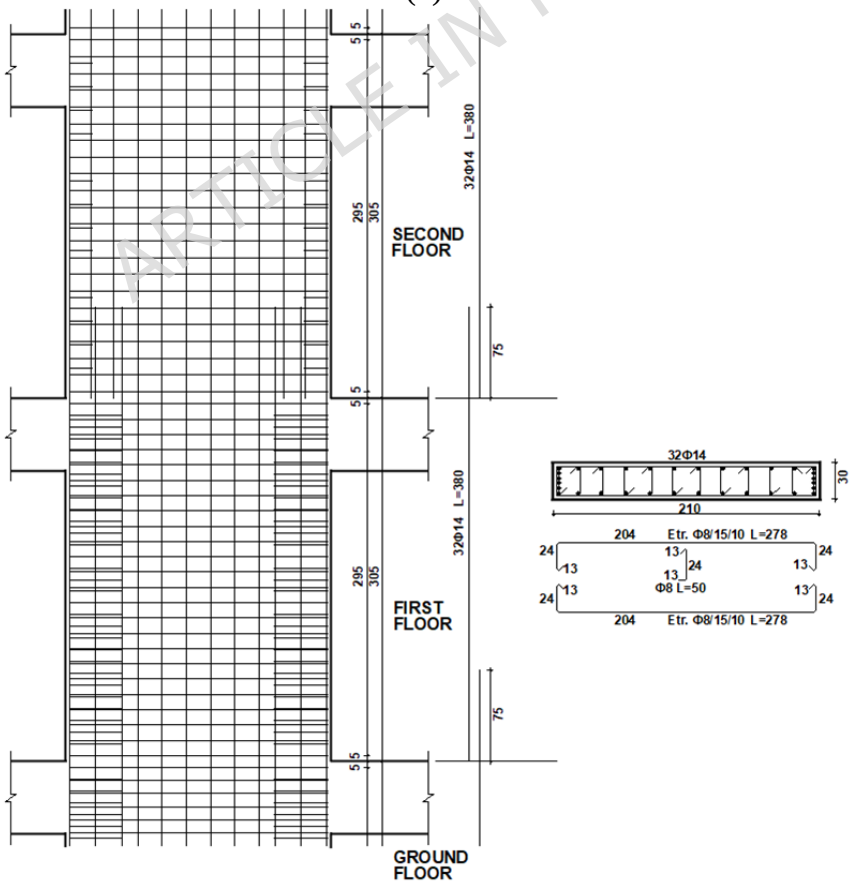


(a)

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(b)



(c)

Figure 16. Typical sections in the examined building: (a) 25x60 cm beam, (b) 30x110 cm column, (c) 30x210 cm RC shear wall

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3.3.2. Behaviour Models for Columns, Beams and Shear Walls

Columns and beams were modelled using frame finite elements. The nonlinear response of the structural system was represented through concentrated plastic hinge formulations assigned to the critical regions of the members. Beam elements were assigned flexural moment hinges (M3), reflecting their predominantly flexure-controlled behaviour under seismic loading. In contrast, column elements were assigned axial force-biaxial moment interaction hinges (P-M2-M3) to accurately capture the coupled effects of axial load and biaxial flexural response. The hinge properties were defined based on section-specific moment-curvature analyses performed in XTRACT using experimentally obtained material properties and actual reinforcement detailing. In addition to the provisions of TBEC-2018, the adopted nonlinear modelling and performance evaluation framework was evaluated in conjunction with internationally recognized guidelines such as FEMA-356, FEMA-440, and ASCE 41 to ensure methodological consistency.

It should be emphasized that default auto-hinge properties available in ETABS (e.g., ASCE 41-based hinge definitions) were not directly used in this study. Instead, user-defined hinge properties were assigned based on section-specific moment-curvature analyses performed in XTRACT, incorporating actual geometry, reinforcement detailing, and experimentally derived material properties. Concentrated plastic hinge modelling was preferred for beams and columns due to its computational efficiency and its widespread use in code-based seismic performance assessment frameworks. This approach allows for an accurate representation of inelastic behaviour at critical regions while maintaining a practical modelling effort. Although fibre-based distributed plasticity models can capture nonlinear behaviour in greater detail, they require significantly higher computational effort and detailed material calibration. Therefore, within the scope of this study, fibre modelling was selectively applied to shear walls, where distributed nonlinear behaviour is more critical, while beams and columns were modelled using concentrated plastic hinges. The plastic hinge properties assigned to beams and columns were derived from moment-curvature analyses conducted in XTRACT. Moment-curvature graphs for each structural element (beam, column, and RC shear wall) are given in Figures 17-19 as examples. After defining the material models, the elements were modeled in the ETABS program, and hinge assignments were made to the elements. The moment-curvature relationships for the beams, as well as the yield surfaces and moment-curvature relationships for the walls and columns, were obtained using the Section Designer module. Figure 16 shows the cross-sectional properties and moment-curvature diagram of a 25x60 beam. Figure 17 and 18 present the cross-sectional properties and moment- curvature diagrams of the 30x110 column and 30x210 RC shear wall, respectively.

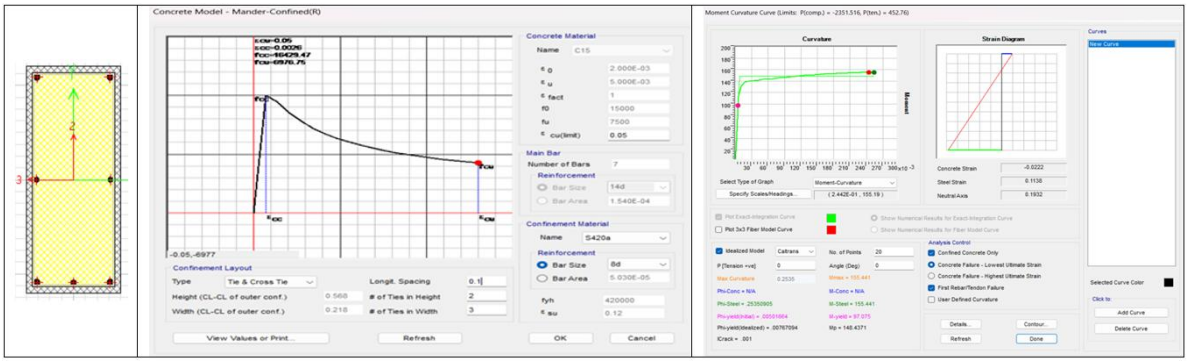


Figure 17. The 25×60 beam cross-sectional properties and moment-curvature diagram

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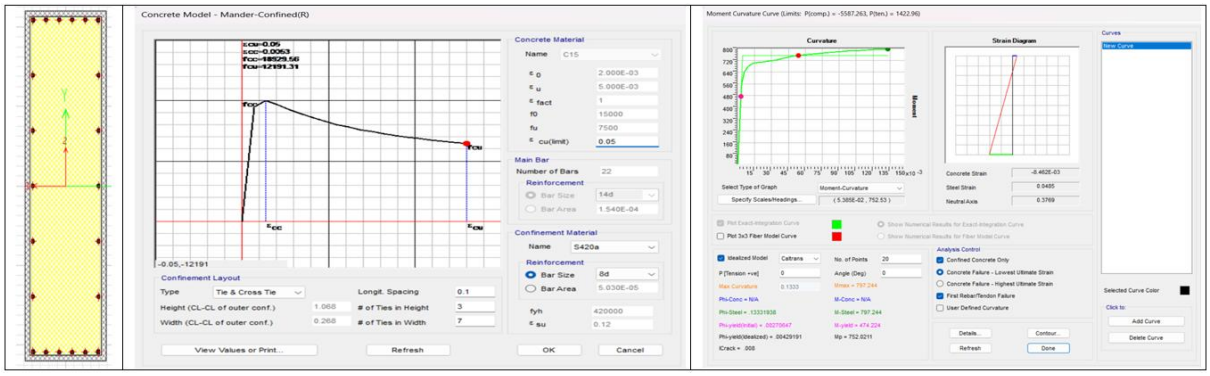


Figure 18. The 30×110 column cross-sectional properties and moment-curvature diagram

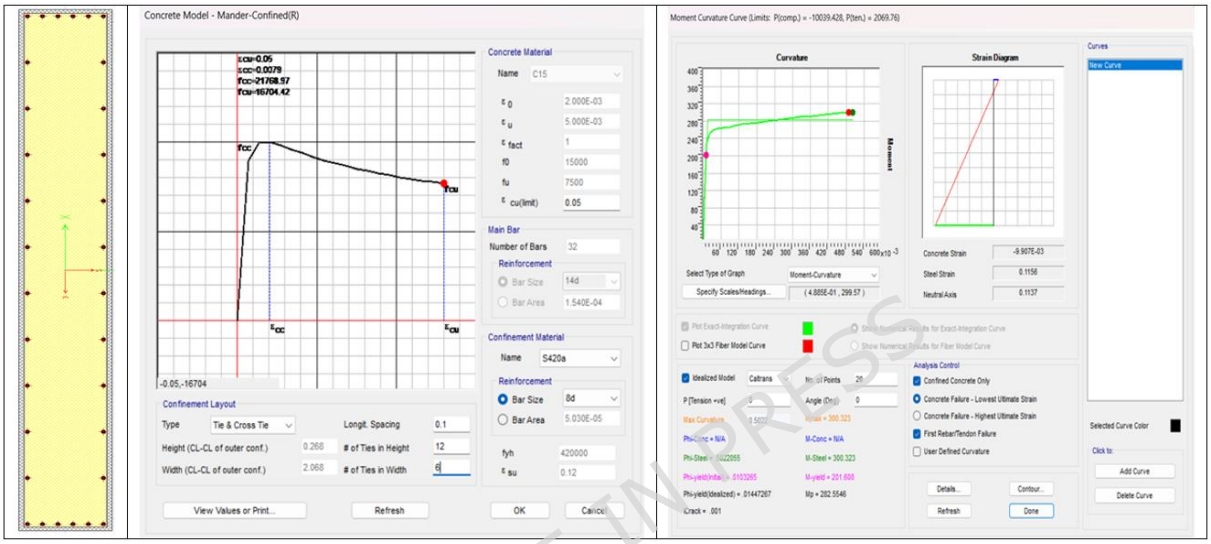


Figure 19. The cross-sectional properties of the 30x210 RC shear wall and the moment-curvature diagram

The axial force-moment interaction behaviour of structural elements was inherently considered through section capacity definitions derived from moment-curvature analyses. Therefore, axial capacity and stress conditions were not evaluated separately using simplified linear methods but were directly incorporated into the nonlinear performance assessment framework. The adopted methodology is consistent with performance-based assessment approaches outlined in FEMA 356 and FEMA 440, where nonlinear analysis is used to directly evaluate structural performance in terms of deformation and damage limits.

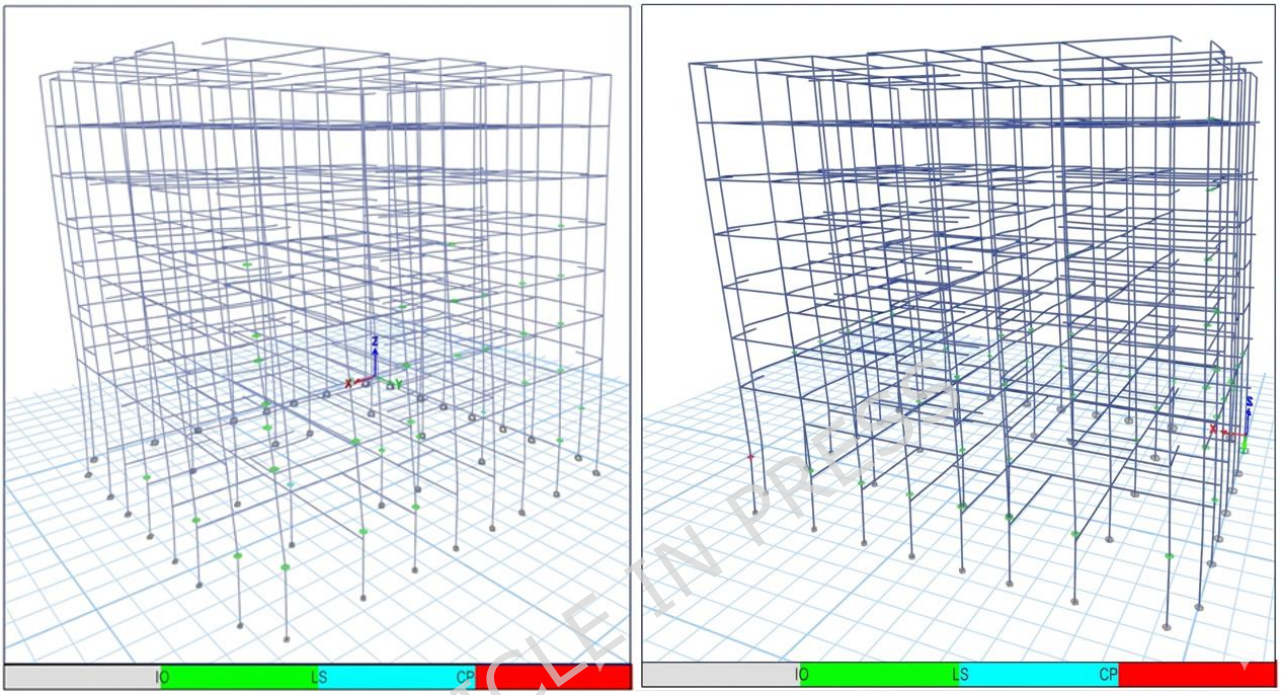
3.3.3. Analysis with Nonlinear Pushover Analysis Method and Evaluation of Results

Before the nonlinear pushover analysis, the structure was subjected to linear elastic analysis under gravity loads to establish the initial stress state and stiffness characteristics. This step ensures that the subsequent nonlinear analysis is based on realistic initial conditions. In addition to the nonlinear hinge-based evaluation, inter-storey drift ratios were calculated and used as key indicators of seismic performance. These parameters provide a direct measure of structural deformation demand and are consistent with both code-based and FEMA performance assessment approaches. Before performing a static pushover analysis on the structure, the combination of static vertical loads was defined according to the following equation (TBEC-2018) and applied incrementally to the structure. The strain and internal force values obtained from this loading solution, applied as a nonlinear static calculation, were used as the initial step of the horizontal earthquake calculation.

