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Research Article

Pushover Analysis of a Reinforced Concrete Frame and Calculation of CO_2 Emissions

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Abstract – This study evaluates the seismic performance of a reinforced concrete (RC) frame structure using pushover analysis, a widely applied nonlinear static analysis method. The analysis focuses on identifying the nonlinear behavior of the reinforced concrete frame structure, including plastic hinge formation and capacity curve characteristics, under seismic loads. The frame model is developed and analyzed in compliance with the Turkiye Earthquake Building Code (TBDY 2018), ensuring adherence to performance-based design principles. Moment – curvature relationships of beams are determined and axial force - moment interaction diagrams of columns are plotted for performing pushover analysis.
The findings demonstrate that pushover analysis effectively captures the progressive damage mechanisms and provides valuable insights into the structure's seismic performance. The study also briefly explores the environmental impact of the materials used in the structure, emphasizing the significance of carbon dioxide emissions in concrete and reinforcement steel. These results highlight the potential for incorporating sustainable materials and optimized designs to balance structural safety with environmental considerations. This study concludes that pushover analysis is a reliable tool for assessing the nonlinear behavior of RC structures and identifying key failure mechanisms. Future research should aim to integrate pushover analysis and environmental impacts and provide innovative methods to form seismic resilient and sustainable structures.

Keywords – Pushover Analysis, Nonlinear Behavior, Reinforced Concrete Frame, Base Shear, Carbon Dioxide Emissions.

I. INTRODUCTION

Nonlinear analysis methods are becoming increasingly important for evaluating the safety of structures under seismic loads. While traditional linear elastic analysis methods are sometimes inadequate to fully reflect the structural capacity limits, nonlinear static analyses, such as pushover analysis, provide more reliable results in determining the performance levels and collapse mechanisms of structures. This method examines the plastic behavior of structures by incrementally increasing lateral loads and enables the determination of structural capacity levels. Guidelines such as FEMA-356 [1] and ATC-40 [2] emphasize the effectiveness of pushover analysis in performance-based evaluation of structures. Similarly, the Turkiye Building Earthquake Code (TBDY 2018) promotes the use of this method, particularly for evaluating the seismic performance of existing structures [3].

Studies in the literature have demonstrated how pushover analysis is applied to different structural systems and what advantages it offers compared to traditional linear analyses. Chopra and Goel [4] highlighted that pushover analysis is a critical tool for identifying collapse mechanisms during seismic events. Fajfar [5] linked pushover analysis to performance-based design methodologies, showing that nonlinear analyses can predict structural behavior under seismic loads more accurately. Krawinkler and Seneviratna [6] stated that nonlinear analyses produce more realistic results compared to conventional elastic analyses and that pushover analysis is applicable to various structural systems.

This study aims to apply pushover analysis to a reinforced concrete frame structure using a structural analysis program and to evaluate the structural capacity curves and plastic hinge formations.

II. MATERIALS AND METHOD

Nonlinear analysis methods are essential for understanding the actual behavior of structures under seismic loads. Traditional linear elastic analyses evaluate only the structural response within elastic limits, whereas nonlinear analyses provide a more accurate assessment of plastic deformations, load-carrying capacity, and collapse mechanisms. For this reason, nonlinear static and dynamic analysis methods are widely used to determine structural capacity limits and predict potential damage zones. Nonlinear analyses are classified into time-dependent and static methods. Time-dependent analyses evaluate the dynamic response of structures under a specific seismic record, while static analyses, such as pushover analysis, determine the load-carrying capacity and plastic deformations by incrementally applying lateral loads. Among these methods, pushover analysis is one of the most employed and practical nonlinear static analysis techniques [3,4].

Pushover analysis is a nonlinear static method used to evaluate the performance of structures under seismic loads. In this method, lateral loads are incrementally applied to the structure to generate a capacity curve, which identifies the load-carrying capacity, elastic limits, plastic hinge formations, and ultimate collapse mechanism. The process begins with a modal analysis to determine the dominant vibration modes. Then, potential regions for plastic deformation in structural elements are identified, and a loading pattern for the pushover analysis is established [1,6]. As the loads gradually increased, internal forces, deformations, and plastic hinge formations are observed. The relationship between the base shear force and displacement response is then determined to create the capacity curve, as shown in Figure 1. This curve reveals the elastic limits, plastic deformation levels, and ultimate load-carrying capacity of the structure.

