©2025 Published in 7th International Symposium on Natural Hazards and Disaster Management
16-18 May 2025 (ISHAD2025 Diyarbakır - Türkiye)

Analytical Modeling of Reinforced Concrete Frame

*1Erkan Bicici
*1Faculty of Engineering, Department of Civil Engineering, Bursa Technical University, Türkiye

Abstract:

Reinforced concrete (RC) structures with no seismic projection are vulnerable to earthquakes. To prevent catastrophic failures, strengthening seismically deficient structures is a significant option. However, the strengthening process starts by understanding and simulating the behavior of not only the RC members but also frames. The under- or overestimation of the capacity in terms of both loading and displacement may lead economical and vital loss. There are several modeling methods for RC members and frames that may confusion. In this study, a tested RC frame was analytically modeled in 2D and frame's behavior under cyclic loading was calculated using different modeling techniques. An open-source structural analysis software, OpenSees, is used for both modeling and analysis. The calculation of the analyses and results from experiments were compared to determine the most efficient modeling technique. The result of this comparison may provide a guidance for the engineers to calculate the lateral behavior RC frames under cyclic loading.

Keywords: reinforced concrete, 2D frame, OpenSees, cyclic analysis, analytical model

1. Introduction

Reinforced concrete (RC) structures are widely used around the world due to their durability, strength, and adaptability. However, many existing RC buildings, particularly those designed before the implementation of modern seismic codes, lack adequate seismic detailing. These deficiencies make them highly susceptible to damage or collapse during earthquakes, posing serious risks to human life and property [1], [2]. Strengthening such structures has therefore become a critical area of research and practice in structural engineering [3].

A fundamental step in the strengthening process is the accurate modeling and analysis of the structural behavior of RC frames under seismic loading. Reliable simulation is essential for assessing performance and predicting potential failure mechanisms. However, capturing the nonlinear behavior of RC members and frame systems under cyclic or dynamic loading presents a significant challenge due to the complex interaction of material nonlinearity, cracking, yielding, and stiffness degradation [4].

Numerous modeling approaches have been proposed in the literature, ranging from simplified lumped plasticity models to more detailed fiber-based distributed plasticity models [5]. While each method has its advantages and limitations, the selection of an appropriate modeling strategy often depends on the balance between computational efficiency and accuracy. Engineers and researchers may find it difficult to choose the most suitable approach for practical applications due to the variability in performance predictions among different techniques.

*Corresponding author: Address: Faculty of Engineering, Department of Civil Engineering Bursa Technical University, 16310, Bursa TÜRKİYE. E-mail address: erkan.bicici@btu.edu.tr, Phone: +905321636420

To address this challenge, this study focuses on evaluating the accuracy and effectiveness of various modeling techniques in simulating the cyclic behavior of RC frames. A previously tested RC frame specimen is modeled in 2D using different approaches within the open-source structural analysis platform OpenSees [6]. The analytical results are compared against experimental data to identify which modeling method best captures the frame's lateral response under cyclic loading. The outcomes of this study aim to provide practical guidance for structural engineers in selecting appropriate modeling strategies for seismic analysis and retrofit design.

2. Tested RC Frame

Ghannoum (2007) [7] conducted an extensive experimental study on a three-story, three-bay reinforced concrete (RC) frame at the University of California, Berkeley (Figure 1). The test structure was constructed at one-third scale to replicate typical office buildings constructed in the 1960s, particularly focusing on the seismic vulnerabilities associated with that era's design practices.