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$$G + nQ + 0.3E_d{}^{(Z)} \quad (1)$$

here, G represents the dead load effect on the structure, n represents the live load participation factor, Q represents the live load effect, and $E_d{}^{(z)}$ represents the vertical earthquake effect. In the calculations, the dead weight of the structural elements, additional dead loads, and wall loads were taken into account as the dead load effect. Because the building is residential, the live load participation factor n is taken as 0.3. A fixed single-mode pushover analysis is based on the principle of gradually increasing the load proportional to the dominant vibration mode shape in the earthquake direction. This analysis was performed for both earthquake directions, and the resulting hinges in the structure in the X and Y directions are shown in Figure 20.



(a) (b)

Figure 20. Plastic hinges formed in the structure in the current situation, (a) X direction, (b) Y direction

The intervals shown below are taken into account in the performance evaluation of structures. These intervals are shown in a simplified form on a symbolic capacity curve in the figure below. The definitions and corresponding performance levels of these intervals are provided in Figure 21, in accordance with ASCE/SEI 41-13 (2014), FEMA-440 (2005), and FEMA-356 (2000).

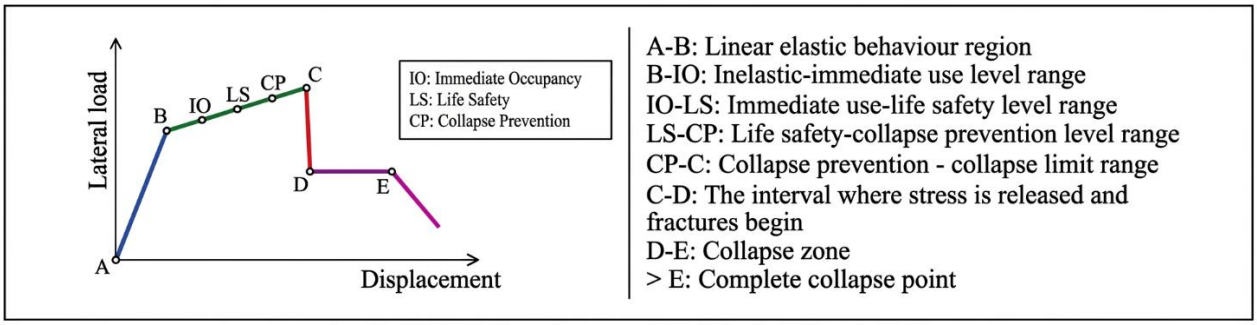
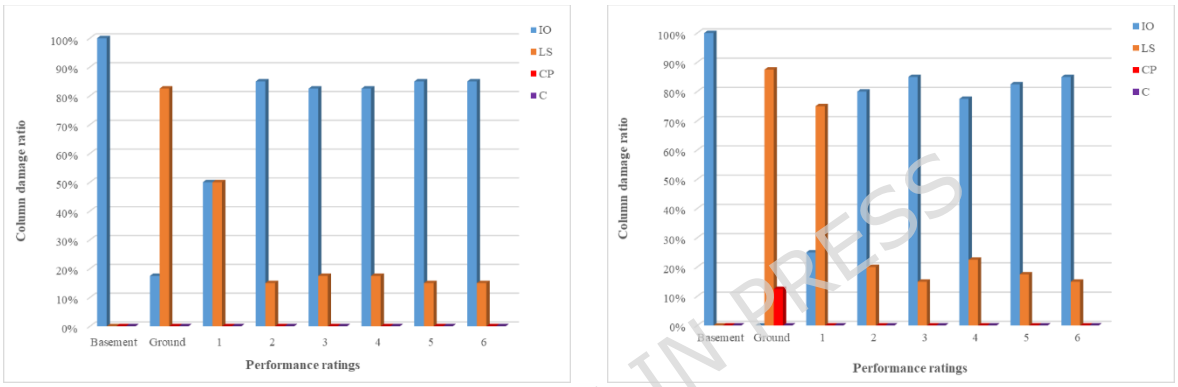


Figure 21. Seismic performance levels

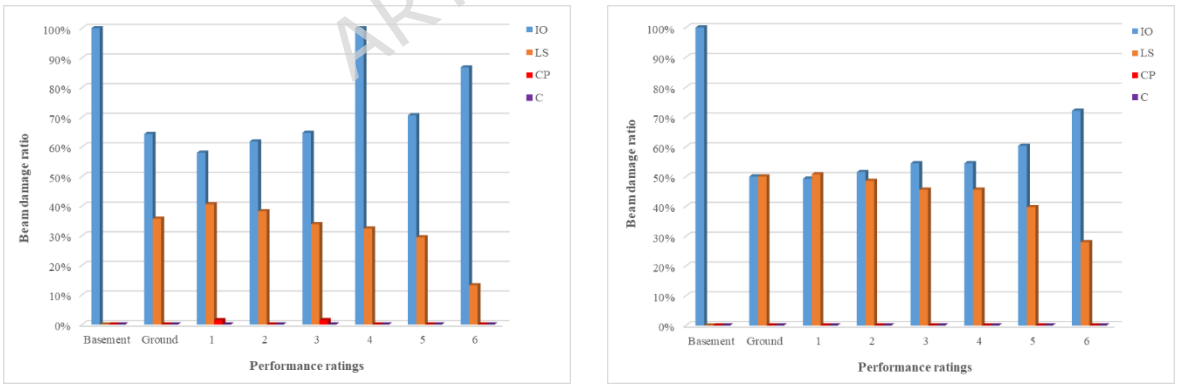
As can be seen in the figures above, the analysis revealed that the concrete and reinforcing steel deformed in the plasticized sections, resulting in a certain amount of plastic rotation. For the existing structure, the deformations and plastic rotations were calculated for all beams, columns, and shear walls, using the equations specified in TBEC-2018, based on various damage limits. The damage zones of the elements were determined by comparing the damage values corresponding to the plastic rotation requirements with the limit values specified in the regulation.

As a result of the analyses performed, when the performances of the columns were evaluated in the current situation, in the X direction, 73.44% of them were undamaged, and 26.56% had obvious damage. In the Y direction, 66.88% were undamaged, 31.56% had obvious damage, and 1.56% had advanced damage (Figure 22). When the performances of the beams were evaluated, in the X direction, 71.72% of them were undamaged, 27.91% had obvious damage, and 0.37% had advanced damage. In the Y direction, 61.49% were undamaged, and 38.51% had obvious damage (Figure 23). When the performances of the shear walls were evaluated, it was seen that all of the shear walls in the X and Y directions had obvious damage (Figure 24).



(a) (b)

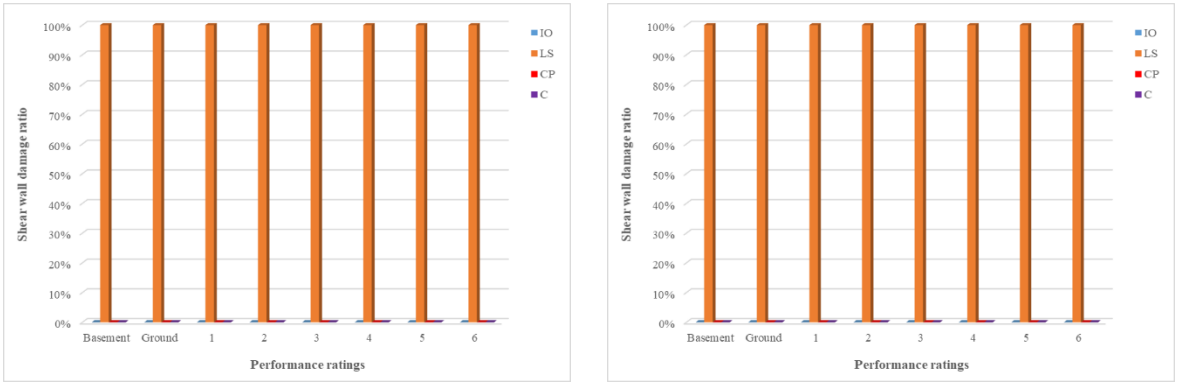
Figure 22. Performance levels of columns in the current state of the residential RC building according to the pushover analysis, (a) X direction, (b) Y direction.



(a) (b)

Figure 23. Performance levels of beams in the current state of the residential RC building according to the pushover analysis, (a) X direction, (b) Y direction.

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(a) (b)

Figure 24. Performance levels of shear walls in the existing residential RC building according to pushover analysis, (a) X direction, (b) Y direction.

As can be seen from the calculations based on the analysis results, the structure's current condition does not provide the required performance in the X and Y directions, nor does it provide the required life-safety performance, and the structure is on the verge of collapse. No further checks were deemed necessary for the collapsed structure. Consequently, the primary reasons for the structure's inadequate performance against such large earthquakes are the lack of shear walls, the most effective seismic resistance elements in a building. The structural system is entirely frame-based, and the concrete quality is inadequate. Based on the results and justifications obtained, it was decided to retrofit the existing structure to ensure it performs adequately against potential future major earthquakes.

3.3.4. Time-History Analysis and Evaluation of Results

Time-history analysis is an advanced computational method based on the numerical solution of dynamic equilibrium equations, which are based on the mass, damping, and stiffness properties of a structure, for each step in time under a specific ground acceleration record. This analytical approach allows for the step-by-step monitoring of time-varying nonlinear behaviors such as plastic hinge formation, cracking, and reinforcement yielding in RC structural elements, and enables the determination of the structure's energy dissipation capacity under actual earthquake effects. Unlike static or spectral analysis methods, this method, which directly includes the frequency content and duration of ground motion in the process and reveals the dynamic response of the structure as a function of time, is considered the most realistic tool in performance-based design and evaluation studies (Georgiou et al., 2023; Pinzon et al., 2023; Kaveh and Ardebili, 2023; Peng et al., 2023; Kumar et al., 2025).

In the nonlinear time-history analyses, the acceleration records obtained from Station 4614 during the 6 February 2023 Mw=7.7 Kahramanmaraş earthquake were selected due to their representation of severe near-field seismic demand affecting the Malatya region. The selection criteria focused on capturing the high-intensity, near-field effects observed during the Pazarcık earthquake (Mw=7.7), specifically utilizing data from Station 4614 located near the epicenter. The selected records were not used in their raw form. To align the selected records with the site-specific seismic hazard, a scaling procedure was implemented. In accordance with Section 2.5 of TBEC-2018, the records were scaled to achieve compatibility with the target DD-2 design response spectrum corresponding to the local ZC soil class of the investigated structure. The scaling process was performed using spectral matching procedures implemented within the ETABS environment to ensure that the response spectra of the selected motions satisfied the code-required spectral compatibility over the specified period range. Peak ground acceleration (PGA), spectral acceleration ordinates, and the

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overall spectral shape were considered as the primary intensity measures during the selection and scaling process. The acceleration-time graph obtained in this way and used in the analyses is shown in Figure 25. Furthermore, given that Malatya province was directly affected by the earthquake, it was determined that the selected record would have a high probability of representing the seismic demand to which the structure was subjected.

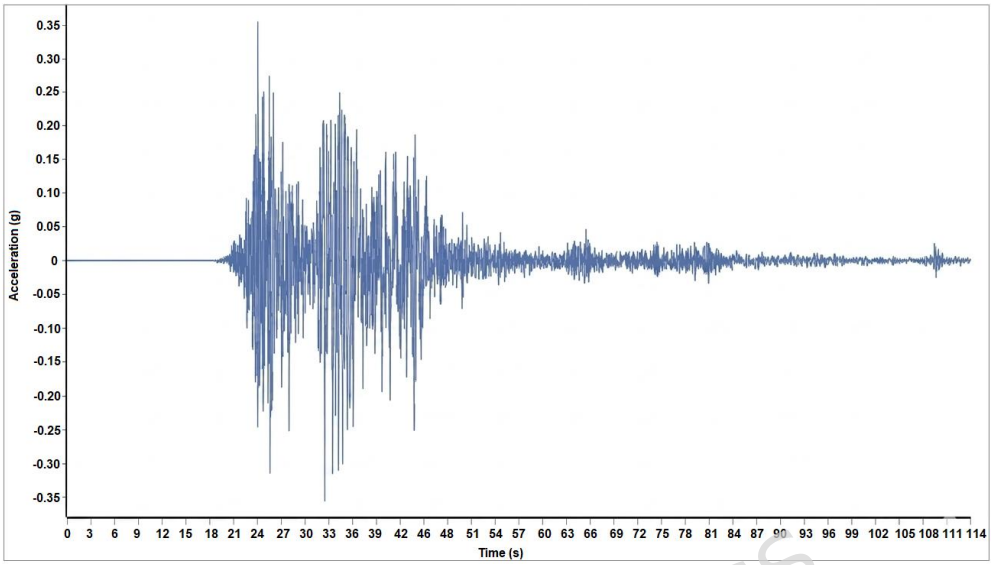


Figure 25. Ground acceleration record used in the time-history analysis

Nonlinear analyses in the time-history investigated the damage propagation and performance levels of structural system elements along the X-direction. Time-history analyses of the building's current condition determined the damage levels of beams, columns, and shear walls. According to performance evaluations based on TBEC-2018, for the X-direction, 78.46% of the beams were undamaged and 21.54% were in the significantly damaged zone; 77.81% of the columns were undamaged, 20.31% were in the significantly damaged zone, and 1.88% were in the severely damaged zone; and 97.92% of the shear walls were in the significantly damaged zone and 2.08% were in the severely damaged zone. The distribution of plastic hinges and the resulting damage patterns across the structural frame are illustrated in Figure 26a, while the statistical breakdown of these damage states for beams, columns, and shear walls is quantified in Figure 26b.

