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MODELING AND ANALYSIS OF STIFFNESS AND STRENGTH DEGRADATION IN SUBSTANDARD REINFORCED CONCRETE BEAM-COLUMN JOINTS UNDER CYCLIC LOADS.

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Abstract

The research focuses on modeling the stiffness and strength degradation of substandard reinforced concrete (RC) beam-column connections under cyclic loads and their impact on the overall structural behavior. It examines the seismic performance and deficiencies of substandard RC frames, particularly beam-column joints. Two analytical models of a full-scale spatial RC structure, intentionally designed for gravity loads, were evaluated using the DRAIN-3DX program with a fiber beam-column element (type 15). The study involved two types of inelastic analyses: pushover analysis with various lateral load patterns and dynamic analysis under different ground acceleration levels. The first model represented the frame without accounting for joint degradation. Comparison with experimental results revealed that the model adequately represented the frame's behavior under low excitation levels. However, at higher excitation levels, joint deterioration became significant and needed to be incorporated into the model. In the second model, pullout fibers were introduced to simulate bar slippage due to inadequate reinforcement detailing, while gap fibers were added to represent concrete crushing. The revised model showed notable improvements in accuracy (15% better than the first model). Strain time-history analysis indicated that rebar slippage occurred at Peak Ground Accelerations (PGAs) of 0.3g and 0.4g. The performance level of the structure was categorized based on PGA levels. At 0.05g and 0.1g, the structure was classified as "Fully Operational," retaining its original stiffness and strength. At 0.2g, the performance level shifted to "Immediate Occupancy," indicating minor damage. However, at 0.3g and 0.4g, the

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structure experienced severe damage. The findings highlight that joint deficiencies increase the vulnerability of both the joint and the overall structure, reducing its performance level. The study demonstrated that DRAIN-3DX could simulate the degradation of deficient joints with 85% accuracy. These conclusions offer valuable insights for enhancing joint rehabilitation techniques and improving design methodologies.

Keywords: Cyclic Load, Substandard Beam-Column Joint, DRAIN-3DX, Time History Analysis, Pushover Analysis, Performance Based Point.

1 INTRODUCTION

Reinforced concrete (RC) beam-column joints are pivotal to the seismic performance of structures, as they facilitate the transfer of forces between beams and columns during seismic events. However, substandard RC beam-column joints are often characterized by inadequate detailing, poor material quality, and non-compliance with modern seismic codes are highly susceptible to stiffness and strength degradation under cyclic loading. This degradation can lead to catastrophic failures during earthquakes, as demonstrated by numerous past seismic events. A thorough understanding of the mechanisms driving stiffness and strength degradation in these joints is crucial for developing effective retrofitting strategies and enhancing the seismic resilience of existing structures.

Recent advancements in computational modeling and experimental testing have provided valuable insights into the behavior of RC beam-column joints under cyclic loads. However, a significant gap remains in the literature regarding the systematic modeling and analysis of substandard RC beam-column joints, particularly those constructed prior to the adoption of modern seismic codes. This study seeks to address this gap by developing a comprehensive model to predict stiffness and strength degradation in substandard RC beam-column joints under cyclic loading, validated through experimental data.

Many existing buildings in Europe constructed before the mid-1970s were designed according to outdated building codes that primarily considered gravity loads for beams and columns, neglecting the role of joints in the overall structural response. Consequently, these buildings often exhibit serious structural deficiencies by modern seismic design standards, stemming from a lack of capacity design principles and poor reinforcement detailing. These deficiencies result in a significant lack of ductility at both local and global levels, as evidenced by the severe damage and collapses observed in recent earthquakes (e.g., Mexico 1999, Turkey 1999, Taiwan 1999, Greece 1999, Iran 2004, and Pakistan 2005) as shown in Figure 1 and Figure 2. During seismic events, beam-column connections in reinforced concrete moment-resisting frames are subjected to high shear stress. Older joints, designed without seismic reinforcement detailing, are ill-equipped to withstand these stresses, leading to poor performance and failure [1]. Experimental studies by Filippou et al. [2] revealed that joint deformation due to bar slippage can account for over 50% of the total deformation in beam-column subassemblies, highlighting the importance of considering bond-slip effects in dynamic analyses. Similarly, Hassan [3] noted that insufficient embedded bar lengths can lead to premature bond pullout failures at less than 25-50% of the joint's actual shear capacity.

