

## Seismic Progressive Collapse Response of Older Reinforced Concrete Structures with Pre-Existing Column Cuts

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Progressive Collapse,  
Older RC Buildings With Pre-Cut Columns,  
Outdated Seismic Codes,  
Seismic Vulnerability,  
Nonlinear Dynamic Analysis

**Abstract:** The February 6, 2023, Kahramanmaraş earthquakes in Türkiye caused severe structural failures, particularly in older reinforced concrete (RC) buildings. A key factor in these collapses was the presence of pre-existing column cuts on ground floors, significantly compromising structural integrity. This study investigates the progressive collapse (PC) behavior of older RC buildings with pre-cut columns under gravity and seismic loads. Two numerical models, representing a low-rise (5-story) and mid-rise (10-story) RC structure, were developed based on the Turkish Earthquake Codes of 1975 and 1998. The PC analysis employed nonlinear dynamic simulations using SAP2000, considering three ground-floor column removal scenarios: exterior corner, edge, and interior columns. Findings reveal that TEC-1998 structures exhibited improved PC resistance under gravity loads compared to TEC-1975 designs, yet both remained highly vulnerable at exterior columns. Under a simulated Mw 7.7 magnitude earthquake, all models experienced ground-floor column failures, leading to total collapse. These results highlight the inadequacy of outdated seismic codes and the urgent need to retrofit pre-2000 RC buildings to meet modern seismic standards. This study contributes to seismic engineering by emphasizing the impact of structural modifications in older RC buildings and advocating for advanced retrofitting strategies to enhance resilience against PC and earthquake-induced failures.

## Önceden Kesilmiş Kolonlara Sahip Eski Betonarme Yapıların Sismik İlerlemeli Göçme Tepkisi

### Anahtar Kelimeler

İlerlemeli Göçme (PC),  
Kesilmiş Kolona Sahibi Eski BA Binalar,  
Eski Deprem Yönetmelikleri,  
Sismik Kırılabilirlik,  
Doğrusal Olmayan  
Dinamik Analiz

**Öz:** 6 Şubat 2023 tarihinde Türkiye'nin Kahramanmaraş ili merkezli meydana gelen depremler, özellikle eski betonarme binalarda ciddi yapısal hasar ve göçmelere neden olmuştur. Bu göçme olaylarının başlıca nedenlerinden birisi, bazı binaların zemin katlarındaki kesilmiş kolonların bulunması ve bu durumun yapısal bütünlüğü ciddi biçimde zayıflatmasıdır. Bu çalışmada, kolonları önceden kesilmiş eski binaların, düşey ve deprem yükleri etkisi altındaki ilerlemeli göçme (PC) davranışları incelenmektedir. Türkiye Deprem Yönetmeliği 1975 ve 1998 esas alınarak, birisi düşük katlı (5 katlı), diğeri orta katlı (10 katlı) olmak üzere iki nümerik model oluşturulmuştur. PC analizleri, SAP2000 programında doğrusal olmayan dinamik analiz yöntemiyle gerçekleştirilmiş ve zemin katta üç farklı kolon kaldırma senaryosu (köşe, kenar ve iç kolon) değerlendirilmiştir. Çalışma sonuçları, 1998 Deprem Yönetmeliği'ne göre tasarlanmış yapıların, 1975 yönetmeliğine göre tasarlananlara kıyasla düşey yük etkileri altında daha yüksek PC dayanımı sergilediğini göstermektedir. Ancak, her iki durumda da dış kolonlar açısından yüksek derecede kapasite yetersizlikleri gözlemlenmiştir. Gerçekleştirilen Mw 7,7 büyüklüğündeki deprem senaryosu altında tüm binalarda zemin kat kolonlarının hasar aldığı ve yapının tamamen çöktüğü belirlenmiştir. Elde edilen sonuçlar, eski deprem yönetmeliklerinin yetersizliğini ortaya koymakta ve 2000 yılı öncesi inşa edilen betonarme yapıların güncel deprem yönetmeliklerine uygun olarak tekrar

değerlendirilmesi gerekliliğine dikkat çekmektedir. Bu çalışma, eski betonarme binalardaki yapısal değişikliklerin yapının sismik performans üzerindeki önemini vurgulamakta ve PC ile deprem kaynaklı göçmelere karşı dayanımı artırmaya yönelik güçlendirme stratejilerinin gerekliliğini ortaya koymaktadır.

## 1. Introduction

Considering that a significant portion of Türkiye's building stock consists of reinforced concrete (RC) structures [1], the impact of the February 6, 2023, earthquakes in Kahramanmaraş region was particularly severe. These earthquakes, with epicenters in Pazarcık and Elbistan, had moment magnitudes of 7.7 and 7.6 respectively, are recorded as the second and third largest in Türkiye's history [2]. These earthquakes resulted in widespread structural failures, with 518,009 residential buildings either demolished, heavily damaged, or collapsed, 86.7% of which were constructed with RC [3]. Most of these failures occurred in buildings constructed before 2000, a period characterized by rare or non-existent site inspections, and used RC construction, which is common in Turkey [4-6].

One of the concerning factors contributing to building collapses during the Kahramanmaraş earthquakes was the presence of pre-existing column cuts at the ground floor. These modifications, often made to create open spaces for commercial use, significantly weakened the buildings' load path, making them highly susceptible to progressive collapse. Notable examples include the Ezgi Apartment in Kahramanmaraş [7] and the Emre Apartment in Gaziantep [8-9], both of which are currently under investigation for structural alterations involving column removal. Similar cases in Türkiye, such as the Küçükçekmece building collapse in Istanbul [10] and the Zümrüt Apartment collapse in Konya [11], highlight the risks associated with column removal. Both cases initially faced allegations of column cutting. However, in the case of Zümrüt Apartment, these allegations were later supported by the study "Lessons Learned from Collapse of Zümrüt Building under Gravity Loads" by Can Balkaya [12], which identified that the building's progressive collapse was initiated by the failure of ground-level columns that could not adequately redistribute loads due to poor material quality and lack of structural continuity. Although the Zümrüt Apartment and Küçükçekmece building collapses were not directly caused by seismic activity, they illustrated how column modifications and inadequate structural detailing can lead to progressive collapse even under gravity loads.

Progressive collapse (PC) occurs when the initial failure of an element within a structure spread to the other elements of the structure, leading to the partial or total collapse of the entire structure [13]. The removal of a vertical load-bearing element, such as column, can lead to PC if the structure is unable to adequately redistribute its loads. Yön et al. [14] observed that in the aftermath of the Kahramanmaraş earthquake, significant damage to RC structures was caused by the reduction or removal of columns and shear walls, which weakened the structural integrity and contributed to the failure of entire buildings.