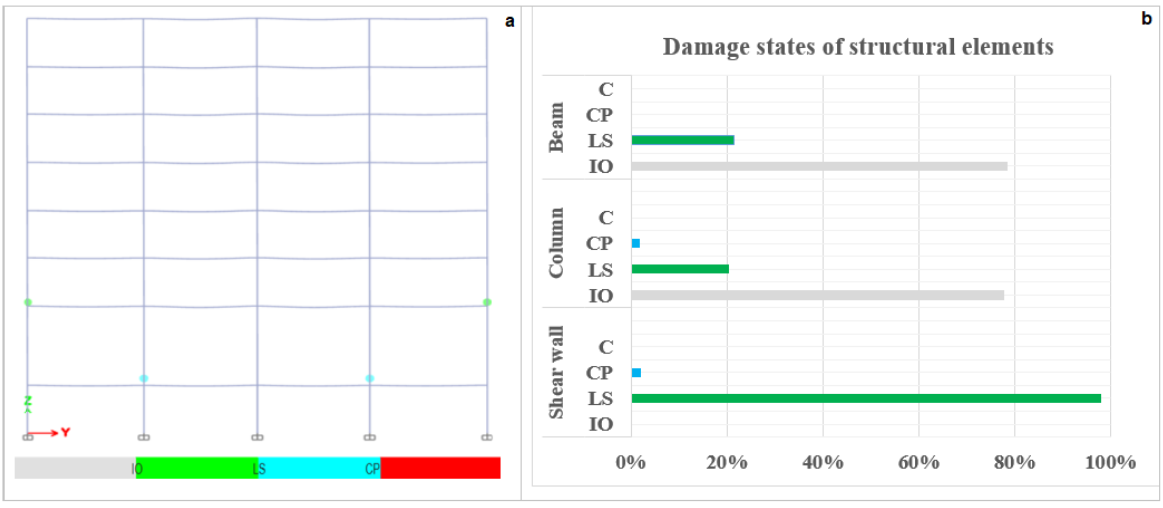


Figure 26. Evaluation of structural performance: (a) Plastic hinge formation and damage distribution on the building frame, (b) Percentage distribution of damage states for different structural elements.

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4. Strengthening Design

Post-earthquake assessment results revealed that the structure's existing structural system lacked sufficient seismic rigidity and was subject to excessive relative storey drifts under horizontal loads. This is a common weakness, particularly in frame-based structures. The structure's lack of horizontal rigidity elements (shear walls) was identified as one of the primary causes of this problem. Therefore, the addition of RC shear walls was chosen as the most appropriate strengthening method for the structure.

4.1. Enhancing Seismic Resilience of the Existing Structure Through RC Shear Walls

In the strengthening design of the existing structure, basic engineering principles were followed, and the provisions specified in TBEC-2018 were taken into consideration. First, the existing structure was evaluated with its own characteristics, and the appropriate strengthening method was determined. Then, the determined strengthening method was applied to the existing structure. In evaluating the seismic performance of the strengthened structure, the analysis and design procedures applied to the existing structure were applied (TBEC-2018). The strengthening application aims to improve the performance of the existing structure under dynamic loading and to increase the strength of the structural elements to safely carry additional loads. The main factors determining the selection of the method are the contribution of the strengthening method to the safety of the building, its applicability in the field, and its economic nature (Kaplan et al., 2011; Tan et al., 2025; Celep, 2002). TBEC-2018 (15.10. Strengthening of Reinforced Concrete Buildings) categorized and detailed the strengthening methods at the element level and structural system level. Among these strengthening methods, the "Adding Reinforced Concrete Shear Wall in the Frame Plane" method was evaluated and implemented as an economical and compatible method that is compatible with the existing structural system and will increase the performance of the building (TBEC-2018; Kaplan et al., 2011; Tan et al., 2025; Celep, 2002).

4.1.1. Analysis with Nonlinear Pushover Analysis Method and Evaluation of Results

For the RC structure that failed to meet the anticipated seismic performance within this study, the aim was to increase the seismic performance of the structure by adding RC shear walls within the frame plane. To improve the seismic performance of the building, 25 cm-thick RC shear walls were added. As seen in the reinforced structural system formwork plan, six additional RC shear walls were installed throughout the structure, starting from the basement and extending to the sixth storey. The positioning of the additional RC shear walls was based on the building's architecture, aiming to ensure a continuous interaction and force transfer between the RC elements of the existing structural system and the structural system designated for reinforcement. The placement of the RC shear walls on the formwork plan is shown in Figure 27.

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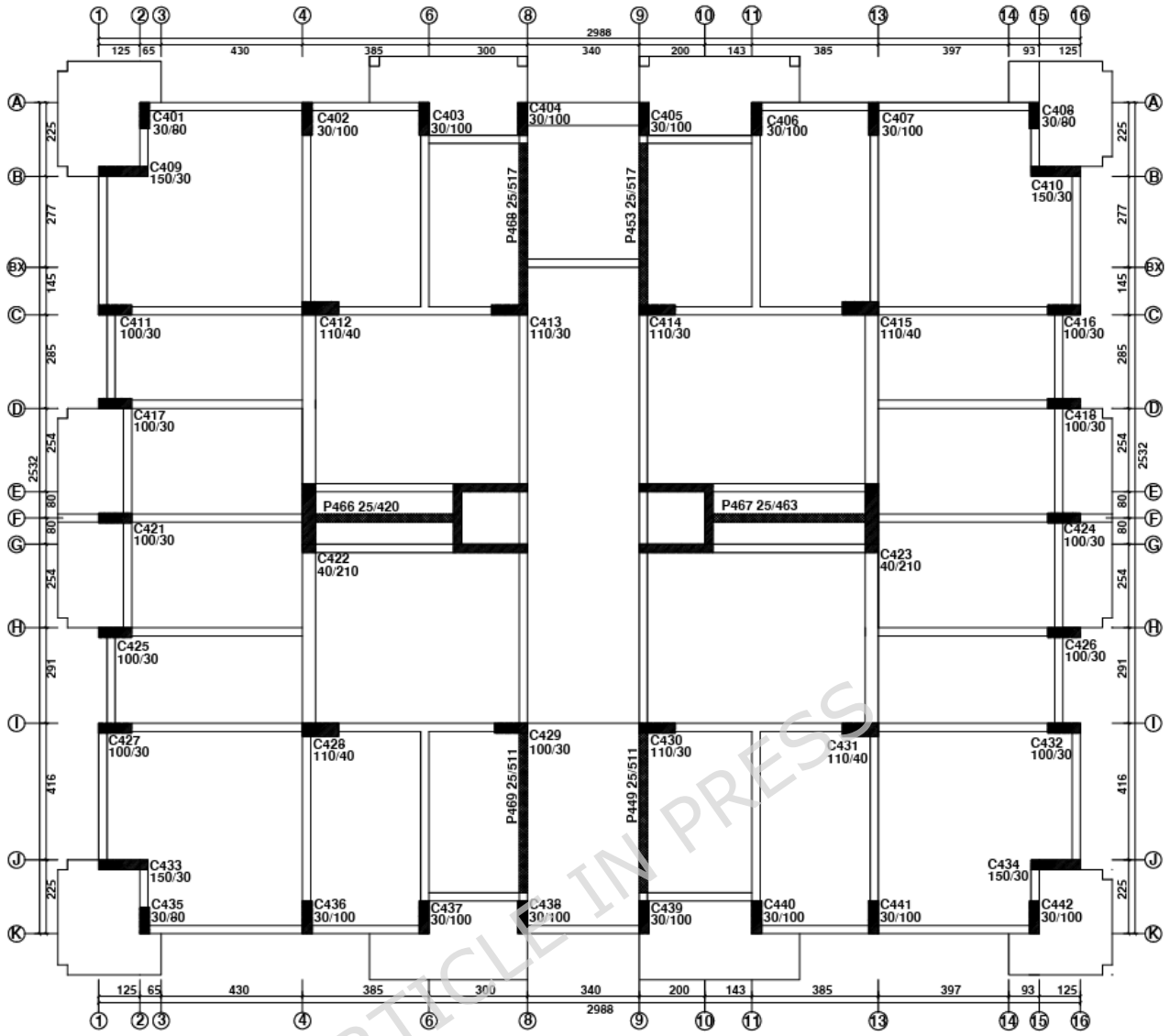


Figure 27. Created storey plan (post-earthquake strengthened system)

To ensure the anticipated seismic performance, the material properties of the additional reinforcement walls were selected in accordance with current earthquake regulations. Self-compacting C30 class concrete was used in the RC wall elements to be added to the structural system. The reinforcing bars employed in the study were B420C grade, characterized by a minimum yield strength of 420 MPa, a tensile strength ranging from 1.15 to 1.35 times the characteristic yield strength, and a corresponding ultimate strain of approximately 8%. The mechanical properties of all materials utilized are summarized in Table 7.

Table 7. Material properties considered in additional RC shear walls

C30 concrete	B420C reinforcement
$f_{ck} = 30$ MPa	$f_{yk} = 420$ MPa
$f_{ctd} = 0.35 \times \sqrt{30} = 1.90$ MPa	$f_{yd} = 420/1.15 = 365$ MPa
$f_{cd} = \frac{30}{1.5} = 20$MPa	$E_s = 2 \times 10^5$ MPa
$E_c = 32000$ MPa	

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The reinforcement details to be used in RC shear walls were determined in accordance with the TBEC-2018. Accordingly, the requirements for determining the reinforcement of the body and end areas of the reinforcement walls were met. Sectional details of the reinforcement walls are shown in Figure 28.

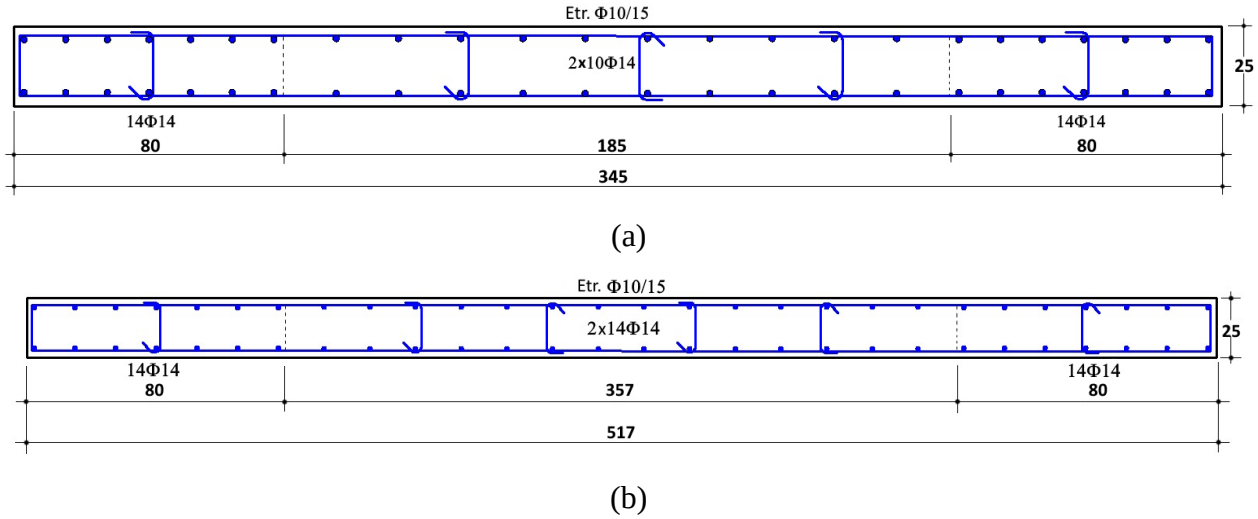


Figure 28. Cross-sectional details of RC shear walls

Following the design of the structural model, the structural system modelling and performance evaluation of the strengthened existing structure were initiated. A 3-D model of the RC shear wall-RC was created using ETABS. A 3-D view of the building is illustrated in Figure 29, and plan views are shown in Figure 30.