Recent research has focused on understanding the cyclic behavior of substandard RC beam-column joints to identify key factors influencing their performance. Velasco et al. [4] conducted a comprehensive review, synthesizing findings on crack patterns, energy dissipation, bond behavior, and stiffness degradation in beam-column joints (BCJs) under cyclic loads. They emphasized that BCJ behavior is influenced by assembly geometry, material characteristics, and external conditions, underscoring the need for detailed assessments of these parameters in design and evaluation processes. Experimental investigations have shown that substandard joints with plain reinforcing bars exhibit significant stiffness degradation and reduced energy dissipation capacity under cyclic loading, further highlighting the vulnerabilities associated with inadequate detailing. Nonlinear finite element analyses of steel fiber-reinforced concrete (SFRC) beam-column joints have demonstrated that SFRC joints experience slower stiffness degradation compared to conventional RC joints, suggesting that incorporating steel fibers can enhance seismic performance.

Lowes and Altoontash [5] developed a model to simulate the response of RC beam-column joints under reversed-cyclic loading, capturing key inelastic mechanisms such as joint core shear failure and anchorage failure of longitudinal reinforcement. This model provides a valuable tool for simulating joint behavior under seismic conditions. Further research by Velasco et al. [6] on seismically non-conforming interior RC beam-column joints revealed high shear stresses in the panel region, significant bond-slip, and strength degradation due to diagonal crack formation, reinforcing the importance of proper joint design and detailing.

Zhang et al. [7] conducted experimental and numerical studies on the cyclic behavior of RC beam-column joints, emphasizing the role of joint shear strength and bond-slip effects. Their findings highlighted the importance of proper detailing in enhancing joint performance under seismic loads. Similarly, Kumar and Sharma [8] developed a finite element model to simulate the cyclic response of RC joints, demonstrating the influence of concrete confinement and reinforcement ratio on joint ductility. Substandard RC beam-column joints often exhibit premature stiffness and strength degradation due to inadequate reinforcement detailing and poor material properties. Ahmed et al. [9] identified shear failure as the primary mode of degradation in substandard joints and emphasized the need for retrofitting techniques to improve their seismic performance. Chen et al. [10] analyzed the effects of corrosion on the cyclic behavior of RC joints, revealing significant reductions in stiffness and energy dissipation capacity due to reinforcement corrosion.

Recent advancements in computational modeling have enabled more accurate predictions of the cyclic behavior of RC joints. Li et al. [11] proposed a modified constitutive model for concrete under cyclic loading, incorporating stiffness degradation and strength deterioration, which showed good agreement with experimental results for both standard and substandard joints. Patel and Lee [12] developed a machine learning-based approach to predict the cyclic response of RC joints, demonstrating the potential of data-driven methods in structural engineering.

Several studies have explored retrofitting techniques to enhance the seismic performance of substandard RC beam-column joints. Wang et al. [13] investigated the effectiveness of fiber-reinforced polymer (FRP) wraps in improving joint stiffness and strength, finding that FRP retrofitting significantly reduces stiffness degradation under cyclic loading. Similarly, Gupta and Singh [14] evaluated the performance of steel jacketing as a retrofitting technique, reporting improved energy dissipation and ductility in retrofitted joints.

This study aims to develop a comprehensive model for predicting stiffness and strength degradation in substandard RC beam-column joints under cyclic loading and to validate the model using experimental data. By addressing the existing gaps in literature, this research seeks to contribute to the development of more effective retrofitting strategies and improve the seismic resilience of existing structures.

Figure 1: Beam-Column Joint Failure in RC Buildings Turkey, 1999 [15].

Figure 2: Joint Failure due to Inadequate Detailing Taiwan, 1999 [3].

2 RESAECH SIGNIFICANCE

This research contributes to the field of structural engineering by providing a deeper understanding of the cyclic behavior of substandard RC beam-column joints. The developed model will enable engineers to predict stiffness and strength degradation more accurately, facilitating the design of effective retrofitting strategies. Additionally, the findings of this study will help improve the seismic resilience of existing structures, particularly in regions prone to earthquakes.