Several studies on PC in RC structures under various conditions have globally been carried out. Dat et al. [15] proposed a simplified method to assess the PC resistance of ordinary RC structures under penultimate column loss, emphasizing beam bottom reinforcement continuity through beam-column connection to mitigate collapse. Sanglikar et al. [16] used nonlinear static pushdown analysis in ETABS to evaluate PC under different column removal scenarios, identifying corner and perimeter column removals as the most critical. Nakamura and Yoshimura [17] investigated structural failures during the 1995 Kobe earthquake, finding that PC was strongly influenced by axial loads and loading history. Helmy et al. [18] analyzed a 10-story RC structure using the Applied Element Method, revealing that buildings designed according to ACI318-08 failed to meet UFC standards. Other studies, such as Elshaer et al. [19] and Brunesi et al. [20] analyzed PC using different computational approaches. Elshaer et al. conducted 3D nonlinear dynamic analyzes with the Applied Element Method to evaluate column loss in multi-story buildings, finding seismic induced failure more critical than gravity induced failure. Brunesi et al. developed fragility functions and fiber-based finite element models to simulate story column removal, incorporating nonlinear responses and Mento Carlo simulations to account for uncertainties.

Despite these global studies, limited research has focused on Turkish RC buildings designed according to the Turkish Earthquake Code (TEC). Demir [21-23] examined the PC responses of various RC structures, including low and mid-rise mercantile buildings, low-rise residential and government RC buildings, and government buildings designed according to the Turkish Seismic Code (TSCB-2019) and TEC-2018. Using nonlinear dynamic analysis with UFC 4-023-03 and GSA-2016 guidelines under column removal scenarios, the studies reveal that mercantile buildings require additional design considerations, while residential buildings experience higher residual displacements compared to government buildings in column loss scenarios. Additionally, Demir [24]

investigated the PC behavior of government buildings designed according to updates of TSC in 2007 and 2019, finding that the building designed according to TSC-2019 is more robust against PC than the previous TSC-2007. Gondobwe and Demir's study [25] found that high-rise buildings designed according to TEC-2018 exhibited sufficient resistance to PC, while Ozgan et al. [26] highlighted the importance of considering soil-structure interaction in PC evaluations.

Türkiye's seismic regulations have evolved significantly since the 1939 Erzincan earthquake, with major updates in 1975, 1998, 2007, and 2018. The 1975 code introduced structural system classifications, while the 1998 update refined earthquake load calculations. Following the 1999 Izmit and Duzce earthquakes, the 2007 revision focused on improving RC structures, and the 2018 update incorporated new rules for high-rise and steel structures, as well as updated seismic calculation methods [27]. Despite these advancements, Turkey's building stock, particularly in earthquake-prone regions, faces challenges due to rapid urbanization and insufficient building regulations. Unplanned growth and rural migration have led to inadequate housing, often lacking legal approval or relying on amnesty laws. Enforcement of building inspection laws has been poor, with 91% of projects showing design flaws and concrete strength falling 40% below standards [28].

To the best of the authors' knowledge, no prior study conducted in Türkiye has performed a detailed analysis of PC behavior in RC structures with pre-existing column cuts, particularly within the context of older buildings constructed under outdated Turkish seismic codes. Given the significant structural damage observed in the Kahramanmaraş earthquakes, this study aims to enhance public safety by identifying vulnerabilities in such buildings and assessing the impact of pre-cut ground floor columns on the PC behavior of RC structures built before 2000 in Kahramanmaraş, Türkiye. Two building models will be designed as low-rise, and mid-rise RC structures, according to the older versions of Turkish Earthquake Codes (TEC-1975 and TEC-1998). Two scenarios will be investigated: (a) PC response under gravity loads, and (b) the seismic response of 7.7 magnitude earthquakes on structures located in Kahramanmaraş, having, and not having pre-cut columns. A numerical study will be conducted using the finite element method (FEM), incorporating nonlinear dynamic analysis techniques. The PC assessment will be performed in accordance with the Alternative Path (AP) method specified in the Unified Facilities Criteria (UFC 4-023-03) and the General Services Administration (GSA-2016) guidelines. The novelty of this study lies in its focus on an overlooked yet critical structural modification (ground-floor column cuts) within the framework of outdated seismic codes and dual load scenarios. By integrating the analysis with real-world failure patterns, the study offers original insights into the structural vulnerabilities of Türkiye's aging RC building stock and makes a valuable contribution to field of seismic engineering.

## 2. Materials and Methods

This study numerically examines the progressive collapse (PC) behavior of RC structures built before 2000 in Kahramanmaraş, Türkiye, giving that significant seismic code advancements were introduced after that period. Two RC buildings, a low-rise (5-story) and mid-rise (10-story) structure, are initially designed using the civil engineering software ideCAD [29], in accordance with the Turkish Earthquake Codes (TEC-1975 and TEC-1998). The buildings' location is assumed to be in Kahramanmaraş, Türkiye, which is classified as a first-degree seismic zone under Turkish seismic regulations. The site conditions are considered as Z2 soil type, based on geotechnical data from AFAD station reports. The soil-structure interaction report of the relevant seismic station describes the topsoil as "brown, gravelly, clayey sand; dense to very dense," which corresponds to Z2 classification in Turkish seismic codes. Although the measured shear wave velocity could suggest a softer classification (e.g., Z3 in the 1975 code), the soil description supports the use of Z2 for both 1975 and 1998 code-based analyses. This consistent classification ensures uniformity across design scenarios and reflects a realistic representation of the local site conditions. These seismic and geotechnical parameters were considered during structural design to accurately reflect the expected performance under both gravity and seismic loading.

Both structures will utilize C25 concrete with a characteristic compressive strength of 25 MPa, and S220-grade reinforcing steel, which has a yield strength of 220 MPa. The buildings will have overall dimensions of 18x24 meters. The shorter side will be divided into four bays measuring 5m, 4m, 4m, and 5m, while the longer side will consist of five spans of 5m, 5m, 4m, 5m, and 5m. Each story will have a constant floor height of 3 meters. Architectural plans and elevations, including the layout of beams and columns, are provided in Figure 1 highlighting critical columns considered for removal in PC analysis.