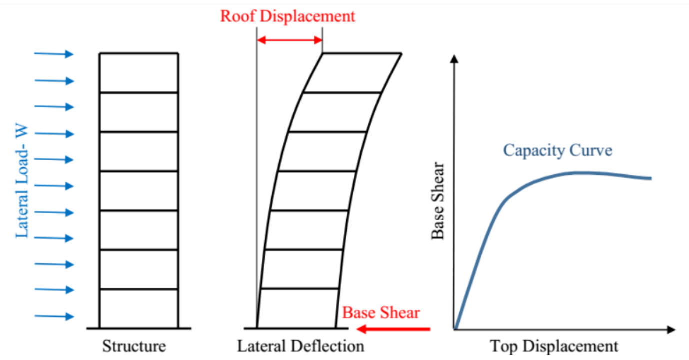

Figure 1. Pushover analysis of structures

Pushover analysis also enables the evaluation of structures at various performance levels, as shown in Figure 2. Using the capacity curve, performance limits such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) are identified, and the compliance of the design with these criteria is assessed. Structural performance assessment guidelines, such as FEMA-356 and ATC-40, emphasize the importance of this approach, which is also recommended in the Turkiye Building Earthquake Code (TBDY 2018) [1,2,3].

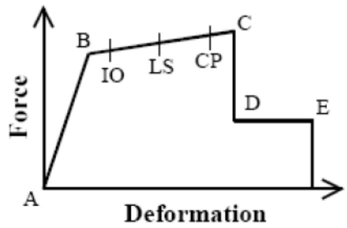

Figure 2. Force–deformation relationship of a typical plastic hinge in FEMA-356 [4]

III. NUMERICAL EXAMPLE AND RESULTS

In this study, seismic performance of a three-story, two-bay reinforced concrete (RC) frame structure is evaluated using pushover analysis. The structural model is created using a finite element analysis program, and modal analysis is performed to determine the dominant vibration modes of the system. The first natural period of the structure is calculated as 0.477 seconds, and the mass participation ratio of the first mode is determined to be 89%, satisfying the Turkiye Building Earthquake Code (TBDY 2018) criteria for pushover analysis [3].

The RC frame structure consists of three different column types (C1, C2, C3) and two different beam types (B1, B2), as shown in Figure 3 and Figure 4. The floor heights are 3.5 m for the basement floor and 3.0 m for the first and second floors, leading to a total building height of 9.5 m.

The vertical loading conditions of the structure are determined as G+0.3Q according to the Turkish Earthquake Code (TBDY 2018) as shown in Figure 5, and the analyses are performed using SAP2000 [7]. Moment-curvature relationships for B1 and B2 beams are presented in Figure 6 - Figure 9 for positive and negative directions. Numerical values of moment curvatures are summarized in Table 1. Axial force - moment interaction diagram for C1, C2 and C3 columns are presented in Figure 10 schematically, and their values are presented in Table 2 – Table 4, respectively. Plastic hinges are modeled at beam-column joints in accordance with FEMA-356 [1] guidelines to evaluate the formation of plastic hinges.

