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Progressive Collapse Analysis of a Reinforced Concrete Structure Using the Enhanced Local Resistance (ELR) Method: A Comparison of UFC 4-023-03 and the Turkish Earthquake Code (TEC 2018)

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Abstract

Disasters cause significant damage to structural elements in the affected regions throughout the service life of buildings. This damage typically manifests as the loss of structural elements or a reduction in load-bearing capacity. Many countries conduct research and publish regulations and analytical methods to minimize such damage. One of the primary references in this context is the UFC 4-023-03 guide, titled "Design of Buildings to Resist Progressive Collapse," issued by the United States Department of Defense. This guide addresses the phenomenon where a structure experiences element loss due to various disasters, potentially leading to progressive collapse. The guide proposes three methodologies for assessing the progressive collapse resistance of structures: the Alternative Path method (AP), the Tie Force method (TF), and the Enhanced Linear Resistance method (ELR). In developing countries such as Türkiye, there are no specific regulations addressing the progressive collapse phenomenon. As a result, structures of critical importance are constructed without such provisions. In this study, a reinforced concrete building was analysed using the Enhanced Linear Resistance method, following the UFC 4-023-03 guidelines and the Turkish Earthquake Code (TEC). The objective is to identify the differences and commonalities between the UFC and the regulatory framework in Türkiye, where structures are not explicitly designed to resist progressive collapse. At the conclusion of the study, shear demand values of structural elements and other relevant parameters were comparatively presented.

Keywords
Progressive Collapse, UFC 4-023-03, TBDY-2018, Earthquake, Reinforced Concrete Structure, Disaster

Geliştirilmiş Yerel Dayanım (GLD) Yöntemi ile Betonarme Bir Yapının Aşamalı Göçme Analizi: UFC 4-023-03 ve Türk Bina Deprem Yönetmeliği (TBDY 2018) Karşılaştırması

Özet

Afetler meydana geldikleri bölgede, yapıların hizmet süresi boyunca yapısal elemanlara büyük zarar vermektedirler. Bu zarar genellikle yapısal eleman kaybı ya da taşıma gücünün zayıflaması olarak karşımıza çıkmaktadır. Birçok ülke bu zararları asgari düzeye indirebilmek için çeşitli araştırmalar ve yönetmeliklerinde ifadeler ile analiz metotları yayınlamaktadırlar. Bunlardan ilki çeşitli afetler sonucu yapının eleman kaybıyla başlayan ve aşamalı göçme ile süreci tamamlanan/tamamlanmayan fenomen için Amerika Birleşik Devletleri Savunma Bakanlığının yayınladığı UFC 4-023-03 'Design of Buildings to Resist Progressive Collapse' kılavuzudur. Kılavuz, yapıların aşamalı göçme direncini belirleyebilmek için Alternatif Yol metodu (AP), Bağ Kirişler metodu (BK) ve Geliştirilmiş Lineer Dayanım (GLD) metodudur. Türkiye gibi gelişmekte olan ülkelerde ise aşamalı göçme fenomenine ait bir düzenleme bulunmamaktadır. Bu tür ülkelerde kritik öneme sahip yapılar bu eksiklikle inşa edilmektedir. Bu çalışmada, betonarme bir yapı örneğinin Geliştirilmiş Lineer Dayanım yöntemi kullanılarak UFC 4-023-03 ile Türk Bina Deprem Yönetmeliği (TBDY2018) esas alınarak analiz sonuçları karşılaştırılmıştır. Bu sayede Türkiye gibi yapıları aşamalı göçmeye karşı direnci bulunmayan ülkenin UFC ile arasındaki farklar ve ortak noktalar belirlenmiş olacaktır. Çalışma sonunda, yapı elemanlarının kesme talebi ve diğer parametreler karşılaştırılmalı olarak sunulmuştur.

Anahtar Sözcükler
Aşamalı Göçme, UFC 4-023-03, TBDY-2018, Deprem, Betonarme Yapı, Afet

1. Introduction

Since the beginning of its existence, humankind has needed shelter to withstand natural conditions. In the early periods, although humans attempted to shelter in open spaces or caves, the necessity for enclosed spaces increased over time. By the present day, various construction materials and structural systems have been utilized to meet housing needs. Notably, with the emergence of concrete in the late 18th century and the construction of the first reinforced concrete structure in

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1852, a solution was found to address humanity's demand for more durable and organized housing (Batıçim, 2025). In the following years, concrete production and the construction of reinforced concrete structures rapidly increased worldwide, making concrete one of the primary building materials driving urbanization.

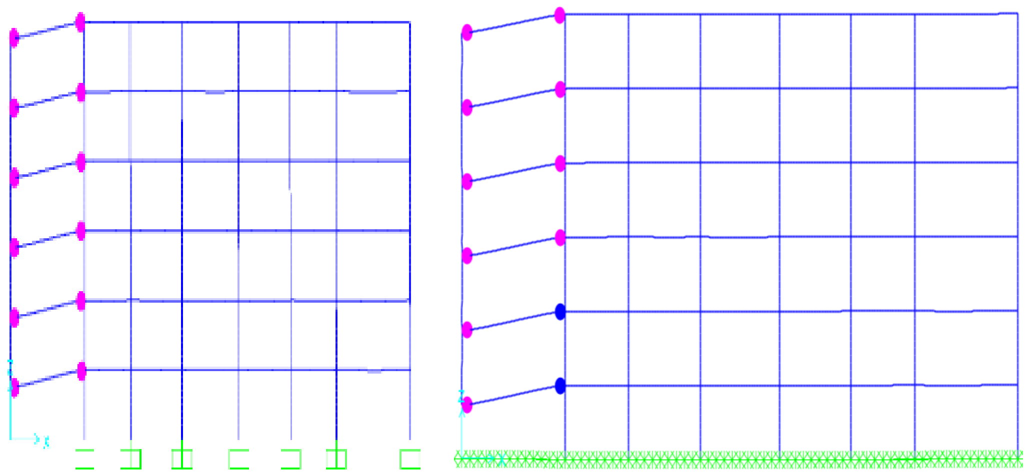
Reinforced concrete structures and their behaviour, one of the primary research areas in structural engineering, have long attracted the interest of researchers. Studies on their construction and load-bearing elements have increased over time. In recent years, particularly in Türkiye, regulations have been updated to address the impact of earthquakes—one of the most significant natural disasters—on reinforced concrete structures. Buildings in seismic regions are designed in accordance with the Turkish Earthquake Code (T.C. Resmi Gazete, 2018). Structural design engineers utilize TS 498 (Turkish Standards Institute, 1997): Design Loads for Buildings and TS 500 (Turkish Standards Institute, 2002): Requirements for Design and Construction of Reinforced Concrete Structures in their design processes. Although regulations and standards provide realistic and accurate guidelines, reinforced concrete structures, like other construction materials, have both advantages and disadvantages. In particular, poor workmanship and low-quality materials significantly increase the level of damage sustained by structures exposed to earthquakes.