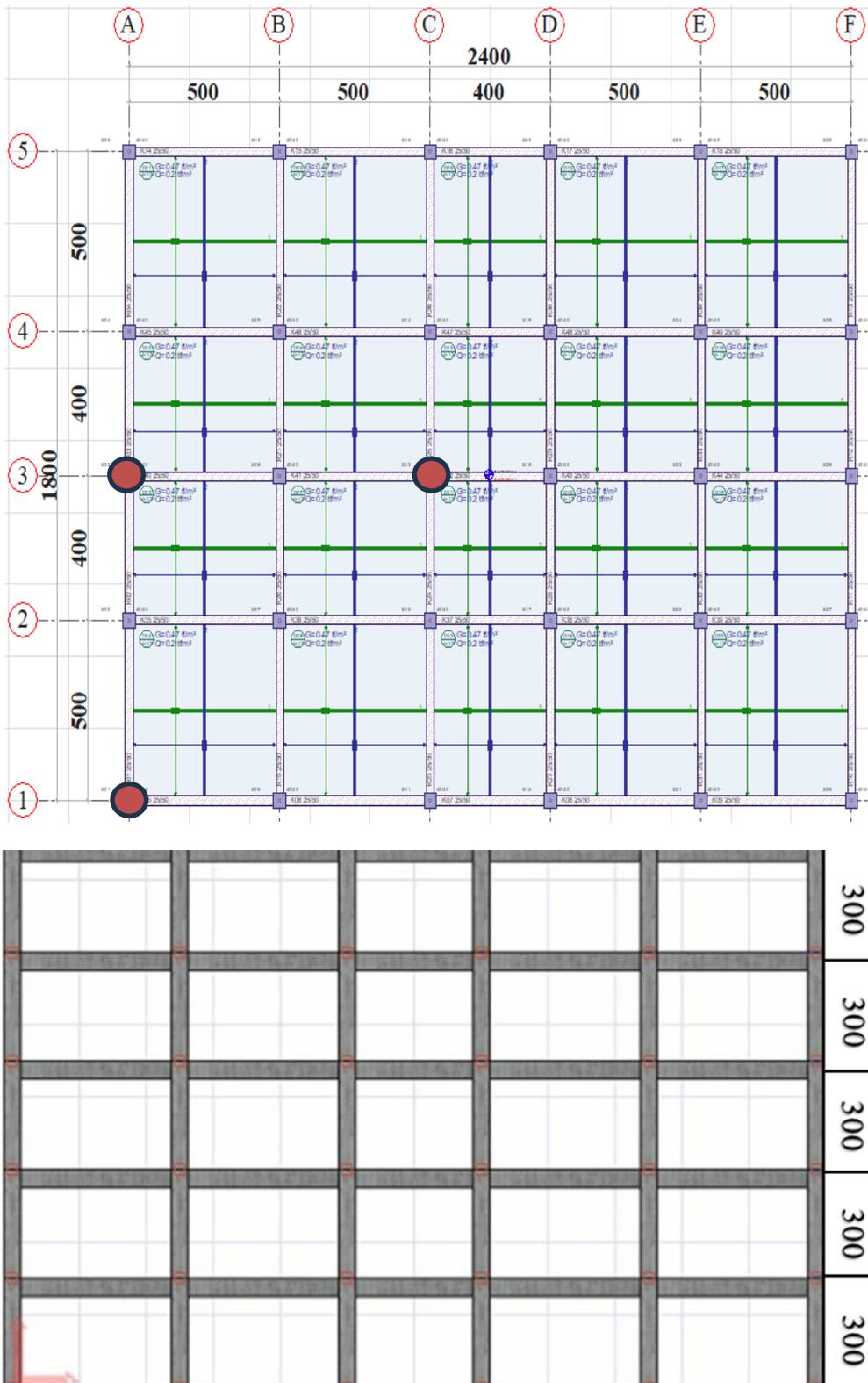


Figure 1. Building Plan (top) and elevation (bottom) views of the buildings (dimensions in cm)

For the 5-story building designed according to TEC-1975, columns will have a uniform cross-section of 40x40 cm, beams will measure 25x50 cm, and slabs will be 12 cm thick. According to TEC-1998, column dimensions will increase to 45x45 cm, while beams and slab thickness will remain unchanged. In the 10-story building, column sizes will vary. According to TEC-1975, the first four stories will have 50x50 cm columns, reducing to 45x45 cm for the 5th to 7th stories and 40x40 cm for the upper three stories. Beam sections will be 25x50 cm throughout, with a constant slab thickness of 12 cm. For TEC-1998, column dimensions will increase to 55x55 cm for the first four stories, 50x50 cm for the 5th to 7th stories, and 45x45 cm for the top floors. Beam sections will be enlarged to 30x50 cm, while slab thickness will remain at 12 cm. Figure 2 will provide sample cross-sectional details of columns and beams, and Table 1 will summarize geometrical and reinforcement details.

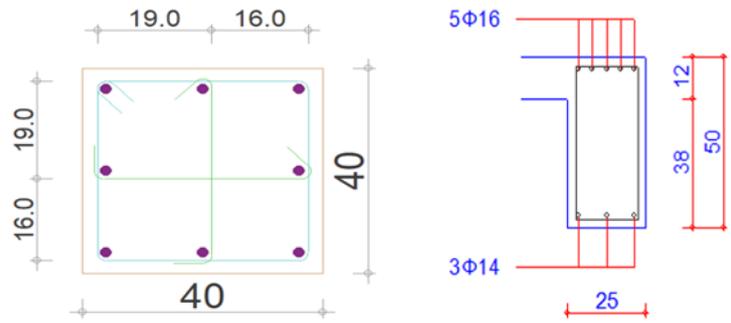


Figure 2. Sample Section Detail of Columns (left) and Beams (right)

Table 1. Geometrical and reinforcing details of the sections

Type of Building	Code	Section Type	B (cm)	H (cm)	Longitudinal Bars		Top Bars	Bottom Bars	Stirrups & Ties	s [cm]
					Major Bars	Minor Bars				
5-Story	TEC-1975	Column	40	40	6φ16	2φ16	-	-	φ8	10
		Beam	25	50	-	-	5φ14	3φ14	φ8	10
	TEC-1998	Column	45	45	8φ16	4φ16	-	-	φ8	11
		Beam	25	50	-	-	5φ16	4φ14	φ8	10
10-Story	TEC-1975	Column (1-4)	50	50	10φ16	4φ16	5φ16	5φ16	φ8	10
		Column (5-7)	45	45	8φ16	4φ16	-	-	φ8	10
		Column (8-10)	40	40	6φ16	2φ16	-	-	φ8	10
		Beam	25	50	-	-	10φ16	6φ14	φ8	10
	TEC-1998	Column (1-4)	55	55	10φ16	6φ16	-	-	φ8	10
		Column (5-7)	50	50	10φ16	4φ16	-	-	φ8	10
		Column (8-10)	45	45	8φ16	4φ16	-	-	φ8	16
		Beam	30	50	-	-	6φ16	4φ16	φ8	10