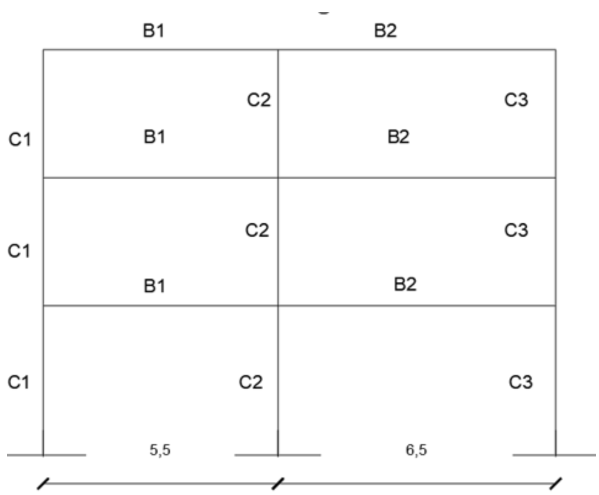

Figure 3. Structural frame model and element labeling

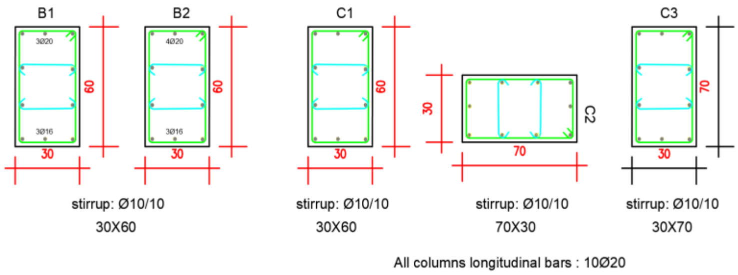

Figure 4. Column and beam details

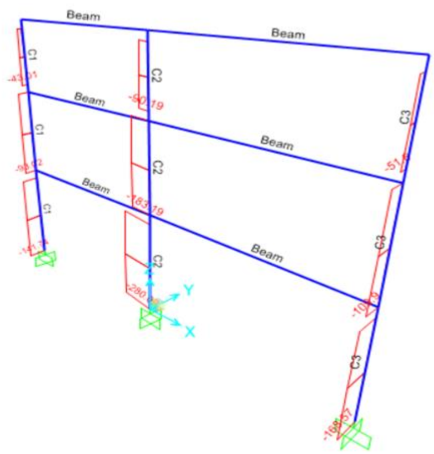

Figure 5. Axial force diagram (G+0.3Q)

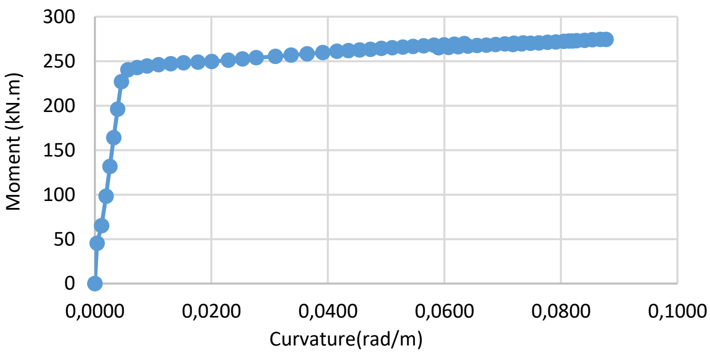

Figure 6. Moment curvature of beam B1(+)

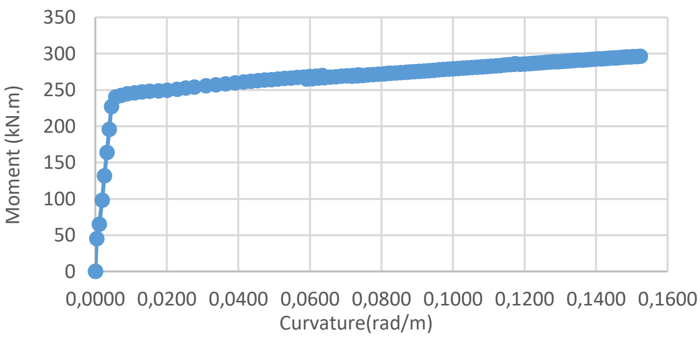

Figure 7. Moment curvature of beam B1(-)

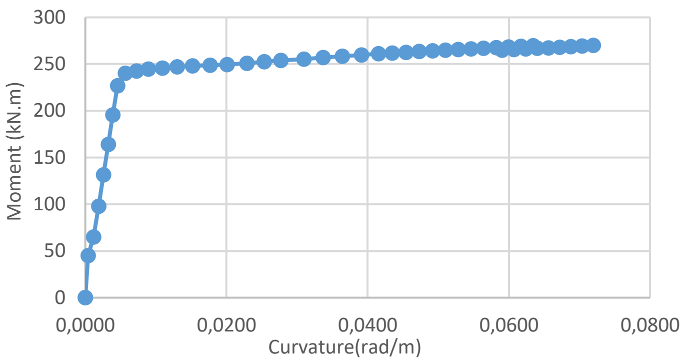

Figure 8. Moment curvature of beam B2(+)

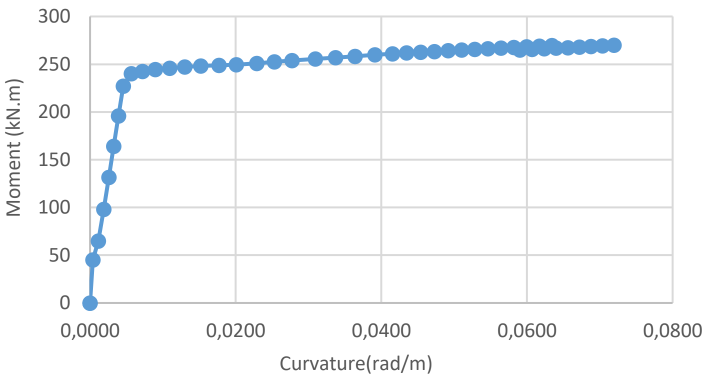

Figure 9. Moment curvature of beam B2(-)