Disasters are not solely caused by natural events; human-induced disasters can also occur. The structural damage caused by such disasters began to gain attention after the 1950s and was introduced into the literature as progressive collapse. As the scale of human-induced disasters increases, structural elements experience a loss of load-bearing capacity, leading to instability in the structural system and an attempt to regain equilibrium. If the structure fails to re-establish balance or redistribute the load, localized or total collapse of the structural system may occur. Although this is not an imminent destruction, when it happens, it can result in significant political and economic losses for nations. The first documented example of progressive collapse occurred in 1968 at the Ronan Point apartment building in London. A gas explosion caused damage to the balcony and part of the kitchen, leading to a progressive collapse (Figure 1).

Figure 1: The Ronan Point disaster (Hashemi, 2013)

Following the disaster at Ronan Point, researchers began investigating the concept of progressive collapse. Recognized as the first documented case of progressive collapse in the literature, the Ronan Point disaster prompted developed countries such as Canada, the United Kingdom, and the United States to incorporate the concept of progressive collapse into their structural design codes in subsequent years. However, beyond merely defining the phenomenon, analytical methods for progressive collapse were later included in guidelines published in the United States, such as the General Services Administration (GSA) "Alternate Path Analysis and Design Guidelines for Progressive Collapse Resistance" and the Unified Facilities Criteria (UFC 4-023-03) "Design of Structures to Resist Progressive Collapse". These guidelines recommend several analytical methods for progressive collapse assessment, including the Alternate Path (AP) Method, Tie Force (TF) Method, and Enhanced Linear Resistance (ELR) Method. The Alternate Path Method is based on load redistribution within the structural system, relying on plastic hinge formation in beams due to rotational deformations following the loss of a primary structural element. The Tie Force Method, on the other hand, is based on mechanically connecting structural components. This method involves separately calculating peripheral, internal, and vertical tie forces, which determine additional reinforcement requirements in columns, slabs, and beam-adjacent regions. The Enhanced Linear Resistance Method, which is also used in this study, is based on the shear force capacity of structural elements. However, research on the Enhanced Linear Resistance Method in the literature remains quite limited. Zhang et al. (2023) reported that fibre-reinforced polymer (FRP) strips have been widely used to retrofit existing reinforced concrete (RC) frame structures to enhance their resistance to progressive collapse. Yuzbasi (2024) presents an experimental and numerical study on the collapse behavior of a 60-meter-high cement silo structure subjected to blast loading.

The collapse mechanism was simulated using SAP2000 (FEM-NDA) and LS-DYNA (FEM-NDA with explicit code) models. Kılıçer (2025) investigated structures damaged by Ukrainian attacks using modern weapons such as UAVs and kamikaze drones during the Russia–Ukraine war, specifically in Russia's Belgorod Oblast, within the context of progressive collapse. Hamad et al. (2021) examined the impact of the proposed method on progressive collapse resistance in multi-story reinforced concrete frames. To accurately model structural behavior and evaluate progressive collapse resistance under sudden column loss scenarios, they conducted dynamic nonlinear analysis following ASCE 41-17 (American Society of Civil Engineers, 2017a) and General Services Administration (2016) guidelines. Yuzbasi (2025) presents a study on the failure of a 63-meter-high (206 feet) reinforced concrete (RC) building subjected to blast loading followed by progressive column removals. The analysis encompasses the entire sequence, beginning with the detonation of the explosive charge and concluding with the building's demolition. LS-DYNA was employed to simulate blast wave propagation and structural interaction, while SAP2000 was used to model the subsequent column removals. Both analyses focused on the most critically loaded columns at the base of the structure, using nonlinear dynamic analysis (NDA). Three explicit methods—Load Blast Enhanced (LBE), Arbitrary Lagrangian-Eulerian (ALE), and Coupling—were evaluated for their applicability. Although the LBE method is time-efficient, it presents challenges in accurately limiting the affected surface or volume. Shaheen et al. (2023) aimed to enhance frame resilience by improving the rotational capacity of connections. Their proposed method involved inserting a hollow steel sleeve with a predetermined wall curvature between a washer and an end plate. The effect of soil-structure interaction on the behavior of reinforced concrete structures was investigated by Kılıçer (2018). In addition to the rigid base assumption, the influence of subsoil was considered using both the Winkler and Vlasov models. Demir (2022) numerically investigated the progressive collapse response of reinforced concrete buildings designed for the 'government buildings' occupancy class. For this purpose, two reinforced concrete frame buildings were initially designed in accordance with the Turkish Earthquake Code (2018). Subsequently, their progressive collapse behavior was assessed using the Alternate Path Method, as defined in the GSA-2016 and UFC 4-023-03 guidelines. Three different column removal scenarios were independently examined through nonlinear dynamic analysis. Ozgan et al. (2023) considered soil-structure interaction in progressive collapse analyses. They analyzed a reinforced concrete school building under different soil conditions using a MATLAB (2018)-based interface with SAP2000 (2018). Yuzbasi & Arslan (2025) compared the Finite Element Method (FEM) and the Applied Element Method (AEM) in analyzing the progressive collapse (PC) behavior of a reinforced concrete (RC) structure. The novelty and significance of this study lie in its comprehensive investigation of the effects of slab thickness, slab type, and damping ratio on failure behavior across 54 different scenarios. These scenarios were generated by combining two analysis methods, six slab models, three slab thicknesses, and three damping ratios. A five-span, five-bay RC structure was analyzed using the SAP2000 and ELS software programs. Kılıçer (2024) compared progressive collapse responses of reinforced concrete and steel structures under various structural types and soil conditions using the Alternate Path Method. The plastic hinge formations from SAP2000 for this comparison are shown in Figure 2.