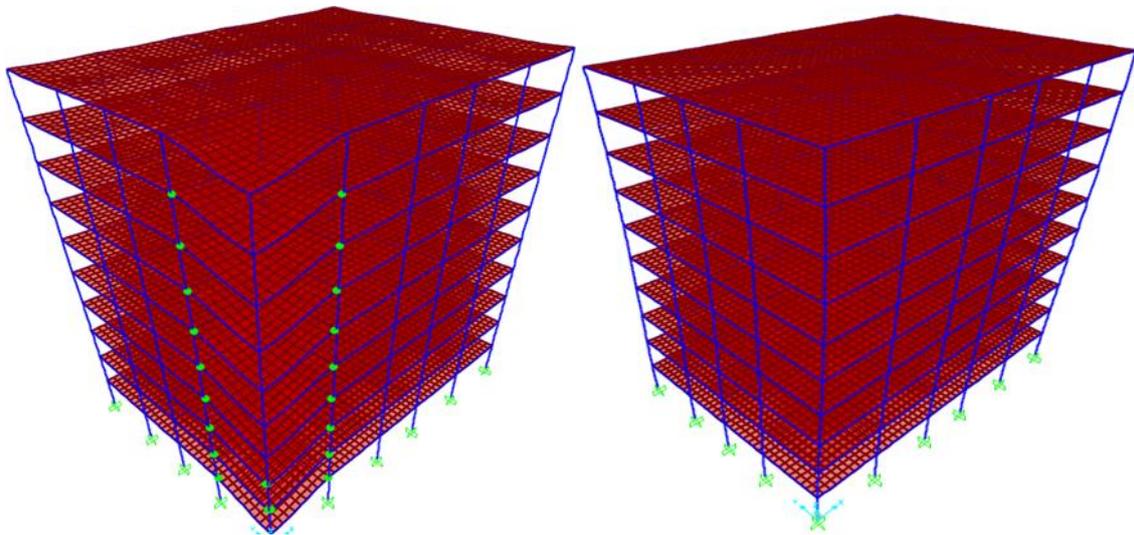
The PC analysis will be conducted using the Nonlinear Dynamic Analysis Method within the Alternate Path (AP) design approach, as specified by the Unified Facilities Criteria (UFC 4-023-03) and General Services Administration (GSA-2016) guidelines [30-31]. These standards provide design strategies to mitigate PC in new and existing governmental and military buildings that may be vulnerable to localized structural damage from unpredictable extreme events. The AP method requires structures to bridge over removed vertical elements at critical locations. Among the three AP analysis methods, Linear Static (LS), Nonlinear Static (NS), and Nonlinear Dynamic (ND), ND is chosen for its ability to accurately capture the response of geometrically irregular buildings.

The analysis was executed using the finite element software SAP2000 [32], utilizing plastic hinges to simulate the nonlinear behavior of structural members. Three column removal scenarios were considered at the ground floor of each model: (1) an exterior corner column, (2) an edge column, and (3) an interior column near the center of the building. The SAP2000 column removal tool was used, selecting the "frame" object type and specifying the corresponding frame element IDs for each scenario. Following standard practice, the total analysis time was set to 5 seconds, discretized into 500-time steps of 0.01 seconds each. The initiation of the column removal was scheduled to occur 0.5 seconds after the completion of the gravity load case, allowing the structure to stabilize under gravity-induced displacements and to avoid the introduction of artificial dynamic effects due to abrupt load changes. The duration of the removal process was set to one-tenth of the fundamental period of each structure. Table 2 presents the fundamental periods of the models considered, as well as the corresponding removal durations.

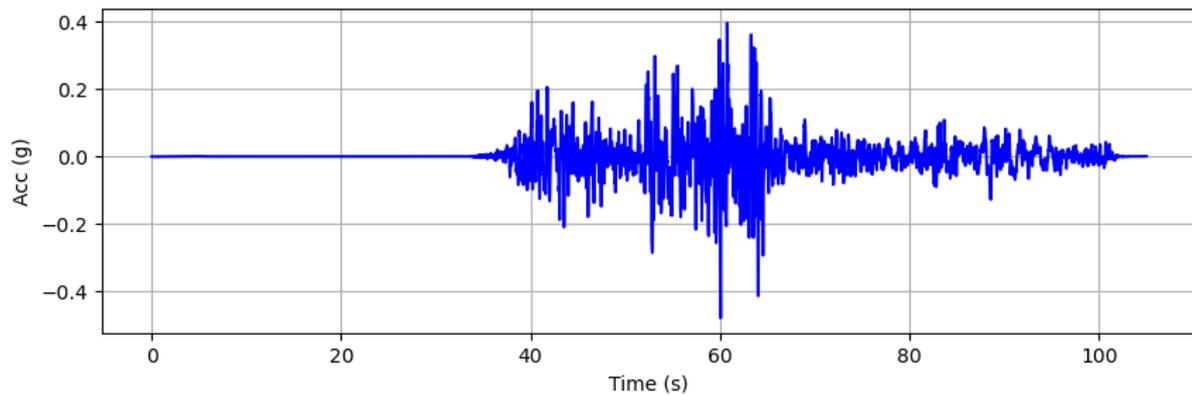
**Table 2.** Fundamental periods of the analyzed models and corresponding column removal durations

Type of Building	Code	Fundamental Period (S)	Removal Duration (S)
5-Story	TEC-1975	1.16	0.12
	TEC-1998	1.07	0.11
10-Story	TEC-1975	2.14	0.21
	TEC-1998	1.95	0.20

A nonlinear direct integration time-history analysis was conducted, starting from the deformed configuration obtained after the gravity load case. The Newmark method was employed for time integration, using parameters  $\gamma = 0.5$  and  $\beta = 0.25$ . A 5% damping ratio was applied using direct integration damping, where SAP2000 automatically computed the mass and stiffness proportional coefficients based on the structure's first period (fundamental mode) and second mode (the first mode exceeding 90% participation in X, Y, and torsion). The "Consider Collapse" option and P-Delta effects with large displacement were activated to accurately capture the PC behavior. This procedure was repeated for 12 different scenarios, implemented across four different models, with three scenarios per model. Figure 3 presents a 3D view of the SAP2000 finite element model both before and after column removal, using the removal of a corner column as a representative example. The structural response was assessed based on key parameters, including the time-history response of nodes above the removed columns, hinge rotations, hinge damage states, and overall structural damage. These evaluations provided insights into the vulnerability of the buildings to PC.

**Figure 3.** 3D illustration of column removal scenario before (left) and after (right) column removal

The ground motion data used in the analysis was obtained from the AFAD strong motion database [33]. Specifically, acceleration records from the Dulkadiroğlu district in Pazarlık (Kahramanmaraş) (Station Code: 4625) were utilized. This station recorded the mainshock of the 6 February 2023 Pazarlık earthquake (Mw 7.7). Located at 37.288°N, 37.043°E and approximately 8.6 km from the epicenter, it provided high quality near fault ground motion data. These acceleration time histories were downloaded from AFAD in processed form and used directly in the nonlinear time-history analysis. Figure 4 presents a sample acceleration time-history from the Pazarlık station in the X-direction.