3 EXPERIMENTAL INVESTIGATION

The structure analyzed in this study is derived from the Ecoleader Project (No. 2) and serves as a case study. This structure was constructed and tested on the AZALEE shaking table at a laboratory in Saclay, France, between October and November 2004 [16]. As reported by Chaudat et al. [16], the structure was intentionally designed to reflect the characteristics of many existing buildings in Europe, adhering to outdated building codes with inadequate detailing and no consideration of capacity design principles. The structure under investigation is a full-scale, one-bay, two-story spatial moment-resisting reinforced concrete (RC) frame. Figure 3 illustrates the primary geometrical features of the frame from a side view.

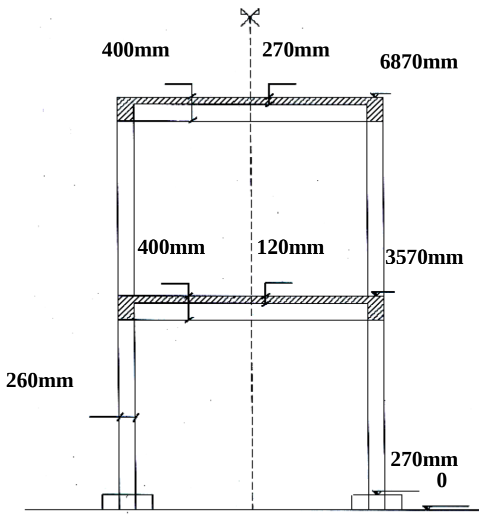


Figure 3: Geometry of the frame from the side view [16].

4 ANALYTICAL MODEL (CASE 1)

4.1 Geometry

The frame was discretized into a series of nodes and elements within the DRAIN-3DX software. The final analytical model of the frame is depicted in Figure 4. As shown in the figure, multiple nodes were defined, each assigned a unique four-digit identifier. The first two digits indicate the node's position along the global Y-axis, while the last two digits specify its location along the global X-axis. At each node, six degrees of freedom were established: translations in the X, Y, and Z directions, and rotations about the X, Y, and Z axes. To simulate the frame as a two-dimensional structure, restraints were applied to the nodes. All nodes, except those at the foundation (1010 and 1020), were permitted to move freely in the X and Y directions and rotate about the Z-axis. The foundation nodes were constrained using a stiff support spring, ensuring the frame moved without relative displacement to the ground. Notably, the program requires this type of support configuration, as a fully fixed support would prevent the analysis from running.

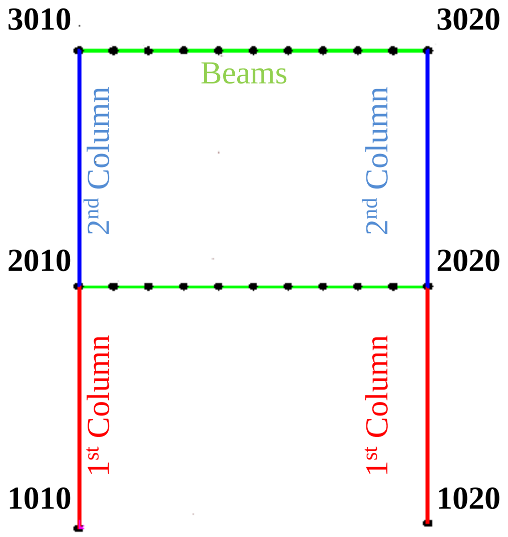


Figure 4: Geometry of the Frame in DRAIN-3DX.

4.2 Mass of the Frame

The mass was modeled as lumped at the nodes. Since the structure was analyzed as a two-dimensional frame, half of the total mass was calculated and assigned to the model. The computed mass for each floor is summarized in Table 1.

Node	2010	2020	3010	3020
Mass (ton)	4.925	4.925	4.65	4.65

Table 1: Mass Distribution.

4.3 Damping of the Frame

Rayleigh damping was employed to represent the damping characteristics of the structure. This approach assumes that viscous damping is proportional to both nodal mass and element stiffness. Consequently, two coefficients, the mass damping coefficient and the element viscous damping coefficient—must be specified in DRAIN-3DX at the start of the analysis. For this study, modal damping ratios of $\zeta_1 = 3\%$ and $\zeta_2 = 2\%$ were utilized.