Rigid E_s=180000 kN/m^2

Figure 2: SAP2000 plastic hinge formation for Rigid and E_s = 180,000 kN/m² conditions

To demonstrate the effectiveness of the proposed method, end plate connections with different sleeve parameters were numerically analysed using validated finite element models. The proposed system enhances the ductility and strength of the connection by 2.6 and 2.5 times, respectively, compared to standard connections. Additionally, without modifying the connection configuration, different ductile responses can be achieved depending on the sleeve parameters.

In this study, the progressive collapse resistance of a reinforced concrete structure was evaluated based on shear forces using Enhanced Linear Resistance method, as outlined in UFC 4-023-03 guideline. The results were presented comparatively using UFC 4-023-03 and Turkish Earthquake Code.

2. Methodology

In the literature, studies on progressive collapse using Enhanced Linear Resistance method are significantly fewer compared to other methods. This method, which has not received sufficient attention to date, is crucial for comparing shear forces and identifying deficiencies in structural designs across different countries. In this study, progressive collapse analysis of a reinforced concrete structure was conducted using Enhanced Linear Resistance method. The analyses were performed following the UFC 4-023-03 guideline and Turkish Earthquake Code. The methodologies used in this study are explained in detail in a sequential manner.

2.1. Enhanced Local Resistance

Enhanced Local Resistance method is one of the three progressive collapse analysis methods outlined in UFC guidelines. It produces element-based results by verifying the shear capacity of structural elements to develop a ductile failure mechanism. ELR aims to prevent shear failure before the structure reaches its flexural capacity. Therefore, shear force was selected as the most meaningful and direct parameter for comparison. This method applies to structures classified under Risk Categories II, III, and IV. However, if a structure has been designed with a specific threat scenario in mind, the application of this method is not required.

The LRFD approach is design Load and Resistance Factor Design for Enhanced Local Resistance. LRFD approach in UFC;

$$\emptyset R_n \geq R_u \tag{1}$$

$\emptyset R_n$, Design strength, $\emptyset$, Strength reduction factor and shall be 1.0 , R_n, Nominal strength, including over-strength factors, R_u, Required strength, shear demand shall be determined for the horizontal out-of-plane direction (i.e., perpendicular to the building perimeter façade). Columns at building corners or re-entrant corners shall be evaluated in both directions normal to building perimeter façade (U.S. Department of Defense, 2016).

Axial load (P_{axial}) of the selected column for ELR method is calculated. This axial load:

$$P_{axial} = N[1.2D + 0.5Q] \times \frac{L_{long}}{2} \times \frac{L_{short}}{2} \tag{2}$$

Is calculated as follows. P_{axial} represents axial load, N denotes the number of stories, D refers to the dead load, Q represents the live load, and L indicates the spans of the slabs connected to column. Thus, axial force of selected column is determined using Equation 2.

In UFC, required shear strength can be found using methods in plastic structural design references or in Table 4-4 of PDC TR-06-01 (U.S. Army Corps of Engineers, 2008): Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS). Re-arranging yields;

$$V_u = 7.5\frac{M_n}{L} \tag{3}$$

Where, V_u, shear demand, M_n, Nominal flexural strength, accounting for axial load, L, column height. In UFC, shear capacity carried by concrete;

$$V_c = 2 \times (1 + \frac{N_u}{2000A_g}) \times \sqrt{f'_c} \times b_w \times d \tag{4}$$

V_c, shear capacity carried by concrete, N_u, axial load, A_g, gross area, f'_c, the concrete strength. In TEC, shear capacity carried by concrete (Doğangün, 2018);

$$V_{cr} = 0.65 \times f_{ctd} \times b \times d \times \left(1 + 0.07 \times \frac{N_d}{A_c}\right) \tag{5}$$

V_{cr}, shear crack resistance, f_{ctd}, Design tensile strength, N_d, axial load, A_c, cross-section area of concrete in a column. In UFC, shear force carried by the steel is

$$\emptyset(V_n) = \emptyset(V_c + V_s) \geq V_u \tag{6}$$

Where, V_u, shear demand, V_c, shear capacity carried by concrete, V_s, the shear force carried by the steel, $\emptyset$, strength reduction factor, V_n, Nominal shear force. In TEC, shear force carried by the steel is

$$V_r = V_c + V_w \geq V_d \tag{7}$$

Where, V_r, shear strength of the column, V_c, shear capacity carried by concrete, V_w, shear force carried by steel, V_d, design shear force.

The procedures followed in the study using Enhanced Local Resistance method are presented in Figure 3.