Table 1. Moment curvature for beams

	B1		B2	
	M_Y (kN.m)	ϕ(rad/m)	M_Y (kN.m)	ϕ(rad/m)
M^+	120.41	0.006	120.515	0.00565
M^-	183.53	0.006	240.14	0.00412

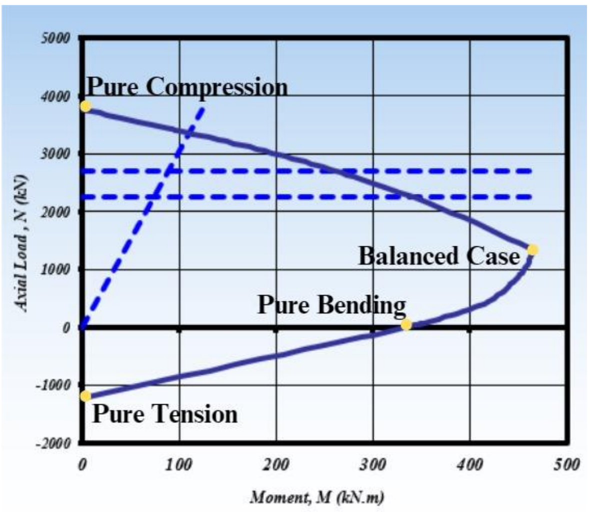

Figure 10. Axial force-Moment interaction diagram

Table 2. P-M analysis for column C1

Column C1		
	M(kN.m)	N(kN)
Pure Comp.	0	3697
Balanced Case	399	1302
Pure Bending	302.1	0
Pure Tension	0	-1147

Table 3. P-M analysis for column C2

Column C2		
	M(kN.m)	N(kN)
Pure Comp.	0	4113
Balanced Case	226.11	1460.8
Pure Bending	144.7	0
Pure Tension	0	-1138.4

Table 4. P-M analysis for column C3

Column C3		
	M(kN.m)	N(kN)
Pure Comp.	0	4122
Balanced Case	506.18	1504
Pure Bending	359.4	0
Pure Tension	0	-1147

According to the results of the pushover analysis, the capacity curve of the structure is determined, and the formation of plastic hinges is evaluated. Formation of the first plastic hinge in the RC frame is presented in Figure 11. The system transitioned to a collapse mechanism when beam B1 reached its predefined plastic rotation capacity of 5%, as defined by the hinge properties in the analysis model, based on FEMA-356 [1] guidelines. The analysis is terminated at this load level. Plastic hinges that occur at the end of members are presented in Figure 12. Pushover curve, base shear-lateral displacement relationship, is plotted in Figure 13.