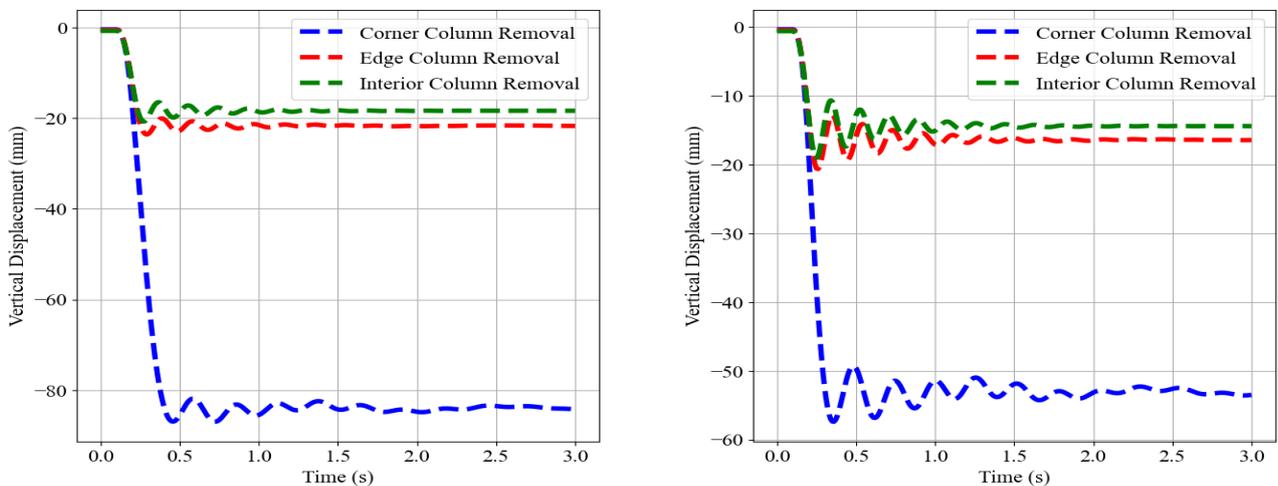
**Figure 4.** Acceleration time history (X-direction) from the 6 February 2023 Pazarlık earthquake

### 3. Results and Discussions

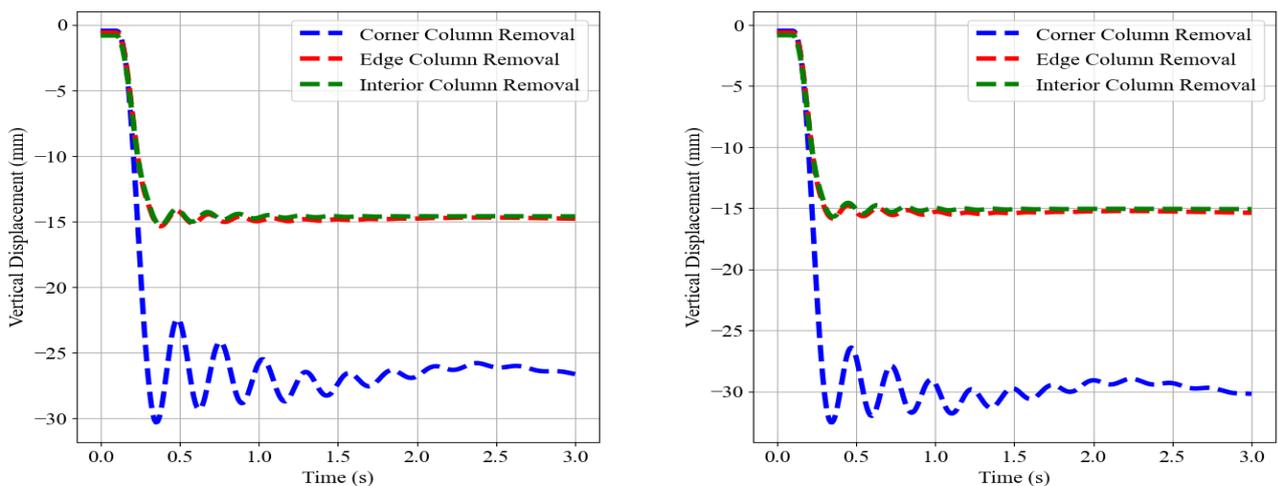
This section presents the results of the study, focusing on the progressive collapse (PC) response of older RC structures under gravity loads and seismic excitation. The findings provide critical insights into the structural vulnerabilities of low-rise and mid-rise buildings in Kahramanmaraş, Türkiye, particularly in cases where ground-floor columns have been removed or compromise. The discussion evaluates the influence of seismic code provisions, structural configurations, and column removal scenarios on the overall stability and damage propagation of these structures. The performance assessment was conducted in accordance with the assessment procedures defined in section 15.8 of TEC-2018 for existing buildings, aligning with the study’s objective of investigating the effect of column cuts on collapse behavior.

#### 3.1 PC Analyzes Under Gravity Loads

The time-history results for vertical displacement of the nodes above the removed column are illustrated in Figures 5-6, corresponding to various column removal cases. The PC analysis under gravity loads, as summarized in Table 3, highlights the structural vulnerabilities of older RC buildings in Kahramanmaraş, Türkiye, particularly in response to column removal. These findings support concerns raised after the Kahramanmaraş earthquakes that prior column cuts at the ground-floor significantly impact structural stability.



**Figure 5.** Vertical Displacement Time-history of the Node Above the Removed Columns for Different Column Removal Cases in the 5-story buildings —TEC-1975 (Left) and TEC-1998 (Right)



**Figure 6.** Vertical Displacement Time-history of the Node Above the Removed Columns for Different Column Removal Cases in the 10-story buildings —TEC-1975 (Left) and TEC-1998 (Right)

**Table 3.** Summary of Displacement and Damage States from PC Analysis Under Gravity Loads

Type of Building	Code	Column Removal Scenarios	Maximum Displacement (mm)	Residual Displacement (mm)	Overall Performance of the Building
5-Story	TEC-1975	Corner Column	-86.96	-84.20	Limited Damage
		Edge Column	-23.60	-21.70	Limited Damage
		Interior Column	-20.72	-18.36	Limited Damage
	TEC-1998	Corner Column	-57.39	-53.40	Limited Damage
		Edge Column	-20.64	-16.40	Limited Damage
		Interior Column	-19.02	-14.40	Limited Damage
10-Story	TEC-1975	Corner Column	-30.31	-26.60	No Plastic Damage
		Edge Column	-15.40	-14.80	No Plastic Damage
		Interior Column	-15.30	-14.60	No Plastic Damage
	TEC-1998	Corner Column	-32.53	-30.20	Limited Damage
		Edge Column	-15.84	-15.37	No Plastic Damage
		Interior Column	-15.70	-15.10	No Plastic Damage