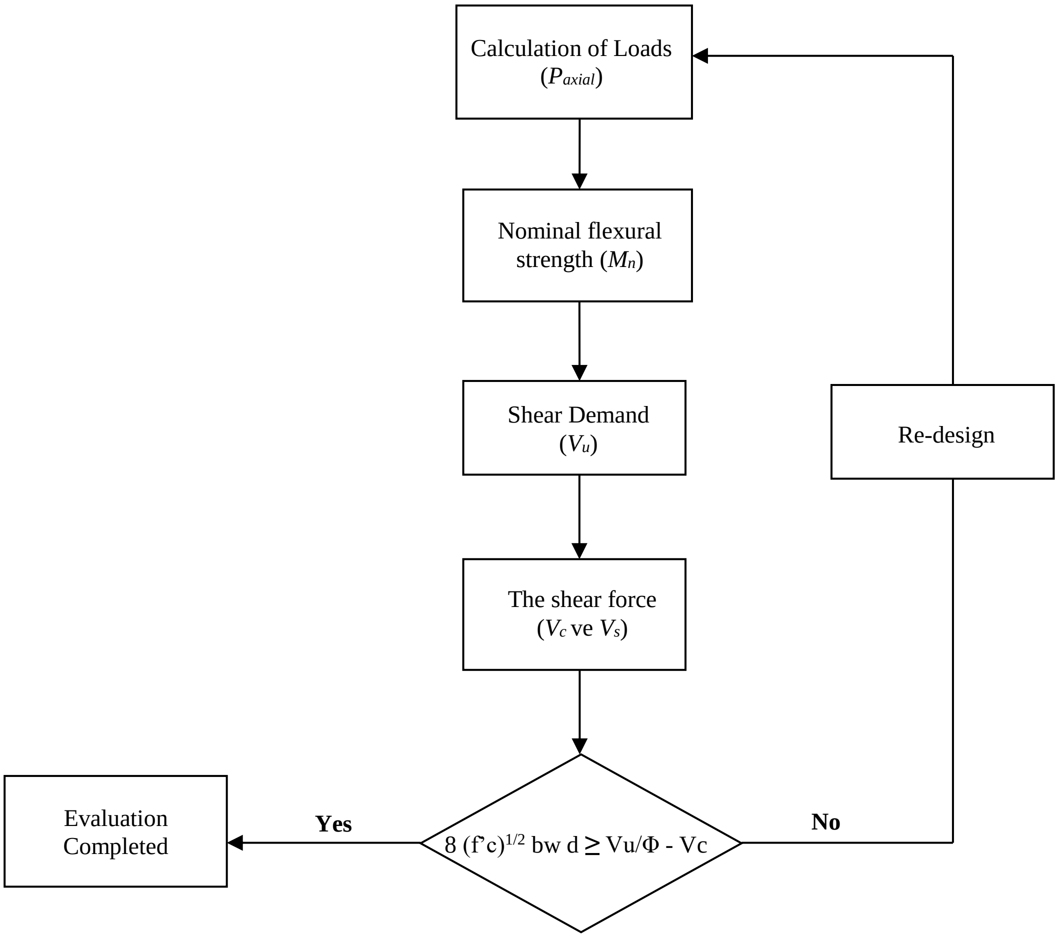


Figure 3: Flow diagram

This flowchart outlines the steps used to assess shear strength of a structural element. The process begins with the calculation of loads, where the vertical and horizontal loads acting on the element are determined to establish the fundamental values for further calculations. Following the load calculations, the nominal flexural strength of the element is determined. This step helps in evaluating the bending capacity of the element. Next, shear demand on the element is calculated, representing shear forces induced by applied loads. Once shear demand is established, the existing shear capacity of the element is assessed. In this step, the components contributing to shear resistance are considered to verify the element's design. Finally, a specific condition is checked to determine whether the shear capacity meets the design requirements. If the condition is satisfied, the evaluation is completed, and element is considered suitable. However, if condition is not met, redesign is necessary. In the redesign process, measures are taken to enhance element's shear strength, improving its load-carrying capacity. Once these modifications are made, steps in the flowchart are repeated to reassess the suitability of the element.

2.2. Turkish Earthquake Code

Countries design their structures by considering their own building codes and a set of guidelines. Each country develops its regulations based on its geographical conditions, material quality, and workmanship standards. For example, Eurocode 8 (European Committee for Standardization, 2024) includes tsunami loads, whereas countries like Türkiye do not have such a load definition in their regulations. This highlights the fact that building codes are tailored to the specific geographical conditions of each country. In Türkiye, earthquakes are the primary natural disaster of concern. The Anatolian Plateau is located on an active fault line. Particularly, the 1999 Marmara Earthquake and the 2023 Kahramanmaraş Earthquakes have served as constant reminders of the vulnerability of Türkiye's building stock and the importance of life safety.

In Türkiye, the seismic accelerations considered in structural design vary depending on the seismic zone where the structure will be built. The Türkiye Earthquake Hazard Map, which is designed to ensure the safe design of buildings and all other structures against earthquake effects, is presented in Figure 4.