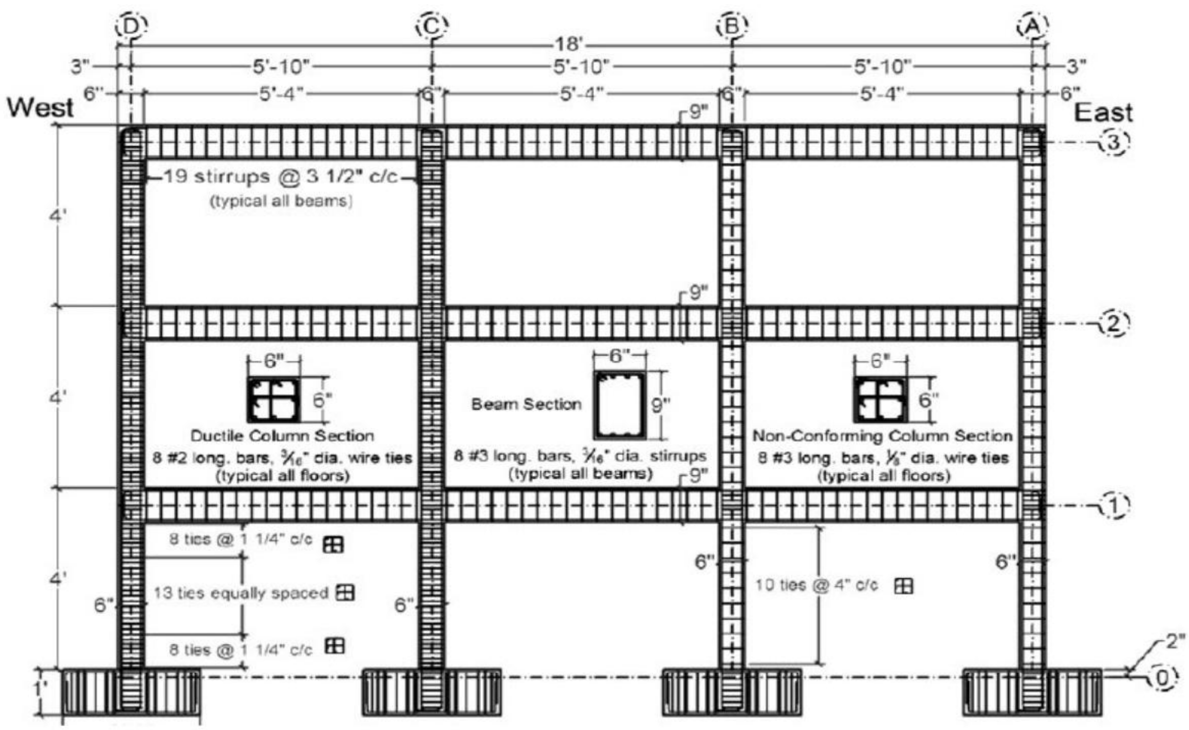

Figure 1. Details of tested RC frame (Ghannoum, 2007) [7]

The frame featured two distinct types of columns. Along the A and B axes, the columns were non-ductile, characterized by widely spaced transverse reinforcement and 90-degree end hooks—typical of pre-1970s construction and known to perform poorly under seismic loading. In contrast, the columns along the C and D axes were detailed in accordance with the seismic provisions of ACI 318-08, representing modern ductile detailing intended to enhance seismic performance. All columns had a square cross-section measuring 150 mm × 150 mm.

Beams in the frame were 150 mm wide and 230 mm deep, and the clear story height was uniformly maintained at 1000 mm across all levels. The axial load-to-capacity ratios applied to the first-story columns were 0.17 for the interior columns and 0.08 for the exterior columns, reflecting typical loading conditions that might be expected in practice. More detailed geometric and material properties of column are shown in Table 1.

Both the beams and the beam-column joints were designed to comply with ACI 318-08 seismic requirements for special moment-resisting frames. This ensured enhanced ductility and energy dissipation capacity during lateral loading. During testing, a weak-column–strong-beam behavior was observed, which was consistent with the intended failure mechanism. No significant damage or failure was recorded in the beams or the beam-column joints, aligning with the design expectations.

The test program included a series of four dynamic tests performed on a shake table, with each test subjecting the frame to progressively increasing ground motion intensities. For the purposes of numerical model validation and performance assessment, the results of the fourth and most severe dynamic test—corresponding to the strongest input ground motion—were utilized.

Table 1. Geometric and material properties of columns in the tested frames

Column Name	L (mm)	b (mm)	h (mm)	a/d	f'_c (MPa)	f_y (MPa)	ρ_l (%)	ρ_v (%)	s (mm)	P (kN)	Axial load ratio
A1	1000	150	150	3.70	24	445	0.024	0.0018	100	45	0.08
B1	1000	150	150	3.70	24	445	0.024	0.0018	100	90	0.17
C1	1000	150	150	3.7	24	445	0.011	0.0125	30	90	0.17
D1	1000	150	150	3.7	24	445	0.011	0.0125	30	45	0.08

2.1. Analytical Modeling of Tested Frame

An open-source structural analysis platform OpenSees [6] is used for modeling and analyzing the previously tested RC frame. The elements of the frame are modeled according to the details provided by Ghannoum (2007). The details of models in element level can be found on Bicici and Sezen (2023).

Two different modeling techniques are used to compare the applicability of each model. The difference between models is using rigid joint model. Figure 2 and 3 show the analytical models for soft and rigid joints, respectively. For rigid joint an element named as ‘Joint2d’ is used from the OpenSees library.