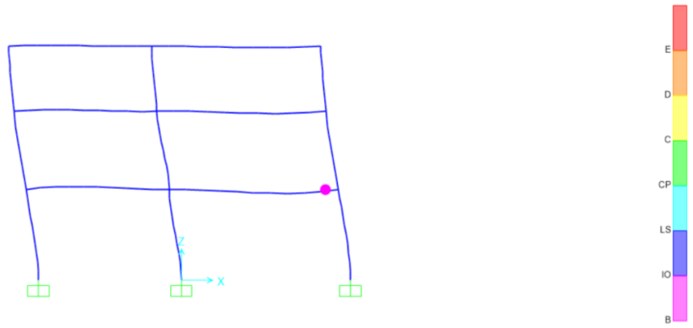

Figure 11. Formation of the first plastic hinge

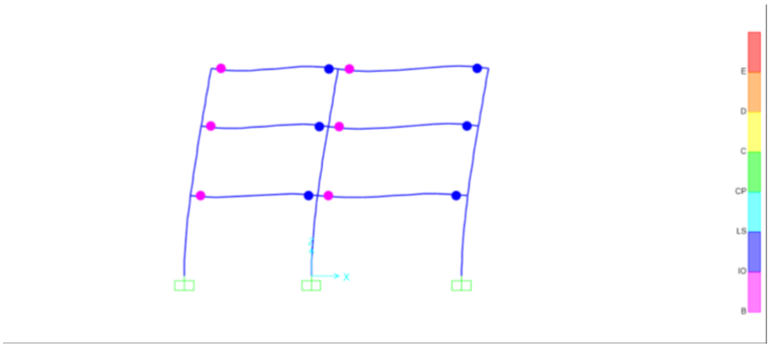

Figure 12. Plastic hinges at the member ends

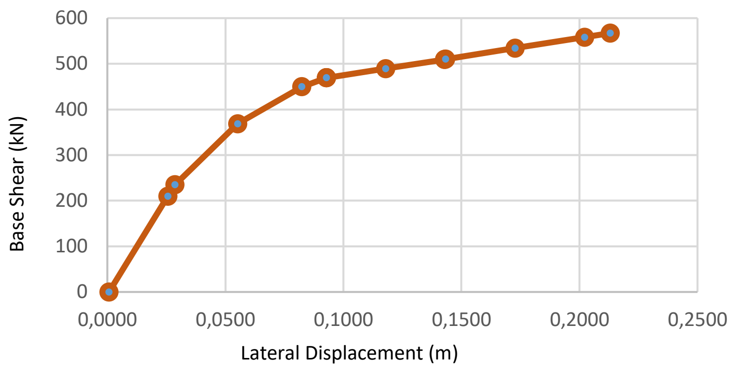

Figure 13. Base shear-lateral displacement relationship

The total mass of the structure is determined based on the computed concrete volume and reinforcement quantities. Considering the dimensions of the columns and beams, the total concrete volume is calculated as 14.17 m^3, which, with an assumed concrete density of 2500 kg/m^3, resulted in a total concrete weight of 35.43 tons. The reinforcement quantity, including both longitudinal and stirrup reinforcements, is estimated to be 3.12 tons. To assess the environmental impact of structural materials, the embodied carbon dioxide emissions are calculated using data from the Inventory of Carbon and Energy (ICE) Database [8]. The embodied CO_2-e coefficient for C25 concrete is considered as 0.113 kg CO_2-e per kg of concrete, while the coefficient for reinforcement steel is assumed as 1.4 kg CO_2-e per kg of steel [8]. Applying these values, the total carbon emissions for the concrete are calculated to be 4003 kg CO_2-e, while the reinforcement steel has contributed 4417 kg CO_2-e, leading to a total embodied carbon footprint of 8420 kg CO_2-e for the entire frame. This assessment indicates that reinforcement steel has a significant contribution to the total emissions, suggesting that future optimizations in material selection and sustainable concrete mixes could further reduce the environmental impact of RC frame designs.

The pushover analysis results reveal the structural capacity curve and plastic hinge formation patterns. Initially, the structure exhibited elastic behavior, but as lateral loads increased, plastic hinges first formed at beam ends (B1, B2) and affecting the global stiffness of the frame.

As the analysis progressed, beam B1 reached its 5% plastic rotation capacity, leading the structure to transition into a collapse mechanism. The capacity curve demonstrated that the structure maintained sufficient ductility up to a critical displacement level, beyond which the strength degraded significantly due to excessive deformation.

Furthermore, the embodied carbon assessment highlighted that for this RC frame, 43% of the CO_2-e emissions originated from the reinforcement steel and 57% from the concrete. This suggests that future research could focus on alternative reinforcement strategies or sustainable concrete mixes to further reduce the environmental impact of RC frame designs.

IV. DISCUSSION

The findings of this study demonstrate the effectiveness of pushover analysis as a tool for assessing the seismic performance of reinforced concrete (RC) frame structures. The analysis results show that plastic hinges formed at beam ends, providing insight into the progressive damage mechanisms under increasing lateral loads. These findings align with previous research emphasizing the capability of pushover analysis to identify structural capacity and predict displacement values.

This study also highlights the importance of understanding environmental impacts in structural design. The embodied carbon footprint of the analyzed frame is calculated primarily due to reinforcement steel and concrete materials. This suggests that optimization of reinforcement layouts and the use of alternative and sustainable materials could significantly reduce CO_2 emissions without compromising structural performance.

V. CONCLUSION

This study is targeted to evaluate pushover analysis of a reinforced concrete frame structure, focusing on plastic hinge formation and base shear – lateral displacement curve characteristics. Pushover analysis proved to be an effective method for assessing the nonlinear behavior of RC frame structures, offering valuable insights into failure mechanisms.

In addition to determining structural performance, the total embodied carbon footprint is calculated emphasizing the significant environmental impact of conventional reinforcement steel and concrete materials. This highlights the need for sustainable material choices to balance structural safety and environmental impacts. Future research to integrate pushover analysis and environmental impacts should be performed to provide seismic resilient and sustainable structures.

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