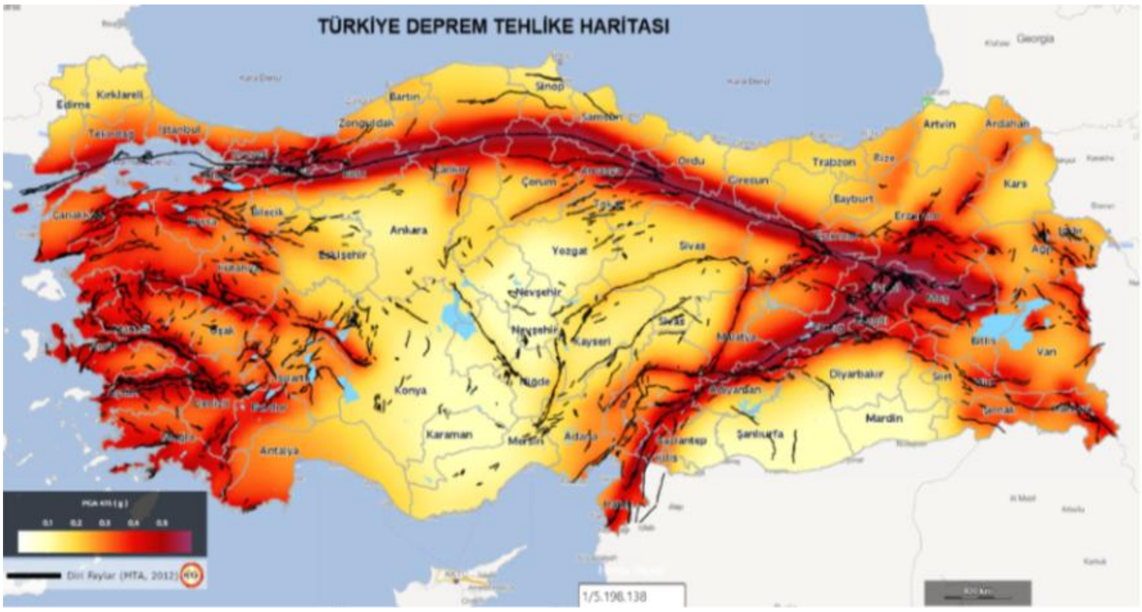


Figure 4: Earthquake hazard map of Türkiye (General Directorate of Disaster Affairs, 2019)

TS 498: Design Loads for Buildings, TS 500: Requirements for Design and Construction of Reinforced Concrete Structures, and Turkish Earthquake Code are the regulations used in the design of reinforced concrete structures. However, since there is no specific regulation for progressive collapse analysis in Türkiye, the procedural steps from UFC 4-023-03 guideline were followed using TS 498, TS 500, and TEC 2018.

2.3. UFC 4-023-03

Currently, specialized analysis methods for progressive collapse are provided in UFC 4-023-03 and GSA guidelines. These analysis methods play a crucial role in understanding structural behavior following column loss and in assessing resistance to progressive collapse. In this study, UFC 4-023-03 "Design of Buildings to Resist Progressive Collapse" guideline, frequently referenced in literature and published by the U.S. Department of Defense (2016), was utilized. This guideline provides engineers with both direct and indirect approaches and proposes three different analysis methods, as illustrated in Figure 5.

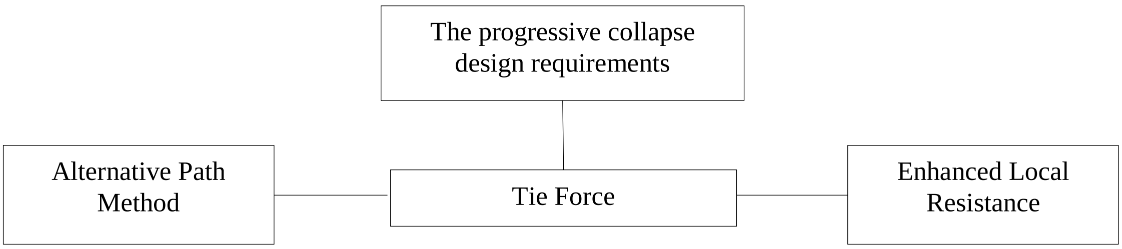


Figure 5: Progressive collapse design requirements

The first of these methods is Alternative Path method, which is based on the principle of continuous load redistribution and structural continuity. The second method is Tie Force method, which assumes mechanical connections between structural elements and aims to ensure sufficient tie forces between them. The final analysis method is Enhanced Local Resistance method, which is based on verifying shear strength of structural elements. In this study, Enhanced Local Resistance Method was used, as it is relatively less explored in the literature.

2.4. Reinforced Concrete Structure

The seven-story reinforced concrete structure has a slab thickness of 12 cm, column dimensions of 30 × 60 cm, and beam dimensions of 60 cm in width and 30 cm in depth. The concrete compressive strength is C25, while the reinforcement material is S420. The reinforced concrete model consists of three spans along both axes, with a story height of 3 meters for each floor. The structure is assumed to be fixed at the base, and soil effects are not considered. The building is symmetrical in both directions, with a total length of 16.20 meters. The live loads have been considered according to the building codes of each respective country. The formwork plan of the structure is presented in Figure 6.

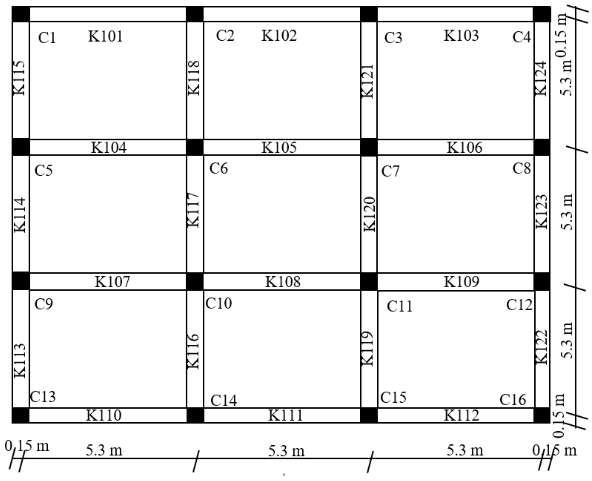


Figure 6: Formwork plan of 7-story reinforced concrete building

The concrete cover is 5 cm. The columns are reinforced with 3Ø20 rebars on each face, with three reinforcement bars per surface. Building is primarily used as an archive facility. Dead load has been calculated as 5.94 kN/m². Live load has been considered as 7.2 kN/m² according to the ASCE 7-16 (American Society of Civil Engineers, 2017b) 7 kN/m², and 5 kN/m² according to Turkish Earthquake Code and TS 498. The analysis was carried out by considering only vertical loads (dead and live loads). The main reason for this approach is the procedure recommended by the UFC 4-023-03 guideline. The guideline clearly states that only vertical loads should be considered in progressive collapse analyses. According to UFC, the purpose of such analyses is to evaluate the load redistribution capacity of the structure following the sudden loss of a vertical load-bearing element (e.g., a column).