4.4 Material Model

In this study, the inelastic stress-strain relationship specified in Eurocode 2 (EC2) [17] was adopted to model the behavior of both concrete and steel materials.

4.5 Element Modelling

DRAIN-3DX offers a variety of element types, ranging from simple elastic elements to advanced fiber-based elements, designed to model bars, connections, beams, and columns, depending on the research objectives [18]. In this study, the fiber beam-column element (Type 15) was utilized to model all beams and columns. This element divides the deformable portion into multiple segments, with behavior monitored at the center of the cross-section within each segment. While cross-section properties remain constant within a segment, they can vary between segments. Each cross-section is either treated as elastic or subdivided into multiple fibers [18]. Unlike lumped plasticity models, where inelastic behavior is concentrated in zero-length plastic hinges, this element model distributes plasticity across the length of the deformable region, representing a distributed plasticity approach [18]. A visual representation of the element model is provided in Figure 5.

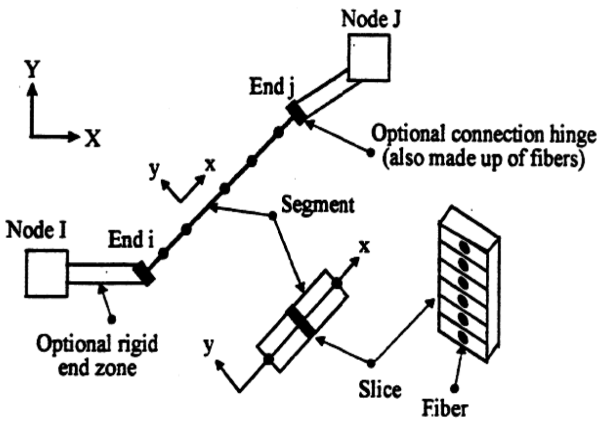


Figure 5: Element Type 15 Model [18].

5 ANALYSIS RESULTS (CASE 1)

5.1 Pushover Analysis

In this analysis, the structure was subjected to various lateral load distributions applied at nodes 2010 and 3010. The load patterns examined include the Eurocode 8 (EC8) [19] modal pattern and the widely used triangular pattern. Node 3010 served as the control node for monitoring the response. Figure 6 illustrates the capacity curves for load distributions of 2:1 and 1.9:1. Under the 2:1 load distribution, the structure collapsed at a base shear of 72 kN. For the 1.9:1 load distribution, a story mechanism formed in the second story at a base shear of 71.92 kN. Figure 7 depicts the progression of plastic hinges and the development of story mechanisms for both load distributions.

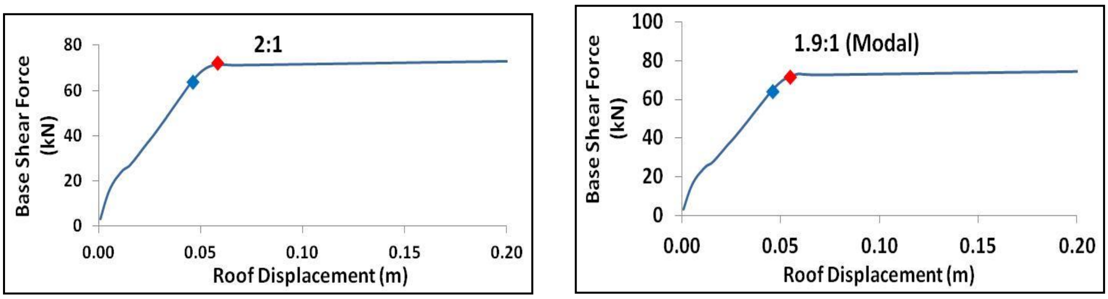


Figure 6: Capacity Curve.