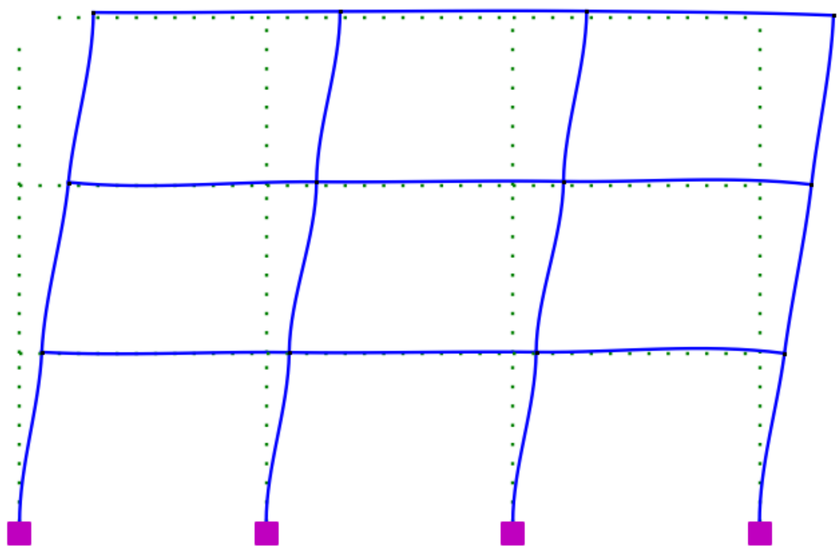

Figure 2. Analytical model of tested frame without rigid joint

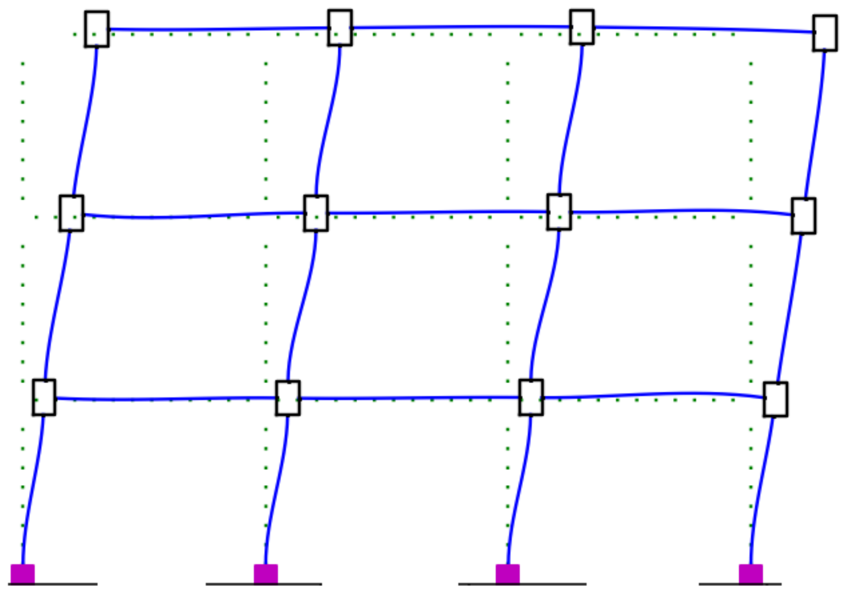

Figure 3. Analytical model of tested frame with rigid joint

3. Analysis Results and Discussion

The previously tested reinforced concrete (RC) frames were modeled and analyzed using the OpenSees finite element platform, incorporating the previously developed analytical model [9]. In the quasi-static analysis, the displacement history recorded during the experiments was applied at the top of the frame to simulate lateral loading. Throughout the analysis, key structural response parameters—including inter-story drifts and column reactions—were monitored and calculated. The resulting lateral load–displacement relationships derived from the numerical simulations were then compared with the corresponding experimental results to evaluate the accuracy and predictive capability of the proposed model. Figure 4 compares measured and calculated latera load-displacement relationship of each 1st –story column.