3. Findings and Discussions

A seven-story reinforced concrete structure was modelled in the SAP2000 v16 software based on the material and geometric properties specified in Section 2.4. The structure was assumed to be fixed at the base, and soil properties were not included in the analysis. The natural vibration periods of the model were obtained as $T_1 = 0.86$ s, $T_2 = 0.64$ s, and $T_3 = 0.61$ s, respectively. A view of the structure in SAP2000 is presented in Figure 7, while the mode shapes corresponding to the first three modes are shown in Figure 8.

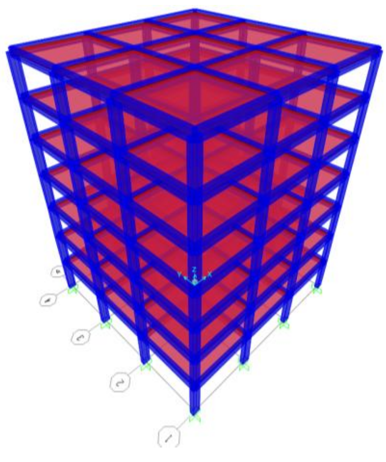


Figure 7: View of the SAP2000

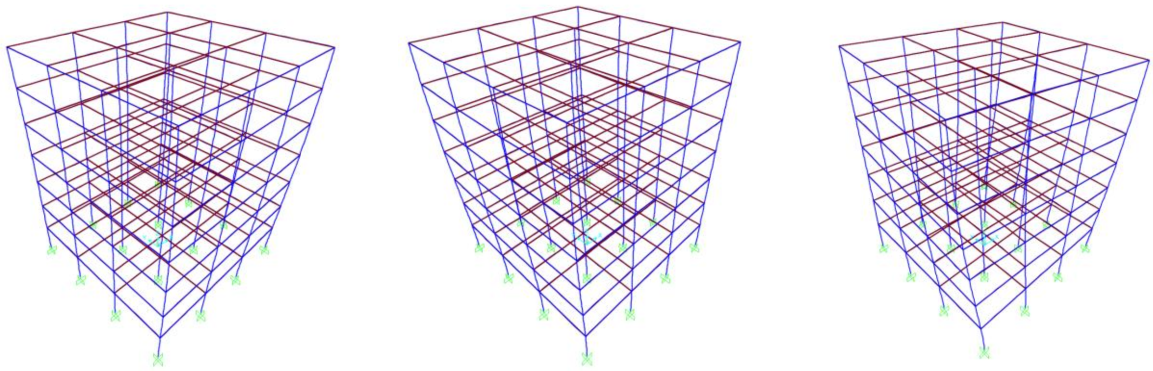


Figure 8. Mode shapes: a) Model 1 b) Mode 2 c) Mode 3

Structural vulnerability to shear failure can lead to sudden and brittle collapse, which is an undesirable condition in earthquake engineering. Similarly, in the construction of progressive collapse-resistant structures, ensuring ductile behaviour is essential. Therefore, in progressive collapse analyses, failure should be prevented before the structure reaches its flexural capacity. Enhanced Local Resistance method is used to evaluate shear strength of structure. However, this method can also be applied to assess structures in different countries. In this study, as mentioned in the previous sections, a seven-story reinforced concrete structure was analysed using the UFC guideline and the Turkish Earthquake Code.

For ELR method, a column is selected from Figure 6 to initiate the scenario. Similar to Alternative Path Method, a corner column is typically chosen. Figure 9 presents the selected column and its representation on the formwork plan.

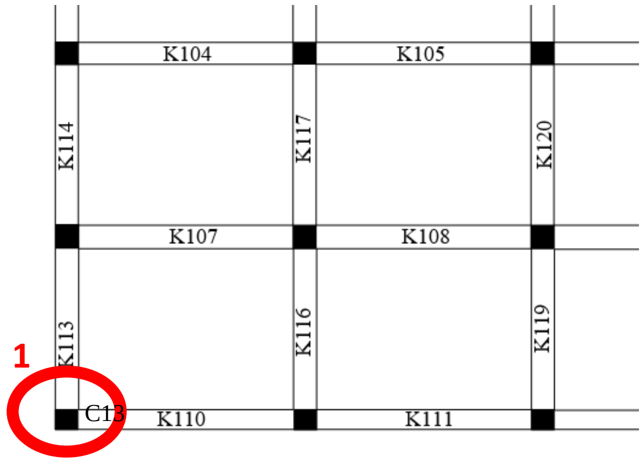


Figure 9: Column specified for the scenario

For ELR analysis, the corner column labelled as Column 1, located at the intersection of beams K110 and K113, C13, is selected. Axial load of column is calculated using Equation 2 based on ELR method. Axial load values computed for Column 1, considering UFC guideline and Turkish Earthquake Code, are presented in Table 1.

Table 1: Paxial load calculation according to UFC and TEC

	N	Dead Load (kN/m^2)	Live Load (kN/m^2)	L_{Long} (m)	L_{short} (m)	P_{axial} (kN)
UFC 4-023-03	7	5.94	7.2	5.3	5.3	527.36
TEC	7	5.94	5.0	5.3	5.3	540.90

Axial load calculations for both UFC 4-023-03 and TEC regulations using ELR method are presented in the table above. For selected corner column shown in Figure 7, axial load calculations were performed considering the dead load, live load, and span lengths as defined in Equation 2. In both regulations, the number of stories (*N*) is 7, and the dead load is calculated as 5.94 kN/m². However, live load values differ, with UFC 4-023-03 considering 7.2 kN/m², while TEC defines this value as 5.0 kN/m².

The axial load obtained according to the TEC is approximately 2.6% higher than that calculated using the UFC. The long (L_{long}) and short (L_{short}) spans of the column are determined as half of the adjacent slab spans in both directions. The column influence area for these slabs is illustrated in Figure 10.