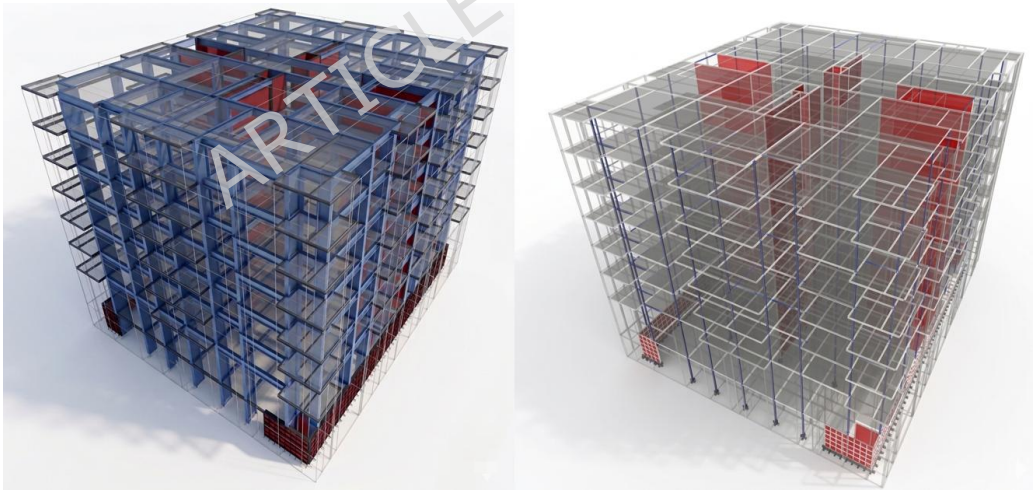


Figure 29. 3D views of the building strengthened with additional RC shear walls

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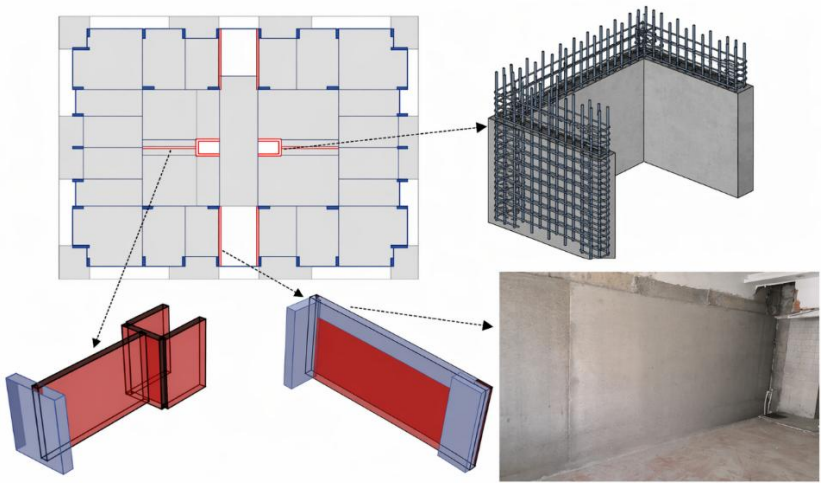
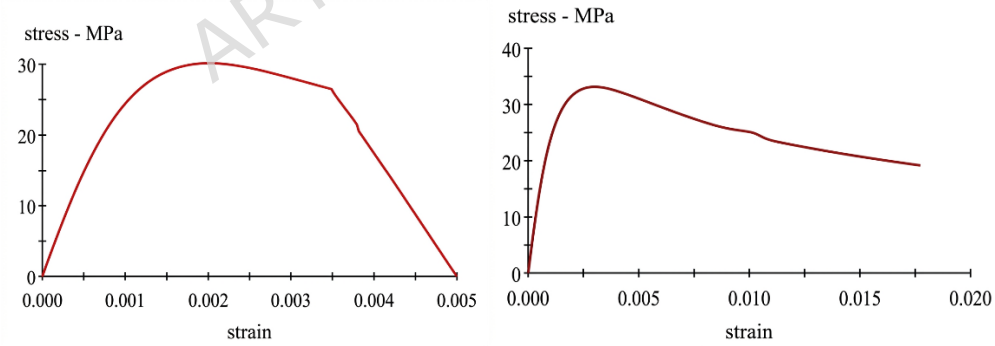


Figure 30. Plan representation, 3D model view, and on-site placement of the RC shear walls

The TBEC-2018 recommends using the calculation methods and assessment principles applied to existing buildings when calculating the seismic safety of strengthened buildings (15.9.1). In this context, the procedures applied to assess the seismic performance of the structural system strengthened with additional RC shear walls were applied, as were those used for the evaluation of the building's current performance. In accordance with existing regulations and calculation principles, the seismic performance of the 8-story RC structure, including the strengthened basement, was assessed using the nonlinear pushover analysis method, a nonlinear analysis method. The definition of material models, sections, and joints for the additional RC shear walls was performed similarly to the pre-retrofitting procedure. A nonlinear material model was defined for the shear elements added to the system to be evaluated alongside the design features of the existing structure in determining the performance of the strengthened structure. Based on the nonlinear material models in TBEC-2018, a confined and unconfined concrete model was defined for C30 concrete, and the corresponding material model is shown in Figure 31.

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(a) (b)

Figure 31. Material models for concrete: (a) Unconfined concrete model for C30 concrete, (b) Confined concrete model for C30 concrete

The material models formulated for the newly added RC shear walls were implemented within the ETABS structural analysis platform. Upon defining the material properties, nonlinear structural behaviour was captured by assigning distributed-plasticity hinges to the shear walls, a choice that allows the simulation of gradual inelastic deformation along the wall length rather than concentrating plasticity at discrete points. For each wall element, a fibre-based P–M3 plastic hinge model was developed. The corresponding yield surfaces and moment–curvature relationships,

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essential for accurate hinge characterization, were derived using the XTRACT software and subsequently imported into ETABS for performance-based analysis. The representative cross-sections of the shear walls, two walls measuring 25 × 345 cm along the X-direction and four walls measuring 25 × 517 cm along the Y-direction, consistently applied across all storeys, are shown in Figure 32.

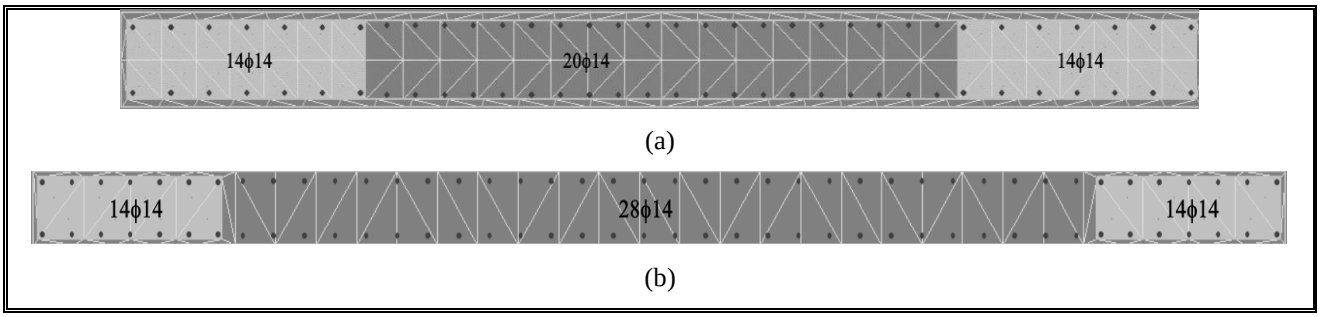


Figure 32. Typical cross-sections of additional walls, (a) additional wall applied in the X direction, (b) additional wall applied in the Y direction

Considering these inputs, a numerical model of the retrofitted building was developed and analyzed using the nonlinear pushover method. To evaluate the structural performance of the retrofitted configuration, a pushover analysis was conducted following the same procedure as for the building's existing condition. The resulting damage patterns were assessed, and the locations of plastic hinges formed along the X- and Y-directions in the retrofitted structure as a result of the analysis, as well as the flowchart of the procedure, are shown in Figure 33 below.

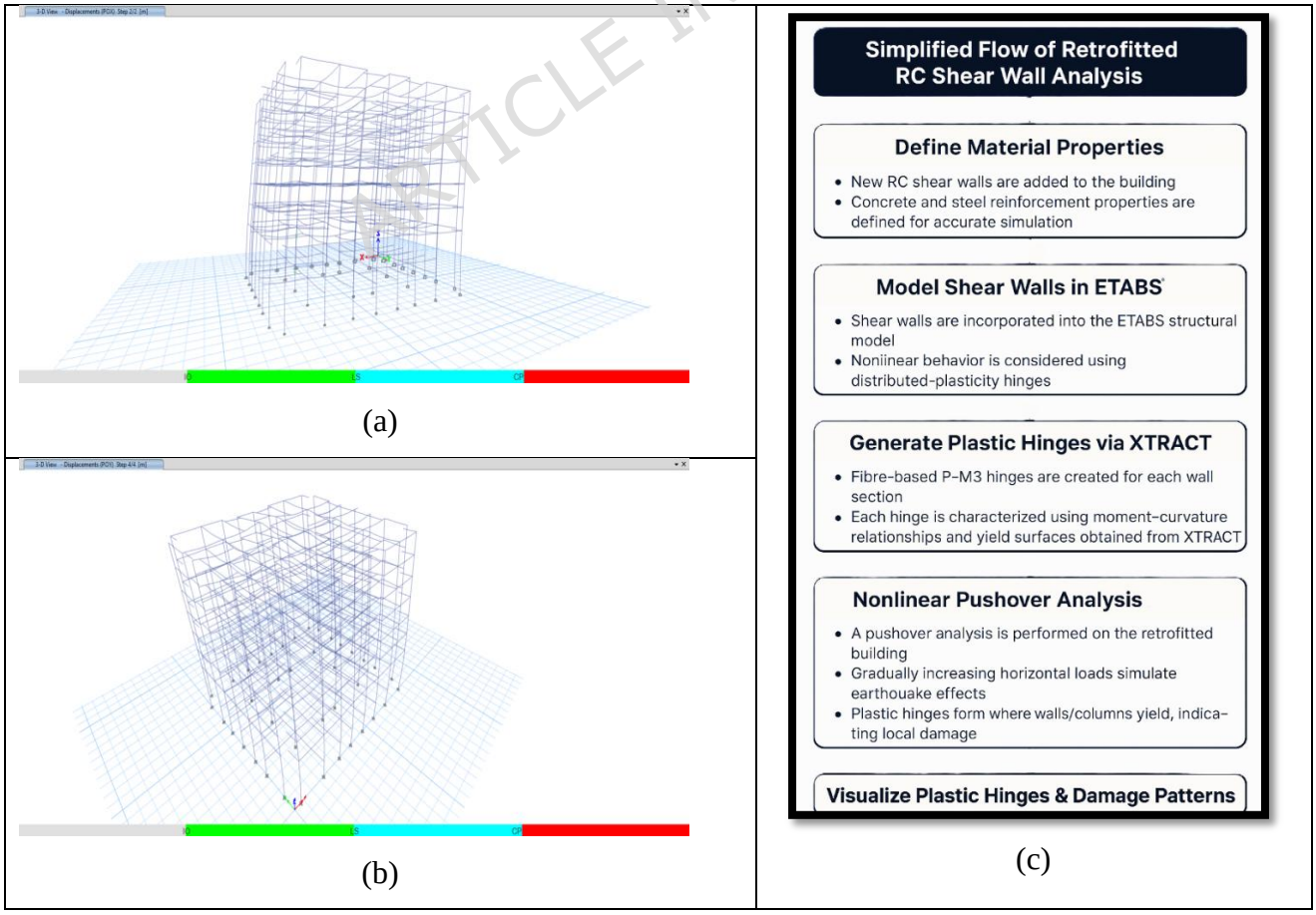
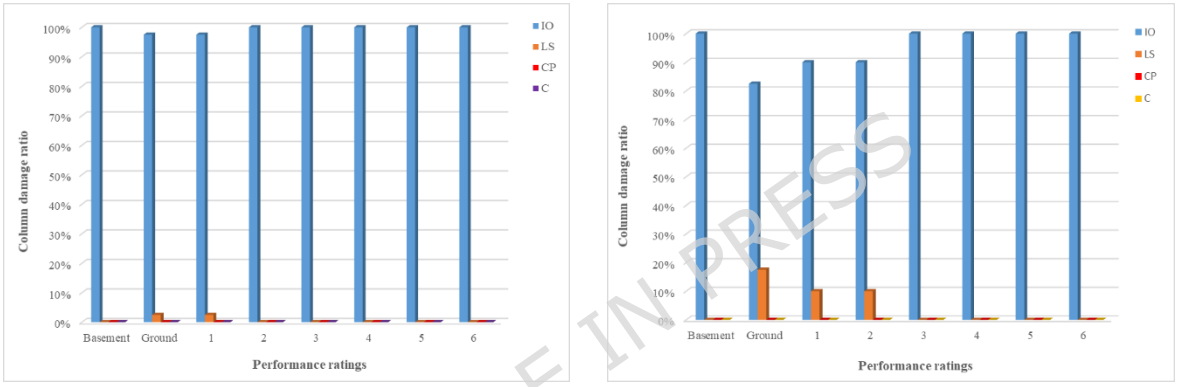


Figure 33. Plastic hinges formed in the structure in the strengthened state, (a) X direction, (b) Y direction, and (c) flowchart of the procedure

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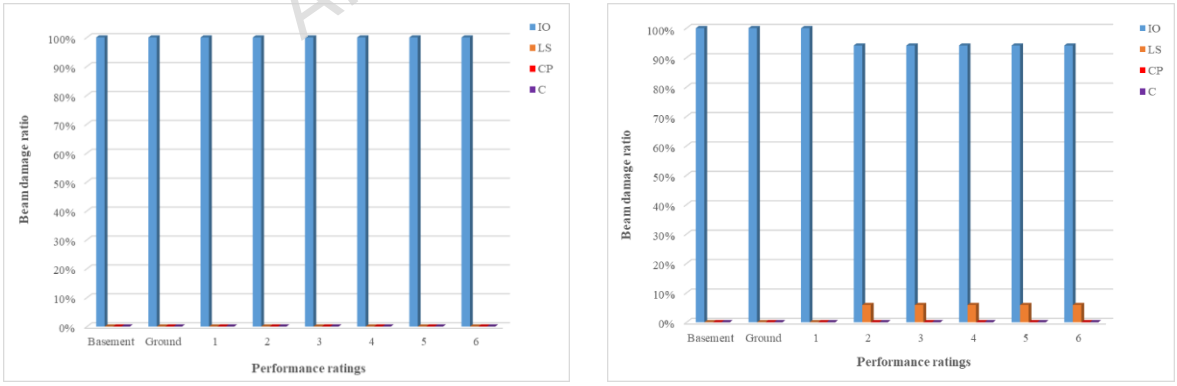
The analysis revealed that the concrete and reinforcing steel deformed in the plasticized sections, resulting in a certain amount of plastic rotation. With this strengthened structural model, the deformation and plastic rotation values for all beams, columns, and shear walls were calculated using the equations specified in TBEC-2018, based on various damage limits. The damage zones of the elements were determined by comparing the damage values corresponding to the plastic rotation requirements with the limit values specified in the regulation.