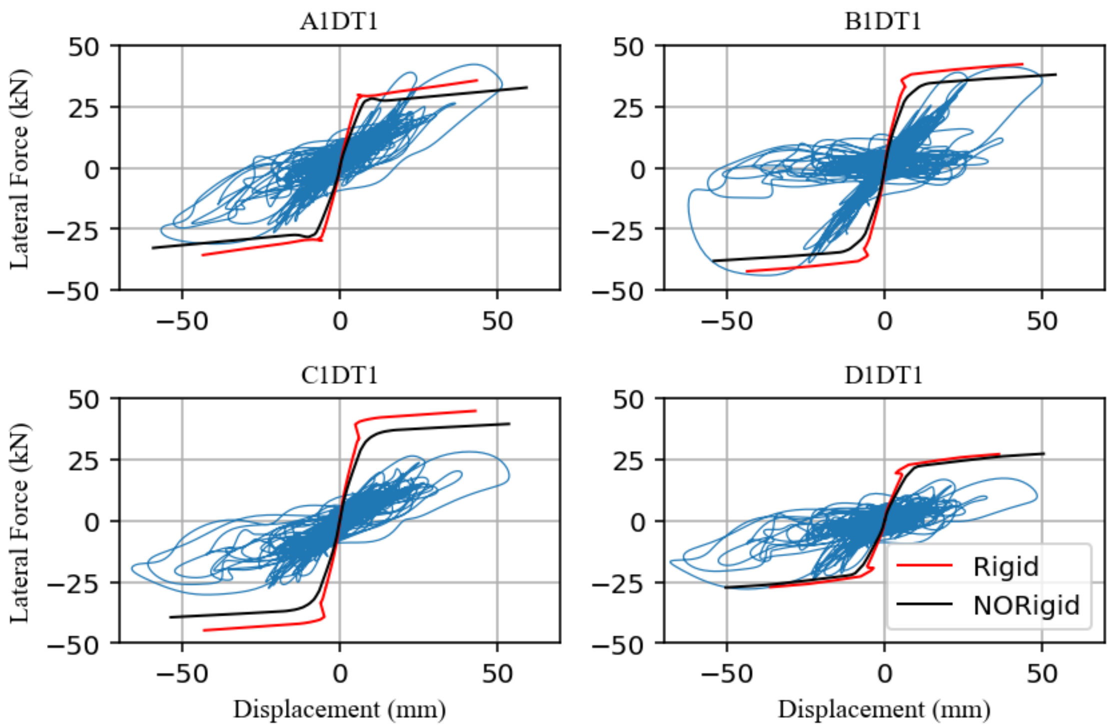

Figure 4. Comparison of measured and calculated lateral load-displacement relation of each 1st-story column

It should be noted that this study highly focuses on the modeling technique of frame joints. Thus, the details of column modeling such as slip and shear displacement are omitted to keep study on scope. This case clarifies the difference between calculated and measured behavior.

Figure 4 highlights the difference between two modeling technique. The model with rigid joints calculates slightly higher strength. Additionally, more stiff behavior is estimated for pre-peak behavior with the model having rigid joints.

Conclusions

A quasi-static analysis of the modeled reinforced concrete (RC) frame was carried out using the OpenSees finite element framework. The numerical responses of the columns were systematically compared with the experimental lateral load–displacement relationships obtained from previously conducted tests. The results of this comparison indicate a high level of agreement between the analytical and experimental data, thereby validating the effectiveness and suitability of the both analytical modeling approach for accurately capturing the nonlinear seismic response of RC frame structures. The model with rigid joint calculates both stiffer pre-peak behavior and higher lateral load strength.

References

[1] FEMA 356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings.

[2] Paulay T, Priestley MJN. Seismic Design of Reinforced Concrete and Masonry Buildings;1992.

[3] Sezen H. Shear Deformation Model for Reinforced Concrete Columns.” Structural Engineering and Mechanics 2008;28(1):39-52.

[4] Mander JB, Priestley MJN, Park R. Theoretical stress-strain model for confined concrete. Journal of Structural Engineering 1988;114(8): 1804-1826 https://doi.org/10.1061/(ASCE)0733-9445(1988)114:8(1804)

[5] Sivaselvan MV, Reinhorn, AM. Hysteretic models for deteriorating inelastic structures. Journal of Engineering Mechanics 2001;127(11). DOI: 10.1061/(ASCE)0733-9399(2001)127:11(1200)

[6] McKenna F, Fenves GL, Scott MH. OpenSees: A framework for advanced earthquake engineering simulation. Software Release; 2010.

[7] Ghannoum WM. Reinforced concrete frame with light transverse reinforcement Ph.D. Dissertation, University of California, Berkeley, 392, 2007.

[8] ACI Committee 318-08 Building Code Requirements for Structural Concrete and Commentary, American Concrete Institution (ACI), Farmington Hills, MI; 2011.

[9] Bicici E, Sezen H. Cyclic displacement model for reinforced concrete columns. Earthquake Engineering & Structural Dynamics 2023;52(1):71–87. https://doi.org/10.1002/eqe.3747.