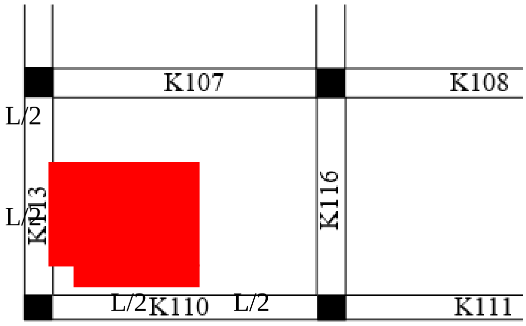


Figure 10: Tributary area of column

According to Equation 2, the axial load is calculated as 527.36 kN based on UFC 4-023-03 regulation and 540.90 kN according to TEC regulation. The difference in axial load between the two methods arises due to variations in live load values. The bending moment of the column is determined using a biaxial moment calculation. The bending capacity (M_n) is calculated separately for each regulation. M_n values computed according to both regulations are presented in Table 2.

Table 2: Moment calculation according to UFC and TEC

	f'c (MPA)	f_y (MPA)	Each face (item)	A_s (mm^2)	a (mm)	P_{axial} (kN)	M_n (kNm)
UFC 4-023-03	25	420	3	942	144.78	527,36	188.96
TEC	25	420	3	942	124.87	540.90	192.90

The moment calculations based on UFC 4-023-03 and TEC regulations are presented comparatively. In both regulations, concrete compressive strength and steel yield strength are considered same. The number and diameter of reinforcement bars are also identical in both regulations, with three reinforcement bars (3Ø20) per face. The total reinforcement area is 942 mm², and the same reinforcement detailing is assumed for both standards. However, due to different coefficients in the regulations, the concrete compression depth (a) values differ, leading to variations in results. For example, β_1 is a coefficient used to determine the height of the stress block formed in the compression zone of concrete. In other words, it is used to calculate the height of the idealized rectangular compression block measured from the neutral axis. According to ASCE 7-16 (American Society of Civil Engineers, 2017b), it is generally considered constant and taken as 1.0, whereas in TS500, it varies depending on the concrete grade. In this study, it is taken as 0.85. The compression depth (a) is calculated as 144.78 mm according to UFC 4-023-03, whereas it is 124.87 mm according to TEC. When comparing bending moment (M_n) values, the moment calculated according to UFC 4-023-03 is 188.96 kNm, while the moment according to TEC is 192.90 kNm, resulting in a slightly higher moment in TEC. A difference of approximately 2% is observed between the two regulations.

After calculating the bending moment according to ELR method, the shear force analysis was performed. First, the ultimate shear force was determined using Equation 3. The shear demand values were calculated separately for UFC and TEC, and the results were compiled in Table 3.

Table 3: Shear force calculation according to UFC and TEC

	P_{axial} (kN)	M_n (kNm)	V_u, V_d (kN)
UFC 4-023-03	527.36	188.96	472.40
TEC	540.90	192.90	482.25

Using Equation 3, the ultimate shear force (V_u) calculated according to UFC is 471.40 kN. In the calculations, the height from the foundation to the first floor was considered approximately 3 meters. Shear force is obtained by dividing 7.5 times the bending moment by column length. According to TEC, shear force was calculated as 482.25 kN, which is approximately %2.1 higher than the value obtained using UFC.

Shear force carried by the column was calculated separately for each regulation and is presented in Table 4. Equation 4 was used for UFC, while Equation 5 was used for TEC.

Table 4: The shear capacity carried by concrete according to UFC and TEC

	P_{axial} (kN)	**V_u, V_d (kN)**	**V_{cr} (kN)**	**V_c (kN)**
UFC 4-023-03	527.36	472.40	---	1652.42
TEC	540.90	482.25	2835.90	2268.72

According to TS 500, the contribution of concrete is assumed to be 80% of the shear cracking capacity (Turkish Standards Institute, 2002). In the table, according to TEC, shear cracking capacity is calculated as 2835.90 kN, and contribution of concrete to the shear capacity is determined as 2268.72 kN. According to UFC guideline, V_{cr} is not calculated; instead, using Equation 4 directly, shear capacity by concrete is determined to be 1652.42 kN.

Shear force carried by the reinforcement was calculated separately for each regulation and is presented in Table 5. Equation 6 was used for UFC, while Equation 7 was used for TEC.

Table 5: Shear force carried by the steel according to UFC and TEC

	V_u, V_d (kN)	**V_c (kN)**	**Φ**	**V_s (kN)**	**V_w (kN)**
UFC 4-023-03	472.40	1652.42	1.0	NaN	---
TEC	482.25	2268.72	---	---	NaN

Shear force to be carried by the reinforcement (V_s, V_w) was calculated by considering design shear force and shear capacity by concrete for both UFC and TEC. The analysis results indicate that the required shear force is fully carried by concrete, making it unnecessary to calculate the shear force contribution from the reinforcement. However, when examining the shear force values carried by the concrete, a difference of approximately 37% was observed between the two regulations. According to TEC, both design shear force and shear capacity carried by concrete were found to be higher compared to UFC guideline.

As another scenario, one of the middle columns, the C6 column, was selected. The C6 column is one of the columns with the largest spans. Figure 11 presents the selected column and its representation on the formwork plan.