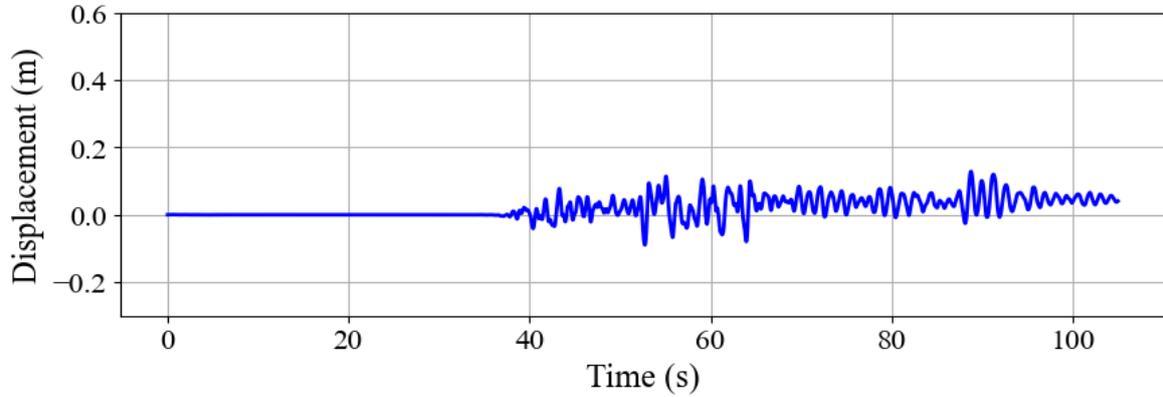
For the 5-story building, structures designed according to TEC-1975 exhibited higher maximum and residual displacements compared to those designed according to TEC-1998 across all removal scenarios. The removal of a corner column led to the most significant displacement in both cases, which can be attributed to the structural role of corner columns in providing support along two orthogonal directions. Unlike interior or edge columns, corner columns are connected on only two sides, limiting the availability of adjacent elements to redistribute loads when removed. This localized loss of support can lead to severe stress concentrations and increased displacement demands in surrounding beams and joints. Additionally, the sudden loss of support at the corner may introduce torsional effects due to eccentric load redistribution, further amplifying displacement demands. This response emphasizes the critical role of exterior support elements in maintaining structural stability. The peak and residual vertical displacements observed in time-history responses also correspond to increased plastic rotations and early formation of plastic hinges in beam-column joints, indicating the onset of damage progression. Although all scenarios in the 5-story building resulted in limited damage, the comparatively lower displacements in TEC-1998 designs indicate that the code improvements introduced in 1998 enhanced the structure's resistance against PC.

For the 10-story building, the performance patterns differed slightly. While TEC-1975 designs maintained structural integrity with no plastic damage observed in any column removal scenario, the TEC-1998 designs exhibited slightly higher maximum and residual displacements in all cases. In particular, under corner column removal, the TEC-1998 model experienced limited damage, in contrast to the TEC-1975 counterpart which remained within the no plastic damage range. This indicates that, despite the general trend of improved performance under newer code provisions, certain localized vulnerabilities, especially at exterior columns in taller buildings, may still lead to unfavorable outcomes under extreme damage conditions. The increased flexibility or redistribution patterns associated with later code provisions may contribute to this effect, underscoring the need for targeted design strategies in high-rise structures.

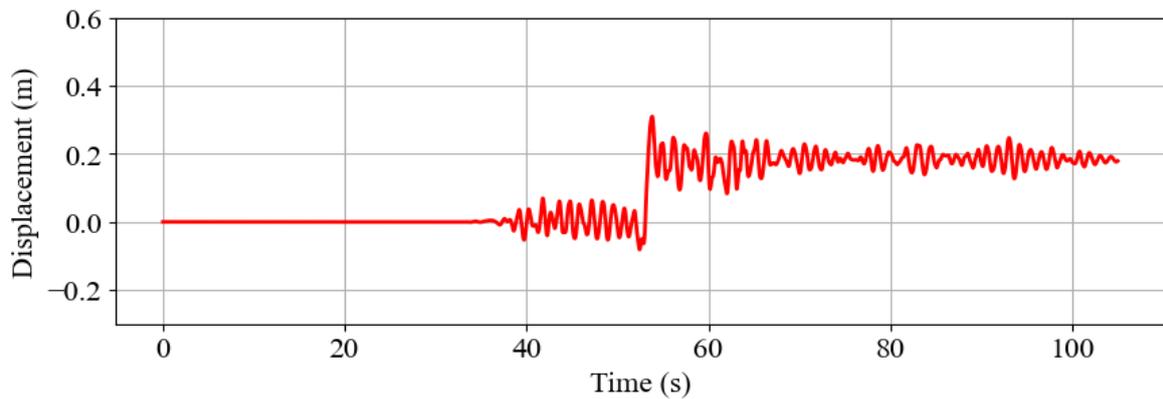
Given the structural variabilities identified under gravity loads, further assessment of the seismic performance of these buildings is essential to fully understand their behavior under earthquake loading conditions. The next section presents these findings.

### 3.2 Seismic Performance of Older RC structures

In Parallel with the gravity load analysis, a numerical assessment was conducted to evaluate the seismic vulnerability of the structures under a simulated earthquake, consistent with the seismicity of Kahramanmaraş. The top displacement time-history curves, presented in Figures 7-10, illustrate the structural response under a 7.7 magnitude seismic event. In this context, the "UX" and "UY" notations used in displacement plots refer to lateral displacements in the global X and Y directions, respectively, and represent how the structure responds to earthquake forces applied in orthogonal directions. These parameters are commonly used in finite element analysis to track roof-level drift during seismic loading.

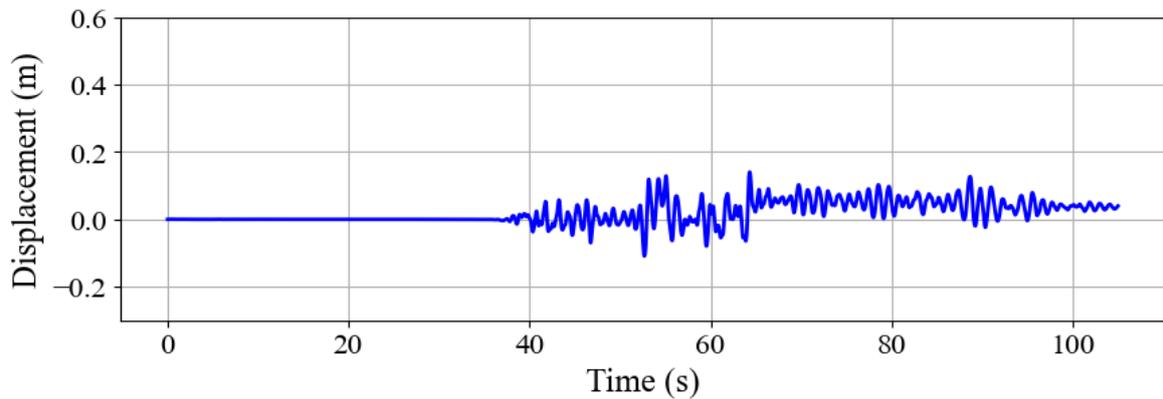


(a)