As a result of the analyses conducted, when the performances of the columns were evaluated in the strengthened condition, it was seen that 99.37% of them were undamaged in the X direction, and 0.63% had significant damage. In the Y direction, it was seen that 95.31% of them were undamaged, and 4.69% had significant damage (Figure 34). When the performances of the beams were evaluated in the X direction, it was seen that all of them were undamaged, while in the Y direction, 96.32% of them were undamaged, and 3.68% had significant damage (Figure 35). When the performances of the shear walls were evaluated, it was seen that 54.16% of them were undamaged, 45.83% had significant damage in the X direction, and 66.67% of them were undamaged, and 33.33% had significant damage in the Y direction (Figure 36).



(a) (b)

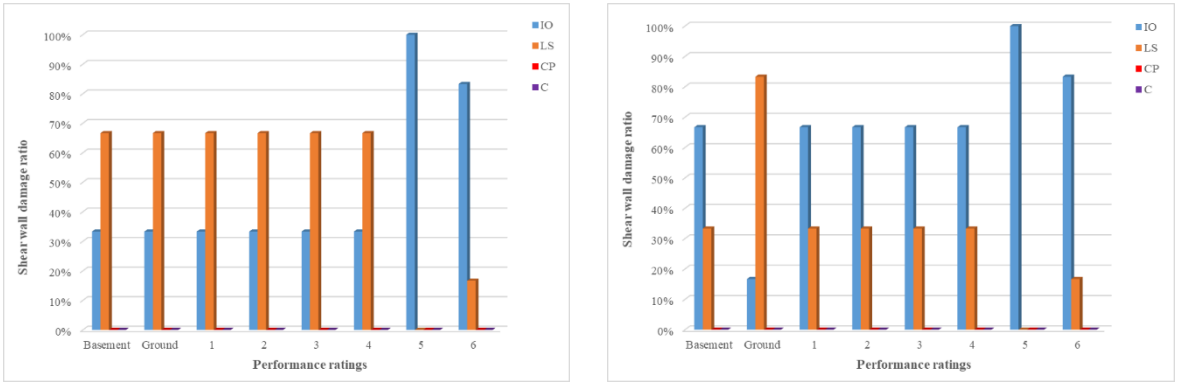
Figure 34. Performance levels of columns in the residential RC building after strengthening, based on pushover analysis: (a) X direction, (b) Y direction.



(a) (b)

Figure 35. Performance levels of beams in the residential RC building after strengthening, based on pushover analysis: (a) X direction, (b) Y direction.

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(a) (b)

Figure 36. Performance levels of shear walls in the residential RC building after strengthening, based on pushover analysis: (a) X direction, (b) Y direction.

According to the results, the RC achieved a life safety performance level, and it did not enter the collapse zone. The comparative results obtained from the structural analyses conducted on the RC building before and after retrofitting are presented in Table 8.

Table 8. Comparison of pre- and post-strengthening values for the existing RC building

Status	Relative Story Drift (Max)	Basement Shear Force (kN)	Maximum displacement (mm)	Maximum rotation (rad)	Period (s)	Performance Level
Pre-strengthening	0.008820	11902.53	282.38	0.001840	1.344	Collapse prevention
Post-strengthening	0.002914	9483.30	58.44	0.000043	0.597	Life safety

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When examining the structure's behaviour before and after retrofitting, significant improvements in seismic performance were observed. Firstly, the maximum relative story drift decreased by 67%, from 0.008820 to 0.002914, indicating a stiffer structure under horizontal loads. Horizontal loads were distributed in a more controlled manner, and the foundation shear decreased by approximately 20%, from 11,902.53kN to 9,483.30kN. The maximum displacement decreased by 79%, from 282.38mm to 58.44mm, and the maximum rotation decreased by 98%, from 0.001840 rad to 0.000043 rad. These ratios indicate that the structural system's deformation capacity was significantly increased by the retrofitting. Additionally, the structure's natural period decreased by approximately 56%, from 1.344s to 0.597s, confirming the increased overall stiffness of the structure. As a result of all these structural improvements, the performance level increased from Collapse Prevention to Life Safety/Better, clearly demonstrating that the retrofitting achieved its intended purpose.

To ensure the reliability of the nonlinear analysis results, a validation process was conducted based on multiple criteria. Firstly, the obtained performance results were evaluated according to the limits defined in TBEC-2018, FEMA-356, and ASCE 41, ensuring that the structural response remained within accepted performance ranges. The distribution of plastic hinges, inter-storey drift ratios, and damage states were carefully examined and interpreted within the framework of performance-based design. Secondly, the analytical damage patterns obtained from the pushover analysis were compared with the observed damage mechanisms in similar RC buildings affected by the 2023 Kahramanmaraş earthquakes. The consistency between observed

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field damage (e.g., column damage, beam yielding, and lack of lateral stiffness) and analytical predictions supports the validity of the developed numerical model. Finally, engineering judgement was incorporated throughout the modelling and evaluation process, ensuring that the results were not interpreted as direct software outputs but as part of a comprehensive structural assessment framework. These steps demonstrate that the study is not based on a black-box approach but on a transparent and validated nonlinear modelling methodology.

4.1.2. Time-History Analysis and Evaluation of Results

For the strengthened RC building, time-history analyses were re-performed in the X direction, taking into account the same seismic acceleration record used before the strengthening (Figure 24). Performance calculations after the strengthening application revealed that 100% of the beams in the X-direction were undamaged; 95% of the columns were undamaged, and 5% were significantly damaged; and 70.83% of the shear walls were undamaged, while 29.17% were significantly damaged. Accordingly, a significant improvement in the seismic performance of the building was achieved with the shear wall addition method. The distribution of plastic hinges and the resulting damage patterns across the structural frame after strengthening are illustrated in Figure 37a, while the statistical breakdown of these damage states for beams, columns, and shear walls after strengthening is shown in Figure 37b.

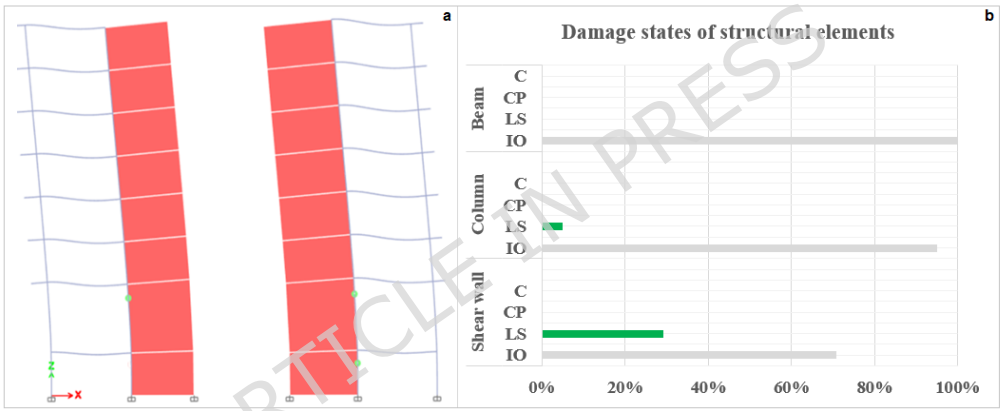


Figure 37. Evaluation of structural performance after strengthening: (a) Plastic hinge formation and damage distribution on the building frame, (b) Percentage distribution of damage states for different structural elements.

4.1.3. Comparison of Analytical Methods

The building's performance was determined using pushover and nonlinear time-history analysis methods. Figures 38, 39, and 40 compare the beam, column, and RC shear wall elements in their current state and after strengthening, based on their damage status. The results obtained from the analyses were found to be consistent in terms of damage distribution and, consequently, seismic performance. This agreement supports the reliability of the numerical model created and confirms the validity of the performance evaluation.

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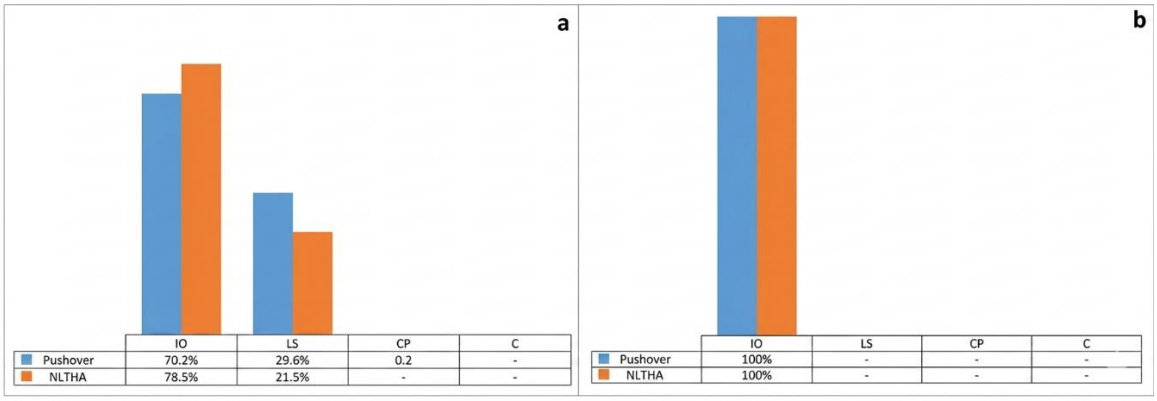


Figure 38. Comparison of damage conditions in beams, (a) current condition, (b) strengthening condition.

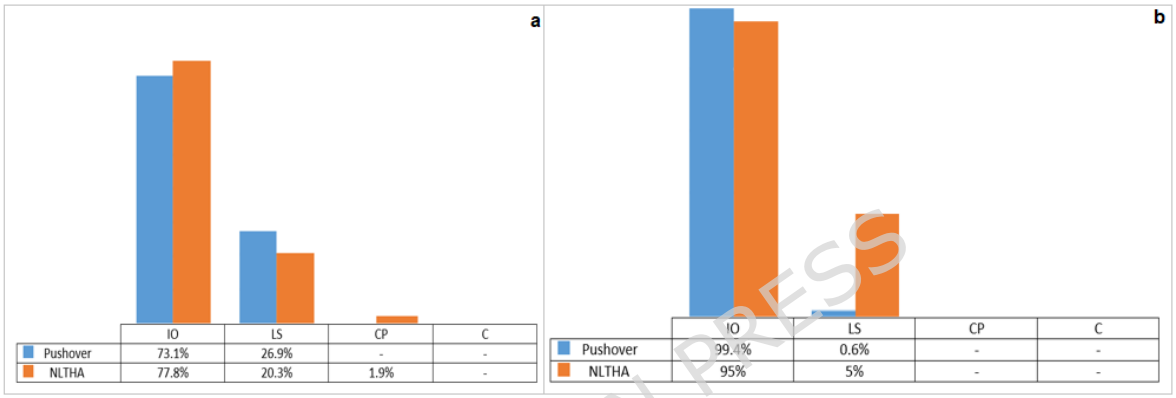


Figure 39. Comparison of damage conditions in columns, (a) current condition, (b) strengthening condition.

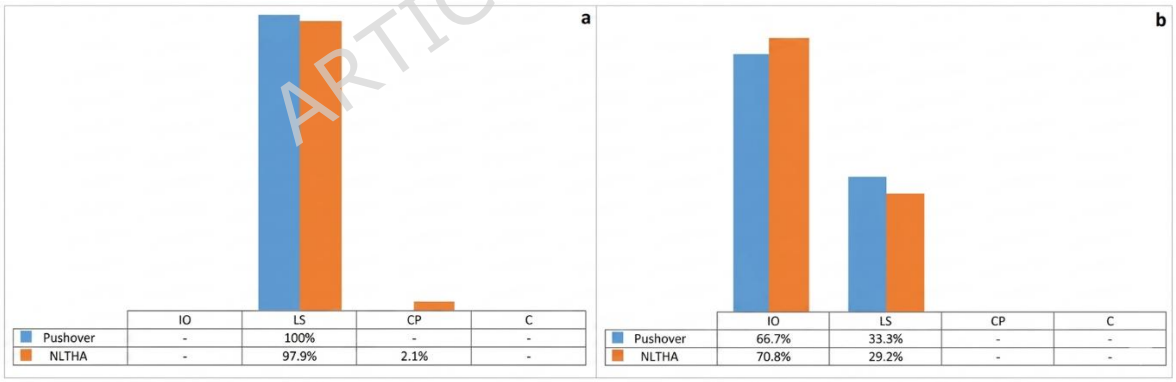


Figure 40. Comparison of damage conditions in RC shear walls, (a) current condition, (b) strengthening condition.