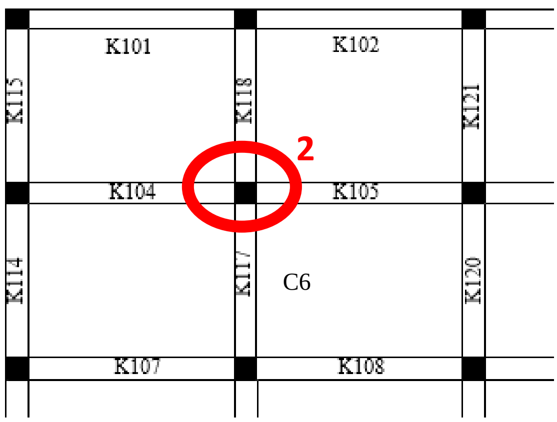


Figure 11: Column specified for the scenario

For ELR analysis, the corner column labelled as Column 2, located at the intersection of beams K104 and K105, C6, is selected. the number of stories (N) is 7, and the dead load is calculated as 5.94 kN/m². However, live load values differ, with UFC 4-023-03 considering 7.2 kN/m², while TEC defines this value as 5.0 kN/m². The long (L_{long}) and short (L_{short}) spans of the column are determined as half of the adjacent slab spans in both directions. In both regulations, concrete compressive strength and steel yield strength are considered same. The number and diameter of reinforcement bars are also identical in both regulations, with three reinforcement bars (3Ø20) per face. The total reinforcement area is 942 mm², and the same reinforcement detailing is assumed for both standards. However, due to different coefficients in the regulations, the concrete compression depth (a) values differ, leading to variations in results.

The compression depth (a) is calculated as 392.96 mm according to UFC 4-023-03, whereas it is 341.23 mm according to TEC. The shear force carried by the steel is given in Table 6 according to the UFC and TEC.

Table 6: Shear force carried by the steel according to UFC and TEC

	P_{axial} (kN)	M_n (kNm)	V_u, V_d (kN)	V_c (kN)	Φ	V_s (kN)	V_w (kN)
UFC 4-023-03	2109.45	139.87	349.68	---	1.0	NaN	---
TEC	2163.60	150.10	375,25	8766.01	---	---	NaN

The results obtained for the middle column according to the ELR method are presented in Table 6. The analysis showed that the required shear force is amply resisted by the concrete. Similar values of Vs and Vw were obtained as in the corner column scenario.

According to ELR method, progressive collapse shear force of a selected column in a reinforced concrete structure can be determined by following the procedural steps outlined above. While each country includes shear force calculations in its respective building codes, specialized analysis methods are required for progressive collapse assessments. In this study, as mentioned earlier, TEC and UFC were compared to observe the numerical differences in shear force calculations on the same structural example, rather than focusing on the advantages or disadvantages of each regulation. Understanding how shear force values diverge between different codes is crucial for design engineers and structural practitioners.

4. Conclusions and Recommendations

The shear demand of a reinforced concrete structure was compared using ELR method, considering both TEC and UFC approaches. In the analyses, corner column of structure was selected, and UFC guideline's procedural steps were followed to compare the shear demand according to ELR method. The results and recommendations of this study are presented below.

- Although the design shear demand obtained from TEC and UFC differ, they are generally within a close range. TEC is approximately 2.1% higher than that of UFC, likely due to the fact that Turkey is situated in a high seismicity region.
- The variation in live load values between the two regulations primarily contributes to the differences in axial load calculations, which subsequently influence the shear force calculations. UFC 4-023-03 considers a live load of 7.2 kN/m², while the Turkish Earthquake Code specifies 5.0 kN/m². This discrepancy in live loads is a key factor in the initial divergence of values between the two codes and significantly affects the structural design outcomes.
- The shear capacity carried by concrete was consistently higher in TEC-based calculations, indicating a stronger emphasis on shear resistance in TEC.
- TEC lacks explicit design criteria for progressive collapse, which represents a critical gap in the code.
- The ELR method, though scarcely represented in the literature, has demonstrated potential in enhancing shear resistance and mitigating brittle failure in structural elements.
- The contribution of reinforcement to shear resistance could not be calculated in this study, as the concrete alone was found to carry sufficient shear.
- Only vertical loads were considered in the progressive collapse analysis; the exclusion of lateral loads likely led to underestimated shear design forces.
- While results vary based on the selected column scenario, TEC generally yields higher shear values compared to UFC.
- Designs based on TEC anticipate approximately 2–3% higher shear forces compared to UFC. This may require more reinforcement and/or larger cross-sections for structural elements. As a result, construction costs may increase directly. However, this increase leads to safer and more durable structures. In the long term, it can reduce indirect costs such as structural damage, maintenance, and loss of life. Therefore, from a cost-benefit perspective, the conservative approach of TEC may be more advantageous.

The results of study are presented above. The recommendations and future planned studies are listed below.

- The concept of progressive collapse has been widely incorporated into codes of developed countries since the early 2000s. It is recommended that this concept and its analysis methodologies be integrated into the seismic and building codes of developing countries, such as Turkey.
- To prevent sudden collapse following column removal, brittle failure must be avoided. Shear force checks should be incorporated into progressive collapse design procedures in developing countries.

- Structural safety is not solely dependent on the load-bearing system. The use of ductile materials is recommended to facilitate the redistribution of loads in the event of local failure.
- More extensive research should be conducted on ELR, Tie Force, and Alternative Path methods. These methods, along with new approaches, should be adapted to the design standards of developing countries to ensure the safety of critical infrastructure.
- Critical structures in Turkey, including hospitals, military facilities, public buildings, and emergency response centers, should be designed to resist progressive collapse. Existing structures should be reassessed based on progressive collapse criteria.
- Since soil-structure interaction significantly affects structural behavior, further investigation is needed into the influence of progressive collapse mechanisms under varying ground conditions.
- Given the limited number of studies on ELR in the literature, more analytical and experimental research is necessary to validate and develop this method.
- Structural assessments in Turkey should not be limited to seismic considerations alone; progressive collapse potential must also be evaluated to ensure comprehensive structural safety.
- Numerous studies have shown that soil-structure interaction significantly affects the superstructure; since the ability of a structure to effectively redistribute loads after column loss varies between structures with and without soil interaction, further research is needed on progressive collapse considering soil-structure interaction.
- The effects of shear force differences between codes on structural safety, member sizing, and cost should be examined in more detail from an engineering perspective in future studies.

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