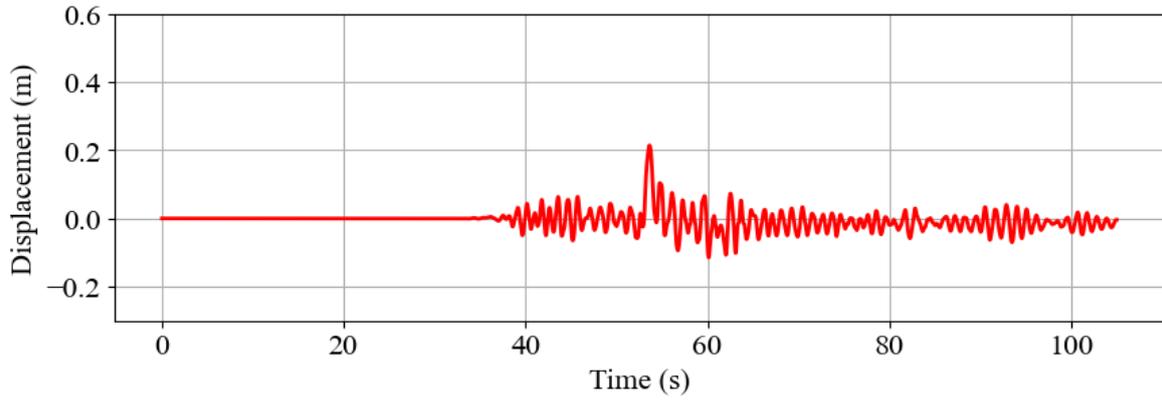


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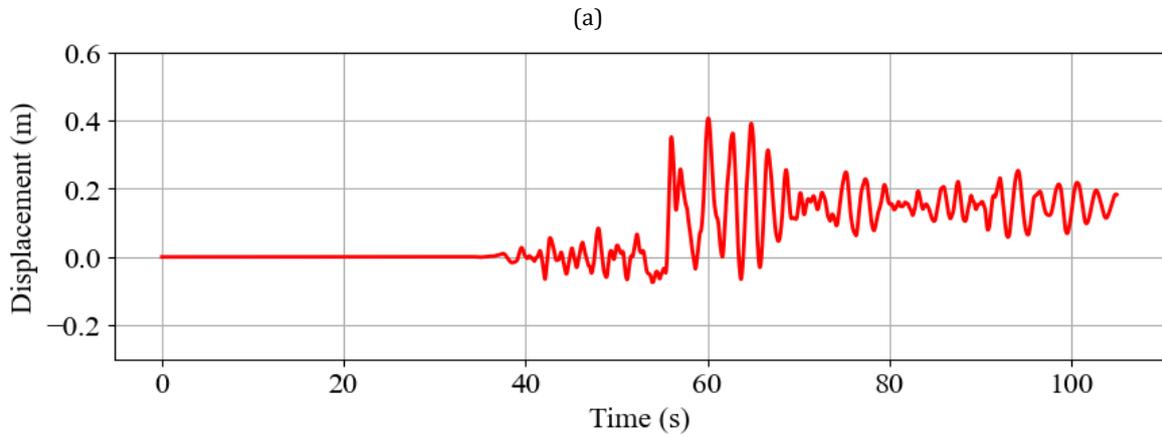
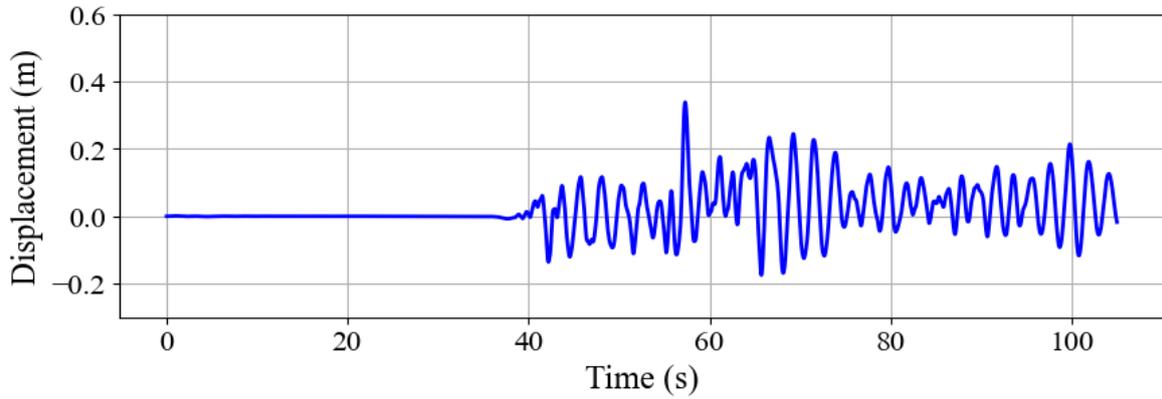
**Figure 7.** Top Displacement Time-history Curves of the 5-story buildings (TEC-1975): UX (a) and UY (b)



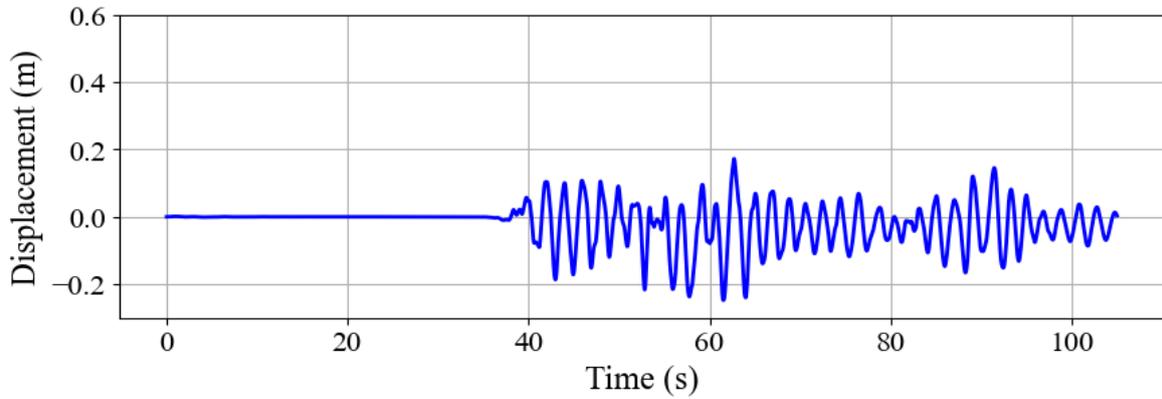
(a)