The comparative assessment of the pushover and nonlinear time-history analysis methods reveals a high degree of consistency in the damage distribution across beams, columns, and RC shear walls for both the current and strengthened states of the building. The strong correlation between the results obtained from these two distinct analytical approaches validates the accuracy of the structural performance evaluation and confirms the reliability of the established numerical model. Consequently, the agreement between the static and dynamic nonlinear procedures provides a robust basis for determining the seismic safety of the structure. Ultimately, the findings demonstrate that both methodologies yield comparable performance metrics, reinforcing the overall validity of the strengthening strategy

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4.2. Comparison of Reconstruction and Strengthening Costs

The approximate reconstruction cost of the 8-story RC building considered in this study can be calculated. For this purpose, building classifications according to architectural services in Türkiye are taken into account, and approximate building costs are determined annually for different building groups, including non-tax overheads (15%) and contractor profit (10%). This classification categorizes buildings based on the architectural services provided. An approximate unit price per square meter is determined for each building class, and these prices are announced annually. The reinforced concrete building considered is classified in group III-C, and according to the "Circular on the Approximate Unit Cost of Buildings to be Used in Calculating Architectural and Engineering Services Fees for 2026" published in the Official Gazette by the Ministry of Environment, Urbanization and Climate Change, the price for Group III-C buildings is determined as 23.400 TL/m2. The total area of the building is multiplied by the unit price to obtain the total construction cost. In addition, 5% of the total construction cost is considered for landscaping and environmental design. In addition, market research conducted through project firms for the reconstruction of the building revealed a total project design cost of 4.250.000 TL. Furthermore, the construction supervision costs during the construction period will be approximately 2.500.000 TL. Taking all these values into account, the current construction cost of the building considered in the study is obtained as 202.523.760 TL. When the 20% tax portion in Türkiye is added to these costs, the total reconstruction cost will be 243.028.512 TL.

In this study, cost calculations for the proposed strengthening method were performed using the Construction and Installation Unit Prices published annually by the Ministry of Environment, Urbanization, and Climate Change. First, the quantities (measurements) for 38 different work items to be carried out during the strengthening application phase were determined. Then, by multiplying these quantities with the unit prices, the static strengthening cost was obtained as 16.033.416 TL. Architectural (50%), electrical (10%), and mechanical (10%) strengthening costs were added to this amount. Additionally, the building inspection costs during the construction period will be approximately 1.000.000 TL. Considering all these values, the strengthening cost was calculated as 28.256.807 TL. When the 20% tax portion in Türkiye is added to these costs, the total strengthening cost will be 33.908.168 TL. In light of these results, the ratio of strengthening cost to reconstruction cost was found to be approximately 14%. Table 9 demonstrates the economic feasibility of the proposed strenthening method for this structure.

Table 9. The comparison of reconstruction and strengthening costs

Cost Component	Reconstruction (TL)	Strengthening (TL)	Ratio (%)
Subtotal (Excl. Tax)	202,167,148	28,256,807	13.98
Tax (20%)	40,433,430	5,651,361	13.98
TOTAL (Incl. Tax)	243,028,512	33,908,168	13.95 ≈ 14%

5. Conclusions

RC structures, which constitute a large portion of the existing urban building stock, fail to demonstrate adequate seismic performance for various reasons. Structural damage in the event of a potential earthquake can be minimized by making decisions as quickly as possible regarding the strengthening or demolition of structures lacking adequate seismic performance. The structural

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damage caused by the Kahramanmaraş earthquake complex on February 6, 2023, which was the disaster of the century for Türkiye, and the resulting large-scale loss of life, has highlighted the seismic performance of existing structures and the importance of future structural improvements. Within the scope of this study, detailed analyses were conducted for the existing mid-rise RC building that was subjected to the Kahramanmaraş earthquake complex on February 6, 2023. As a result of the analysis, reinforced concrete shear walls were used to strengthen the structure, which failed to demonstrate adequate seismic performance without shear walls, and the results were compared.

The February 6, 2023, Kahramanmaraş earthquakes revealed that the seismic performance of the existing RC building stock is not at the anticipated level. Incomplete, defective, and/or complete failure to implement earthquake-resistant design principles during the design and construction phases, along with poor material properties, play a critical role in damage and destruction. In addition, it has been observed that the environmental and mechanical effects to which structures are exposed over time negatively affect the structural capacity of structural elements. RC structures built before 2000 do not meet design criteria consistent with current earthquake regulations, and structural irregularities, inadequate reinforcement ratios, and deficiencies in connection details increase the risk of serious damage to these structures in the event of an earthquake.

The destruction and damage caused by these and similar earthquakes clearly demonstrate the need to evaluate and strengthen the seismic performance of existing RC buildings. To increase the earthquake resistance of structures, the existing condition of the structures must first be examined in detail, and weak points must be identified using performance assessment methods. Strengthening work should be carried out with engineering solutions appropriate to the structure's structural system. Seismic resistance should be enhanced through methods such as enhancing the strength of RC columns, beams, and shear walls, improving connection details, and adding new structural elements when necessary. This minimizes earthquake-related risks and ensures the sustainability and safety of the existing structure stock. This is one of the most effective measures that can be taken within the scope of modern disaster management for existing structures.

When reinforcing using RC shear walls, the additional reinforcement walls must be adequately anchored to the existing RC structural elements, and foundations must be established to ensure these walls can safely transfer the ground load. It should be noted that this situation, which would otherwise only increase the weight of the structure, would cause the structure to be damaged more easily and rapidly in a potential earthquake. Furthermore, when reinforcing with additional reinforced concrete shear walls, careful attention should be paid to the placement of the walls, and their potential impact on the stability and rigidity of the structural system should be accurately analysed. Irregularities in the structure should be taken into account when using reinforced concrete shear walls. As with other RC structural elements, the concrete quality and reinforcement layout for additional RC shear walls should be designed and implemented according to earthquake-resistant design principles.

This study demonstrates that the use of RC shear walls in an existing RC structure lacking sufficient seismic performance increased the rigidity and seismic performance of the structure under horizontal loads. As a consequence of these structural enhancements, the building’s performance level improved from “Collapse Prevention” to “Life Safety/Better,” clearly indicating that the retrofitting measures effectively fulfilled their intended objective. Therefore, it has been observed that the reduction in horizontal displacement limits will contribute to reducing damage that may occur during an earthquake. The post-strengthening analyses demonstrated a consistent improvement in the structural performance across both analytical methods. The significant

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enhancement in the capacity curves obtained from the pushover analysis is in agreement with the reduction in peak displacements and the improved plastic hinge distribution observed in the nonlinear time-history analyses. This correlation validates that the strengthening strategy effectively enhances both the static lateral stiffness and the dynamic response of the structure.

When the data obtained in this study are evaluated holistically, it is observed that the proposed strengthening method not only improves the seismic performance of the structure but also provides an economically optimized solution. Structural analyses, conducted through both pushover and nonlinear time-history methods, clearly demonstrate the enhancement in structural capacity and energy dissipation capability. Parallel to these technical improvements, cost analyses have proven that the strengthening expenditure remains significantly lower than the potential costs of heavy damage repair or total reconstruction after a seismic event. Consequently, it is concluded that the implemented strategy ensures structural safety while representing a sustainable and cost-effective engineering approach in terms of efficient resource allocation.

Although the structural analyses in this study were performed assuming fixed-base conditions, the adequacy of the existing foundation system should be carefully evaluated in practical applications. Field investigations revealed that the building is supported by an approximately 80 cm thick raft foundation. However, the addition of RC shear walls introduces additional vertical loads and alters the distribution of internal forces within the structural system. Therefore, it is essential to verify whether the existing foundation system can safely sustain the increased gravity loads and seismic demands. This evaluation should include checks for soil bearing capacity, potential differential settlements, and foundation shear forces. If the existing foundation is found to be inadequate, strengthening measures limited to the superstructure, such as the addition of shear walls, may not be appropriate. In such cases, alternative retrofitting strategies that do not significantly increase foundation demand such as energy dissipation devices or other advanced seismic protection systems should be considered. This consideration is critical to ensure that strengthening interventions improve the overall structural performance without introducing new vulnerabilities at the foundation level.

It should be noted that the validation performed in this study is primarily qualitative, based on code compliance and comparison with observed damage patterns. Future studies may incorporate experimental calibration or soil-structure interaction modelling to further enhance validation accuracy.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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Data Availability Statement

All data generated or used during the study appear in the submitted article.

References

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1.Adalier, K., & Aydingun, O. (2001). Structural engineering aspects of the June 27, 1998 Adana–Ceyhan (Turkey) earthquake. Engineering Structures, 23(4), 343-355.
2.Ahmadizadeh, M., & Shakib, H. (2004). On the December 26, 2003, southeastern Iran earthquake in Bam region. Engineering structures, 26(8), 1055-1070.
3.Akhlaghi, M. M., Bose, S., Mohammadi, M. E., Moaveni, B., Stavridis, A., & Wood, R. L. (2021). Post-earthquake damage identification of an RC school building in Nepal using ambient vibration and point cloud data. *Engineering Structures*, *227*, 111413.
4.Aksoylu, C., & Kara, N. (2020). Strengthening of RC frames by using high-strength diagonal precast panels. *Journal of Building Engineering*, *31*, 101338.
5.Aksoylu, C., Mobark, A., Hakan Arslan, M., & Hakkı Erkan, İ. (2020). A comparative study on ASCE 7-16, TBEC-2018 and TEC-2007 for reinforced concrete buildings. *Revista de la Construcción*, *19*(2), 282-305.
6.Aksoylu, C., Uysal, Y., Başaran, B., Özkılıç, Y. O., & Arslan, M. H. (2025). Effect of stirrup spacing on strengthening beams with insufficient shear capacity using innovative mechanical steel stitches. *Structural Concrete*.
7.Altıok, T. Y., Şevik, M., & Demir, A. (2024). Seismic performance of retrofitted and non-retrofitted RC school buildings after the February 6th, 2023, Kahramanmaraş earthquakes. *Bulletin of Earthquake Engineering*, 1-36.
8.Altiok, T. Y., Cetin, K., & Demir, A. (2025). Effect of shear wall opening and reinforcement around opening on the structural strengthening. *Bulletin of Earthquake Engineering*, *23*(8), 3421–3449.
9.Aly, N., AlHamaydeh, M., & Galal, K. (2020). Quantification of the impact of detailing on the performance and cost of RC shear wall buildings in regions with high uncertainty in seismicity hazards. *Journal of Earthquake Engineering*, *24*(3), 421–446.
10.Aras, F., Doğan, T. P., Öztürk, M., Tün, M., Işık, E., & Arslan, M. H. (2025). Assessment of the damage caused by the 6 February 2023 earthquakes on old and new dated reinforced concrete buildings in Elbistan, Turkey. *Advances in Structural Engineering*, 13694332251375194.
11.Arslan, M. H., Dere, Y., Ecemiş, A. S., Doğan, G., Özturk, M., & Korkmaz, S. Z. (2024). Code-based damage assessment of existing precast industrial buildings following the February 6th, 2023 Kahramanmaraş earthquakes (Pazarcık Mw 7.7 and Elbistan Mw7. 6). *Journal of Building Engineering*, *86*, 108811.
12.ASCE/SEI 41-13. Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers; American Society of Civil Engineers: Reston, VA, USA, 2014.
13.Aslan, S., Erkan, İ. H., Aksoylu, C., & Arslan, M. H. (2024, April). An experimental investigation and cost analysis of flexural or shear strengthening pre-damaged RC beams. In *Structures* (Vol. 62, p. 106091). Elsevier.
14.Atmaca, B., Altunışık, A. C., Atmaca, E. E., Başağa, H. B., Günaydın, M., Adanur, S., ... & Karahasan, A. K. (2025). What is the Reason for Collapses on February 6, 2023 Kahramanmaraş Earthquakes: Insights from a Dataset of 400 Collapsed RC Buildings Post-Earthquake Analysis. *Journal of Building Engineering*, 112660.
15.Avcil, F., Bilgin, H., Arkan, E., & Işık, E. (2025). Numerical Analysis of Structural Behavior and Damage Mechanisms in Shear-Deficient Reinforced Concrete Columns Retrofitted with RC Jacketing. *Türk Doğa ve Fen Dergisi*, *14*(2), 150-161.
16.Aydın, M. C., Işık, E., Büyüksaraç, A., Ulu, A. E., & Avcil, F. (2025). Technical and socio-economic perspective on the disaster of the century (6 February 2023 earthquake) in Türkiye on the second anniversary. *Geological Journal*.
17.Aydogdu, H. H., & İlki, A. (2026). Assessment of repair/reconstruction costs to existing reinforced concrete and masonry buildings following the 2023 Kahramanmaraş earthquakes.
18.Aydogdu, H. H., Atasever, K., Maeda, M., & İlki, A. (2025, July). A case study on seismic retrofitting of sub-standard RC buildings using FRPs: A building damaged during the 2023 Kahramanmaraş earthquakes. In *Proceedings of the International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering* (pp. 470–481). Springer.
19.Bassurucu, M., Yildiz, O., & Kina, C. (2025). Seismic Performance Assessment of an RC Building Due to 2023 Türkiye Earthquakes: A Case Study in Adıyaman, Türkiye. *Buildings*, *15*(4), 521.