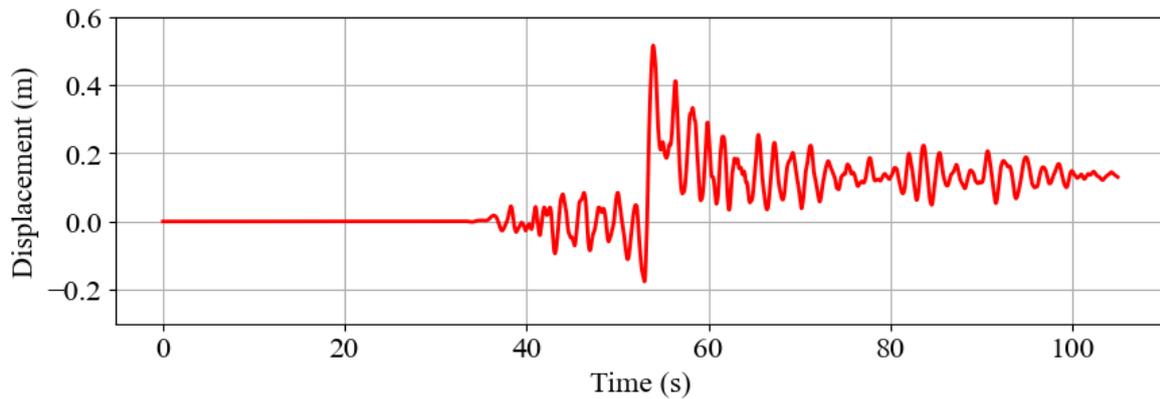
(b)  
**Figure 8.** Top Displacement Time-history Curves of the 5-story buildings (TEC-1998): UX (a) and UY (b)



(b)  
**Figure 9.** Top Displacement Time-history Curves of the 10-story buildings (TEC-1975): UX (a) and UY (b)



(a)



(b)

**Figure 10.** Top Displacement Time-history Curves of the 10-story buildings (TEC-1998): UX (a) and UY (b)

The mid-rise building designed according to TEC-1975 exhibited substantial structural deficiencies when subjected to seismic forces. Specifically, 20 of the 30 ground-floor columns reached the Severe Damage Region, while the remaining 10 entered the Moderate Damage Region. According to TEC-2018 performance criteria, this level of damage was deemed excessive, leading to a classification of collapse.

In all other structures, ground-floor column failure was observed, with every column entering the Collapse region. This complete structural failure rendered further upper-story analysis and column removal scenarios unnecessary, as the buildings were incapable of sustaining seismic forces even with intact columns.

Furthermore, as evidenced in figures 7, 8, 9, and 10, the top displacement time-history responses exhibit significant residual displacements, indicating permanent plastic deformations within the structural systems. These residual drifts align with hinge formation at critical joints and irreversible internal damage, confirming progressive structural deterioration during the seismic excitation. Such unrecoverable displacements are indicative of severe structural compromise and serve as clear evidence of irreversible damage. This dynamic response behavior not only confirms the critical performance deficiencies identified but also underscores the severity of the seismic-induced failure mechanisms observed in these buildings.

These results underscore the urgent need to retrofit older buildings to comply with modern seismic codes and mitigate catastrophic failures. The uniform collapse of ground-floor columns across all structures highlights the importance of strengthening existing RC buildings to enhance resilience against seismic-induced PC.

#### 4. Conclusion

This study investigated the progressive collapse (PC) response and seismic vulnerability of older RC structures with pre-existing column cuts in Kahramanmaraş, Türkiye. The analysis focused on low-rise (5-story) and mid-rise (10-story) buildings designed according to TEC-1975 and TEC-1998 seismic codes, evaluating their structural stability under both gravity loads and a simulated 7.7 magnitude earthquake.

The findings highlight that older RC buildings exhibit significant structural vulnerabilities, particularly when subjected to column removal scenarios. Under gravity loads, the 5-story structure designed according to TEC-1998 exhibited improved resistance to PC compared to its TEC-1975 counterpart. However, for the 10-story building, the TEC-1975 design showed slightly better performance, with lower displacements and no plastic damage under all column removal scenarios.

The seismic analysis revealed that outdated design standards are a major factor contributing to building failure. While column modifications may exacerbate damage, they were not the primary cause of collapse. Instead, the inability of TEC-1975 and TEC-1998-designed structures to withstand seismic forces, particularly at the ground-floor columns, was the main reason for structural failure. The mid-rise building designed according to TEC-1975 suffered severe damage, with most ground-floor columns reaching the Severe Damage Region. Similarly, all other structures experienced complete ground-floor column failure under seismic loading, rendering them structurally unsustainable.

These results emphasize the urgent need for retrofitting older RC buildings to comply with modern seismic codes such as TEC-2018. Strengthening critical structural elements, particularly ground-floor columns, is essential to mitigate the risk of catastrophic failure. Future research should explore advanced retrofitting techniques and

alternative construction materials to enhance the seismic resilience of existing structures in earthquake-prone regions.

Additionally, the finding of this study aligns with those of Demir [24], who investigated the PC behavior of government buildings according to updates of TSC-2007 and TSC-2019. Both studies confirm that newer seismic code implementations improve structural resilience against PC. However, this research extends the discussion by incorporating seismic excitation effects and focusing on older residential structures, further highlighting the necessity of strengthening pre-2000 RC buildings to withstand both gravity loads and seismic events.

In conclusion, this study not only identifies key structural deficiencies in Türkiye's older RC buildings but also underscores the life-safety implications of failing to address these risks. The continued presence of unauthorized column cuts and non-ductile detailing in the existing building stock presents a serious threat in future seismic events. As part of a comprehensive seismic risk mitigation strategy, progressive collapse assessments should be incorporated into the structural evaluation of existing buildings, particularly in densely populated and seismically active regions. The main contribution of this study lies in its integration of nonlinear dynamic analysis, outdated code-based structural design, and column removal scenarios to evaluate the PC potential of vulnerable RC structures.

While this study offers valuable insights, it's important to acknowledge its limitations and outline avenues for future research to enhance the accuracy and applicability of the findings. These improvements include:

- Future studies should move beyond idealized prototypes to incorporate the complexities of actual buildings. This involves considering undocumented alterations, construction flaws, and material degradation often present in existing structures. Additionally, accounting for variable construction quality, aging effects, and unauthorized structural modifications prevalent in pre-2000 reinforced concrete (RC) buildings will significantly improve model accuracy.
- Future research would benefit from using multiple ground motion records that represent a wider range of seismic characteristics, rather than relying on a single earthquake record. Furthermore, expanding the analysis to include various failure mechanisms beyond just vertical load-bearing element (column) removal, such as beam failure, soft-story mechanisms, or shear wall degradation, will provide a more comprehensive understanding of structural behavior.
- This study focused on only two structural typologies (5-story and 10-story RC frames). Future work should consider structures with irregular geometries, mixed-use functions, or different height classifications to increase the generalizability of the findings. Finally, integrating soil-structure interaction (SSI) effects into the dynamic analysis will lead to a more realistic assessment of structural response.

Addressing these limitations in future research will significantly enhance the generalizability and practical value of the results, particularly in supporting seismic risk reduction policies and structural safety strategies for Türkiye's existing building stock.

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