ARTICLE IN PRESS

ARTICLE IN PRESS

20.Belbachir, A., Benanane, A., Ouazir, A., Harrat, Z. R., Hadzima-Nyarko, M., Radu, D., & Amziane, S. (2023). Enhancing the seismic response of residential RC buildings with an innovative base isolation technique. *Sustainability, 15*(15), 11624.
21.Brunesi, E., Peloso, S., Pinho, R., & Nascimbene, R. (2019). Shake-table testing of a full-scale two-story precast wall-slab-wall structure. *Earthquake spectra*, *35*(4), 1583-1609.
22.Büyüksaraç, A., Işık, E., & Bektaş, Ö. (2022). A comparative evaluation of earthquake code change on seismic parameter and structural analysis; a case of Turkey. *Arabian Journal for Science and Engineering*, *47*(10), 12301-12321.
23.Castro, J. M., Araújo, M., D'Aniello, M., & Landolfo, R. (2017). Strengthening of RC buildings with steel elements. In *Strengthening and retrofitting of existing structures* (pp. 139–162). Springer.
24.Celep, Z. Mevcut Betonarme Binaların Deprem Güvenliğinin Belirlenmesi ve Güçlendirilmesinde Genel Kurallar. Prof. Dr. Kemal Özden'i Anma Semineri, İTÜ, İstanbul, 2002.
25.Chandiwala, A. (2012). Earthquake analysis of building configuration with different position of shear wall. International Journal of Emerging Technology and Advanced Engineering, 2(12), 347-353.
26.Cheng, S., He, H., & Chen, Y. (2025). Performance evaluation and repair strategy of seismic damages to RC structures based on residual deformation. *Structure and Infrastructure Engineering*, *21*(1), 129-147.
27.Çalım, F., Güllü, A., & Yüksel, E. (2026). A comprehensive state-of-the-art review on energy-based procedures in earthquake-resistant structural design. *Archives of Civil and Mechanical Engineering*, *26*(2), 45.
28.Çelebi, E., & Kırtel, O. (2025). Seismic performance of reinforced concrete framed buildings with ribbed slabs at the affected region by 2023 Kahramanmaraş earthquakes. *Bulletin of Earthquake Engineering*, 1-24.
29.Çelebi, E., Aktas, M., Çağlar, N., Özocak, A., Kutanis, M., Mert, N., & Özcan, Z. (2013). October 23, 2011 Turkey/Van–Ercis earthquake: structural damages in the residential buildings. Natural Hazards, 65(3), 2287-2310.
30.Dahesh, M. A., Tuken, A., & Siddiqui, N. A. (2015). Controlling the earthquake-induced lateral displacement of RC buildings using shear walls: Parametric study. *Arabian Journal of Geosciences*, *8*(11), 9913–9927.
31.Dedeoglu, I. O., Yetkin, M., Tunc, G., & Ozbulut, O. E. (2025). Evaluating earthquake-induced damage in Doganşehir, Malatya after 2023 Kahramanmaras earthquake sequence: Geotechnical and structural perspectives. *Journal of Building Engineering*, 112266.
32.Di Sarno, L., & Pugliese, F. (2020). Seismic fragility of existing RC buildings with corroded bars under earthquake sequences. *Soil Dynamics and Earthquake Engineering*, *134*, 106169.
33.Dindar, A. A., Bozer, A., Özkaynak, H., Güllü, A., Müderrisoğlu, Z., Çalım, F., & Hasanoğlu, S. (2025). Optimal seismic design of code-compliant RC moment frames through analytic hierarchy process. *Turkish Journal of Civil Engineering*. Advance online publication.
34.Dogan, G., Arslan, M. H., & Ilki, A. (2023). Detection of damages caused by earthquake and reinforcement corrosion in RC buildings with deep transfer learning. *Engineering Structures*, *279*, 115629.
35.Dogan, G., Ecemis, A. S., Korkmaz, S. Z., Arslan, M. H., & Korkmaz, H. H. (2021). Buildings damages after Elazığ, Turkey earthquake on January 24, 2020. Natural hazards, 109(1), 161-200.
36.Doğan, T. P., Kalkan, H., Aldemir, Ö., Ayhan, M., Böcek, M., & Anıl, Ö. (2024). Investigation of RC structure damages after February 6, 2023, Kahramanmaraş earthquake in the Hatay region. *Bulletin of Earthquake Engineering*, *22*(10), 5201-5229.
37.Ekici, M. Y., Yavariabdi, A., Dogan, G., & Arslan, M. H. (2025, March). Adjacent-NET: Deep learning classification of adjacent buildings for assessing pounding effects using building facade images in earthquake-prone regions. In *Structures* (Vol. 73, p. 108332). Elsevier.
38.Elnashai, A. S., & Di Sarno, L. (2015). *Fundamentals of earthquake engineering: from source to fragility*. John Wiley & Sons.
39.Erbaş, Y., Mercimek, Ö., Anıl, Ö., Çelik, A., Akkaya, S. T., Kocaman, İ., & Gürbüz, M. (2025). Design deficiencies, failure modes and recommendations for strengthening in reinforced concrete structures

ARTICLE IN PRESS

exposed to the February 6, 2023 Kahramanmaraş Earthquakes (Mw 7.7 and Mw 7.6). *Natural Hazards*, *121*(3), 3153-3194.

40.FEMA 356. Prestandard and commentary for the seismic rehabilitation of buildings; Federal Emergency Management Agency: Washington DC, USA, 2000.

41.FEMA 440. Enhanced at the state of the art seismic evaluation of buildings (FEMA Publication No. 440); Federal Emergency Management Agency: Washington DC, USA, 2005.

42.Freddi, F., Galasso, C., Cremen, G., Dall'Asta, A., Di Sarno, L., Giaralis, A., ... & Woo, G. (2021). Innovations in earthquake risk reduction for resilience: Recent advances and challenges. *International Journal of Disaster Risk Reduction*, *60*, 102267.

43.Freddi, F., Wu, J. R., Cicia, M., Di Sarno, L., D'Aniello, M., Gutiérrez-Urzúa, F., ... & Strepelias, E. (2025). Seismic Retrofitting of Existing Steel Frames with External BRBs: Pseudo-Dynamic Hybrid Testing and Numerical Parametric Analysis. *Earthquake Engineering & Structural Dynamics*, *54*(3), 1064-1083.

44.Gao, C., Huang, L., Wang, L., Sun, Q., & Li, Y. (2025). Simulation and numerical analysis of the seismic performance of the quick repaired seismic-damaged RC frame. *Soil Dynamics and Earthquake Engineering*, *188*, 109083.

45.Georgiou, A., Kotakis, S., Loukidis, D., & Ioannou, I. (2023). Case study of seismic assessment of a short irregular historic reinforced concrete structure: Time-history vs. pushover nonlinear methods. *Journal of Earthquake Engineering*, *27*(16), 4761–4785.

46.Gönülcü, E., Gökçe, T., Yüksel, E., & Orakdöğen, E. (2025). Damping capability enhancement of the polyurethane seismic isolation device for HV post insulators and its numerical evaluation with the 2023 Kahramanmaraş, Türkiye earthquake sequence. *Earthquake Spectra*, *41*(2), 1642–1668.

47.Hadzima-Nyarko, M., Işık, E., Radu, D., Bulajić, B., Lozančić, S., Radić, J., & Ereš, A. (2025). Effectiveness of High-Performance Concrete Jacketing in Improving the Performance of RC Structures. *Applied Sciences*, *15*(21), 11421.

48.Imtiaz, A., Saloustros, S., Beqiraj, M., Cortés, G., Devaux, M., Lattion, E., ... & Sehaqui, H. (2025). Understanding building damage through the lens of the Swiss post-seismic reconnaissance mission of 2023 Al Haouz, Morocco, earthquake. *Scientific Reports*, 15(1), 16587.

49.Işık, E. (2021). A comparative study on the structural performance of an RC building based on updated seismic design codes: Case of Turkey. *Challenge*, *7*, 123-134.

50.Işık, E. A Study on Strengthening RC Structural Elements with Fibers Based Polymers. *Bitlis Eren Üniversitesi Fen Bilimleri Dergisi*, *14*(2), 1269-1286.

51.Işık, E., Avcil, F., Büyüksaraç, A., & Arkan, E. (2025a). Comparative analysis of target displacements in RC Buildings for 2023 Türkiye earthquakes. *Applied Sciences*, *15*(7), 4014.

52.Işık, E., Hadzima-Nyarko, M., Tayeh, B.A., Harrat, Z.R., Avcil, F., & Arkan, E. (2025b). Comparison of Reinforcement Methods With Advanced Materials for R/C Columns. *Advanced Engineering Letters*, 4(1), 1-13.

53.Işık, E., Radu, D., Harirchian, E., Avcil, F., Arkan, E., Büyüksaraç, A., & Hadzima-Nyarko, M. (2025). Failures in Reinforced-Concrete Columns and Proposals for Reinforcement Solutions: Insights from the 2023 Kahramanmaraş Earthquakes. *Buildings*, *15*(9), 1535.

54.Işık, E., Shao, Y. B., Hadzima-Nyarko, M., Radu, D., Bulajic, B., & Lozancic, S. (2026). Enhancing the seismic safety of upgraded RC buildings using FRP retrofitting: analytical and field evidence from the 2023 Kahramanmaraş earthquakes. Bulletin of Earthquake Engineering, 24(3), 1467-1501.

55.Ivanov, M. L., & Chow, W. K. (2023). Structural damage observed in reinforced concrete buildings in Adiyaman during the 2023 Türkiye Kahramanmaraş Earthquakes. Structures, 58, 105578. https://doi.org/10.1016/j.istruc.2023.105578.

56.İnce, E. G. (2025). Seismic performance of RC buildings with one-way joist slab: Insights from the 2023 Kahramanmaraş earthquakes. *Structural Concrete*.

57.John, S. K., Cascardi, A., Verre, S., & Nadir, Y. (2025). RC-columns subjected to lateral cyclic force with different FRCM-strengthening schemes: experimental and numerical investigation. *Bulletin of Earthquake Engineering*, 1-30.

58.Kaltakci, M. Y., Arslan, M. H., & Yavuz, G. (2010). Effect of internal and external shear wall location on strengthening weak RC frames. *Scientia Iranica*, *17*(4), 312–321.

ARTICLE IN PRESS

59.Kaltakci, M. Y., Arslan, M. H., Yilmaz, U. S., & Arslan, H. D. (2008). A new approach on the strengthening of primary school buildings in Turkey: An application of external shear wall. *Building and Environment, 43*(6), 983–990.

60.Kap, T. (2026). The effects of reinforced concrete shear wall on the earthquake behaviour of the buildings with various column sections. *Journal of Asian Architecture and Building Engineering, 25*(2), 1203–1217.

61.Kaplan, H., Yilmaz, S., Cetinkaya, N., & Atimtay, E. (2011). Seismic strengthening of RC structures with exterior shear walls. *Sadhana, 36*(1), 17–34.

62.Kaplan, H., Yilmaz, S., Cetinkaya, N., and Atimtay, E. Seismic strengthening of RC structures with exterior shear walls. Sadhana, 36, 17-34, 2011.

63.Karadoğan, F., Yüksel, E., Khajehdehi, A., Özkaynak, H., Güllü, A., & Şenol, E. (2019). Cyclic behavior of reinforced concrete cladding panels connected with energy dissipative steel cushions. *Engineering Structures, 189*, 423–439.

64.Kaveh, A., & Ardebili, S. R. (2023). Optimal design of mixed structures under time-history loading using metaheuristic algorithm. *Periodica Polytechnica Civil Engineering, 67*(1), 57–64.

65.Kazaz, İ., Avşar, Ö., & Dilsiz, A. (2024). Importance of building inspection on the seismic response of a severely damaged RC structure during the February 6, 2023 Kahramanmaraş earthquake sequence. *Engineering Failure Analysis, 162*, 108410.

66.Kazaz, İ., Bilge, İ. H., & Gürbüz, M. (2024). Near-fault ground motion characteristics and its effects on a collapsed reinforced concrete structure in Hatay during the February 6, 2023 Mw 7.8 Kahramanmaraş earthquake. Engineering Structures, 298, 117067. https://doi.org/10.1016/j.engstruct.2023.117067.

67.Ko, Y. Y., Tsai, C. C., Hwang, J. H., Hwang, Y. W., Ge, L., & Chu, M. C. (2023). Failure of engineering structures and associated geotechnical problems during the 2022 ML 6.8 Chihshang earthquake, Taiwan. Natural Hazards, 118(1), 55-94.

68.Kuang, J. S., & Ho, Y. B. (2008). Seismic behavior and ductility of squat reinforced concrete shear walls with nonseismic detailing. *ACI Structural Journal, 105*(2), 225–234.

69.Kucukgoncu, H., & Altun, F. (2020). The seismic behaviour of RC exterior shear walls used for strengthening of intact and damaged frames. *Bulletin of Earthquake Engineering, 18*(8), 3683–3709.

70.Kumar, P., Madhuri, S., & Ahmed, M. (2025). Sequential nonlinear time history analysis of asymmetric reinforced concrete buildings under the 2011 Great Japan earthquake and tsunami. *Buildings, 15*(13), 2170.

71.Landolfo, R., D'Aniello, M., Safaei, S., Fiorino, L., Di Sarno, L., Le Maoult, A., & Rastiello, G. (2025). Shake table test on a steel moment resisting frame with nonstructural elements. *Engineering Structures, 333*, 120191.

72.Lemnitzer, A., Massone, L. M., Skolnik, D. A., de la Llera Martin, J. C., & Wallace, J. W. (2014). Aftershock response of RC buildings in Santiago, Chile, succeeding the magnitude 8.8 Maule earthquake. *Engineering structures, 76*, 324-338.

73.Lin, M. L., Lin, C. H., Li, C. H., Liu, C. Y., & Hung, C. H. (2021). 3D modeling of the ground deformation along the fault rupture and its impact on engineering structures: Insights from the 1999 Chi-Chi earthquake, Shigang District, Taiwan. Engineering Geology, 281, 105993.

74.Mercimek, Ö., Anıl, Ö., Akkaya, S. T., Erdem, R. T., Çelik, A., Kopraman, Y., & Abukan, A. (2025). Experimental behavior of shear deficient RC beams strengthened with CFRP strips against reversible cyclic earthquake load. *Structural Concrete*.

75.Ministry of Public Works and Settlement. (2007). *Specification for buildings to be built in seismic zones (Turkish Earthquake Code 2007)*. Ankara, Turkiye.

76.Müderrisoğlu, Z., Dindar, A. A., Bozer, A., Özkaynak, H., Güllü, A., Güngör, B., & Hasanoğlu, S. (2023). A quantitative investigation on the effects of flexure-dominated reinforced concrete column characteristics on the dissipated energy. *Turkish Journal of Civil Engineering, 35*(2), 87–102.

77.Narlitepe, F., Kian, N., Demir, U., Demir, C., & İlki, A. (2025). A novel hybrid thin jacketing method for seismic retrofitting of substandard reinforced concrete columns. *Engineering Structures, 342*, 120879.

ARTICLE IN PRESS

78.Nascimbene, R., & Bianco, L. (2021). Cyclic response of column to foundation connections of reinforced concrete precast structures: numerical and experimental comparisons. *Engineering Structures*, *247*, 113214.

79.O'Reilly, G. J., & Calvi, G. M. (Eds.). (2025). *Engineering Research Infrastructures for European Synergies: Proceedings of ERIES-IW2025* (Vol. 718). Springer Nature.

80.Olabi, M. N., Dok, G., & Çağlar, N. (2026). Collapse prevention limit states for substandard RC shear walls using a novel bond-slip-based steel model. *Bulletin of Earthquake Engineering*, 1–31.

81.Ozkul, T. A., Kurtbeyoglu, A., Borekci, M., Zengin, B., & Kocak, A. (2019). Effect of shear wall on seismic performance of RC frame buildings. *Engineering Failure Analysis, 100*, 60–75.

82.Ozturk, M., Arslan, M. H., & Korkmaz, H. H. (2023). Effect on RC buildings of 6 February 2023 Turkey earthquake doublets and new doctrines for seismic design. *Engineering Failure Analysis*, *153*, 107521.

83.Ozturk, M., Arslan, M. H., Dogan, G., Ecemis, A. S., & Arslan, H. D. (2023). School buildings performance in 7.7 Mw and 7.6 Mw catastrophic earthquakes in southeast of Turkey. *Journal of Building Engineering*, *79*, 107810.

84.Pandey, M., Viljoen, C., Way, A., Fischer, K., Sýkora, M., Diamantidis, D., ... & Lenner, R. (2025). Life safety in the Reliability-Based design and assessment of structures. *Structural Safety*, *113*, 102453.

85.Peker, F. Ü., Yuzbasi, J., Işık, E., Büyüksaraç, A., & Avcil, F. (2025, October). Damage assessment, regional ground motion record evaluation, and seismic performance analysis of a high-rise 14-story dual system building after the 2023 Kahramanmaraş earthquakes. In *Structures* (Vol. 80, p. 109897). Elsevier.

86.Peng, W. J., Li, Z. A., & Tao, M. X. (2023). Evaluation of performance and storey drift ratio limits of high-rise structural systems using time history and incremental dynamic analysis. *Structures, 56*, 104961.

87.Pinzón, L. A., Hidalgo-Leiva, D. A., Alva, R. E., Mánica, M. A., & Pujades, L. G. (2023). Correlation between seismic intensity measures and engineering demand parameters of reinforced concrete frame buildings through nonlinear time history analysis. *Structures, 57*, 105276.

88.Qin, W., Xi, Z., Liu, X., Feng, P., Ou, X., & Yang, J. (2022). Experimental and theoretical analyses of the progressive collapse resistance of NSM strengthening RC frames after the failure of a corner column. Journal of Building Engineering, 47, 103805. https://doi.org/10.1016/j.jobe.2021.103805.

89.Rubini, G., Calvi, G. M., & Gentile, R. (2025). Direct loss-based seismic retrofit of reinforced concrete frames. *Bulletin of Earthquake Engineering*, *23*(1), 327-357.

90.Saeed, N. M., Ali, B. H., Bigonah, M., Jamal, A. S., & Hassan, H. Z. (2025). Impact of structure height on retrofitted RC structures for progressive collapse prevention. *Journal of Building Pathology and Rehabilitation*, *10*(1), 1-32.

91.Scalvenzi, M., Gargiulo, S., Freddi, F., & Parisi, F. (2022). Impact of seismic retrofitting on progressive collapse resistance of RC frame structures. Engineering Failure Analysis, 131, 105840. https://doi.org/10.1016/j.engfailanal.2021.105840.

92.Sert, H., Horzum, M. B., Eren, M. G., Pelin, M., & Ucgul, K. (2024). The disaster of the century, Kahramanmaras earthquake: A qualitative study on the experiences of the earthquake victims and search and rescue teams. *International Journal of Disaster Risk Reduction*, *107*, 104462.

93.Sivrikaya, O., Türker, E., Cüre, E., Atmaca, E. E., Angin, Z., Başağa, H. B., & Altunişik, A. C. (2025). Impact of soil conditions and seismic codes on collapsed structures during the 2023 Kahramanmaraş earthquakes: An in-depth study of 400 reinforced concrete buildings. Soil Dynamics and Earthquake Engineering, 190, 109119. https://doi.org/10.1016/j.soildyn.2024.109119.

94.Takagi, J., & Wada, A. (2019). Recent earthquakes and the need for a new philosophy for earthquake-resistant design. *Soil Dynamics and Earthquake Engineering*, *119*, 499-507.

95.Tan, M. T., Binici, B., Kale, O., & Ozcebe, G. (2025). The successful performance of a reinforced concrete building with FRP strengthened infill walls and externally installed shear walls subjected to Kahramanmaras and Hatay 2023 earthquakes. Bulletin of Earthquake Engineering, 23(3), 1183-1202. https://doi.org/10.1007/s10518-024-02062-0.

ARTICLE IN PRESS

96.Tan, M., Avşar, Ö., Yıldızhan, F., & Atmaca, N. (2025). Effect of infill walls on the seismic performance of a severely damaged substandard RC building during the February 6, 2023, Kahramanmaras earthquake sequence. *Engineering Failure Analysis*, *169*, 109117.

97.TBEC, Turkish Building Earthquake Code 2018, Republic of Türkiye Ministry of Interior Disaster and Emergency Management Authority, Ankara, Türkiye, 2018.

98.TS 500. (2000). *Betonarme yapıların tasarım ve yapım kuralları*. Türk Standartları Enstitüsü.

99.Tura, C., Orakcal, K., Kusunoki, K., & İlki, A. (2025). Seismic response simulation of a reinforced concrete wall-frame building that collapsed during the February 2023 Kahramanmaraş earthquake. *Journal of Earthquake Engineering*, *29*(16), 3423–3447.

100.Türkiye Cumhuriyeti Cumhurbaşkanlığı (2023). *2023 Kahramanmaraş ve Hatay depremleri raporu*. Retrieved April 20, 2023, from https://www.sbb.gov.tr/wp-content/uploads/2023/03/2023-Kahramanmaras-ve-Hatay-Depremleri-Raporu.pdf

101.Uysal, Y., Ecemiş, A. S., Aksoylu, C., & Arslan, M. H. (2025). Effects of shear wall ratio and location on Earthquake performance of reinforced concrete buildings having different ribbed slab configurations. *Journal of Building Engineering*, 113958.

102.Vuran, E., Serhatoğlu, C., Timurağaoğlu, M. Ö., Smyrou, E., Bal, İ. E., & Livaoğlu, R. (2025). Damage observations of RC buildings from 2023 Kahramanmaraş earthquake sequence and discussion on the seismic code regulations. *Bulletin of Earthquake Engineering*, *23*(3), 1153-1182.

103.Wang, W., Li, L., Chen, J., & Dai, K. (2025). Experimental and analytical study on flexural behavior of corroded RC beams strengthened with CFRP rods and UHPC. *Engineering Structures*, *323*, 119299.

104.Wang, W., Xie, M., Xu, Z., Liao, J., Abdullah, M., & Zhang, M. (2025). A comparative experimental study on seismic retrofitting techniques for RC frames: RC jacketing, steel jacketing, and base isolation. *Buildings*, *15*(19), 3539.

105.Wang, Z., Li, Z., & Feng, P. (2023). Cyclic axial compressive performance of the RC columns reinforced with FRP confined concrete core encased rebar. Engineering Structures, 274, 115166. https://doi.org/10.1016/j.engstruct.2022.115166

106.Wang, Z., Li, Z., Yang, J. Q., Huang, F., & Feng, P. (2022). Axial compressive and seismic performance of GFRP wrapped square RC columns with different scales. Journal of Building Engineering, 62, 105342. https://doi.org/10.1016/j.jobe.2022.105342.

107.Wen, Y., Cai, G., Malla, P. B., Kikuchi, H., & Xie, C. (2024). Seismic behavior of resilient reinforced concrete columns with ultra-high-strength rebars under strong earthquake-induced multiple reversed cyclic loading. *Buildings*, *14*(12), 3747.

108.Wu, H., Lu, J. X., & Cheng, Y. H. (2025). Collapse analysis approach of RC frame structures under earthquake-explosion disaster chains. *Engineering Structures*, *338*, 120613.

109.Xiao, Z., Wang, L., & Huang, R. (2026). Seismic performance of reinforced concrete beam column joints strengthened with ECC shells. *Scientific Reports*, 16, 8137.

110.Yang, J. Q., Feng, P., Liu, B., Wang, H., Zhao, W., & Hu, L. (2022). Strengthening RC beams with mid-span supporting prestressed CFRP plates: An experimental investigation. *Engineering Structures*, *272*, 115022. https://doi.org/10.1016/j.engstruct.2022.115022.

111.Yön, B., Dedeoğlu, İ. Ö., Yetkin, M., Erkek, H., & Calayır, Y. (2025). Evaluation of the seismic response of reinforced concrete buildings in the light of lessons learned from the February 6, 2023, Kahramanmaraş, Türkiye earthquake sequences. *Natural Hazards*, *121*(1), 873-909.

112.Yuzbasi, J. (2024a). Post-Earthquake Damage assessment: Field observations and recent developments with recommendations from the Kahramanmaraş earthquakes in Türkiye on February 6th, 2023 (Pazarcık M7. 8 and Elbistan M7. 6). *Journal of Earthquake Engineering*, 1-26.

113.Yuzbasi, J. (2025a). Controlled demolition: novel monitoring and experimental validation of blast-induced full-scale existing high-rise building implosion using numerical finite element simulations. *Journal of Civil Structural Health Monitoring*, *15*(3), 891-914.

114.Yuzbasi, J. (2025b). Fundamentals of Controlled Demolition in Structures: Real-Life Applications, Discrete Element Methods, Monitoring, and Artificial Intelligence-Based Research Directions. *Buildings*, *15*(19), 3501.

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115.Yuzbasi, J., & Arslan, H. M. (2025, March). Applied element method and Finite element method for progressive collapse assessment: A comparative study on the influence of slab types, thicknesses, and damping via three incremental column removals. In *Structures* (Vol. 73, p. 108358). Elsevier.

116.Yuzbasi, J., Hadzima-Nyarko, M., Işık, E., Demirci, A., Harirchian, E., Büyüksaraç, A., Avcil, F., & Özçelik, A. (2026). Influence of shear wall area-to-floor area ratios and configurations on the seismic response of tall RC building structures: An overview of Adana after the 2023 Kahramanmaraş earthquakes. *Buildings*, *16*(9), 1658.

117.Yüzbaşı, J., & Yerli, H. R. (2018). Betonarme yapıların deprem etkisi altında performans analizlerinin yapılması ve güçlendirilmesi. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, *33*(2), 273-286.

118.Zad, N., & Melhem, H. (2021). A parametric study on the effects of shear wall locations in a typical five-story reinforced concrete structure subjected to a severe earthquake. *Current Trends in Civil & Structural Engineering*, *7*(5), 1–15.

119.Zhang, Y., & Mueller, C. (2017). Shear wall layout optimization for conceptual design of tall buildings. Engineering Structures, 140, 225-240.

120.Zhao, B., Taucer, F., & Rossetto, T. (2009). Field investigation on the performance of building structures during the 12 May 2008 Wenchuan earthquake in China. Engineering Structures, 31(8), 1707-1723.

ARTICLE IN PRESS