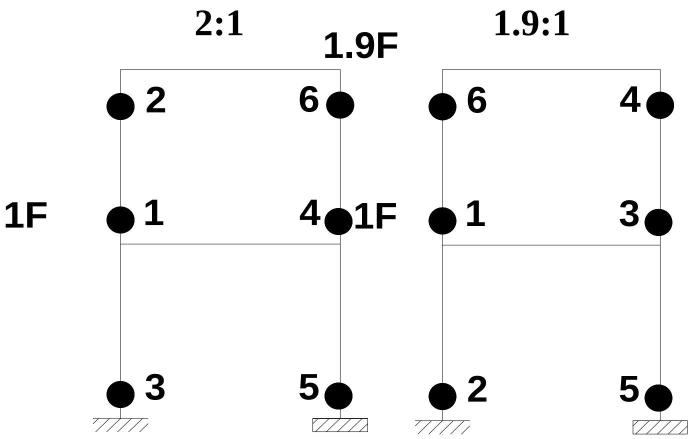
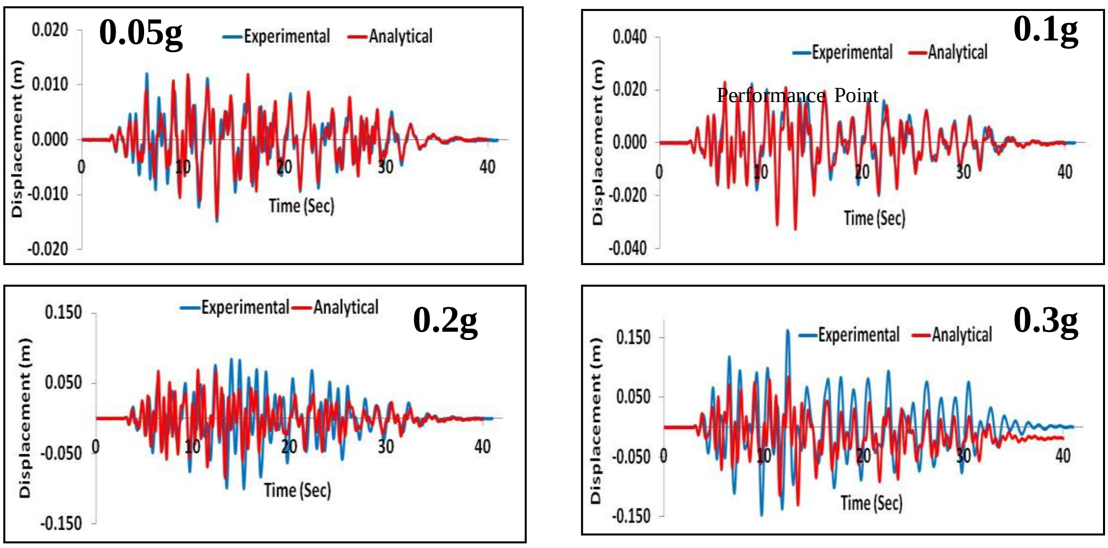


Figure 7: Plastic Hinge Distributions.

5.2 Time-History Analysis

To evaluate the actual behavior of the frame under seismic conditions, displacement records derived from artificial earthquake records with peak ground accelerations (PGA) of 0.05g, 0.1g, 0.2g, 0.3g, and 0.4g were utilized. Figure 8 presents a comparison between the analytical and experimental results at node 3010 for varying PGA levels. As evident from the figure, the model accurately captures the structure's behavior at lower PGA levels (0.05g and 0.1g). However, significant discrepancies arise at higher PGA levels, indicating limitations in the model's ability to fully represent the structure's response under more intense seismic actions.



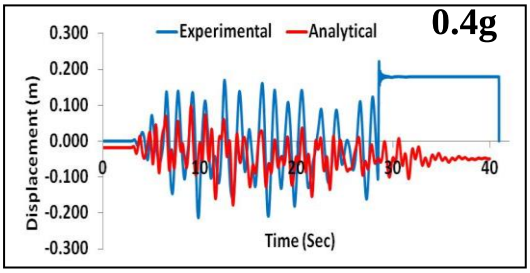


Figure 8: Displacement Time-Histories.

5.3 Performance Point

As defined by ATC-40 [20], the performance point is the intersection of the demand and capacity curves, representing the expected damage level of the structure. It provides a performance evaluation of the structural behavior and indicates whether localized collapse is likely to occur. Figure 9 demonstrates the performance levels of the structure under PGA levels of 0.05g, 0.1g, and 0.2g. At 0.05g and 0.1g, the capacity curve exceeds the demand curve, indicating that the structure maintains its original strength and stiffness, and the performance level is classified as "Fully Operational." However, at 0.2g, the performance level shifts to "Immediate Occupancy," suggesting the structure may experience minor damage and cracking. These analytical results align closely with the damage observed during laboratory testing.

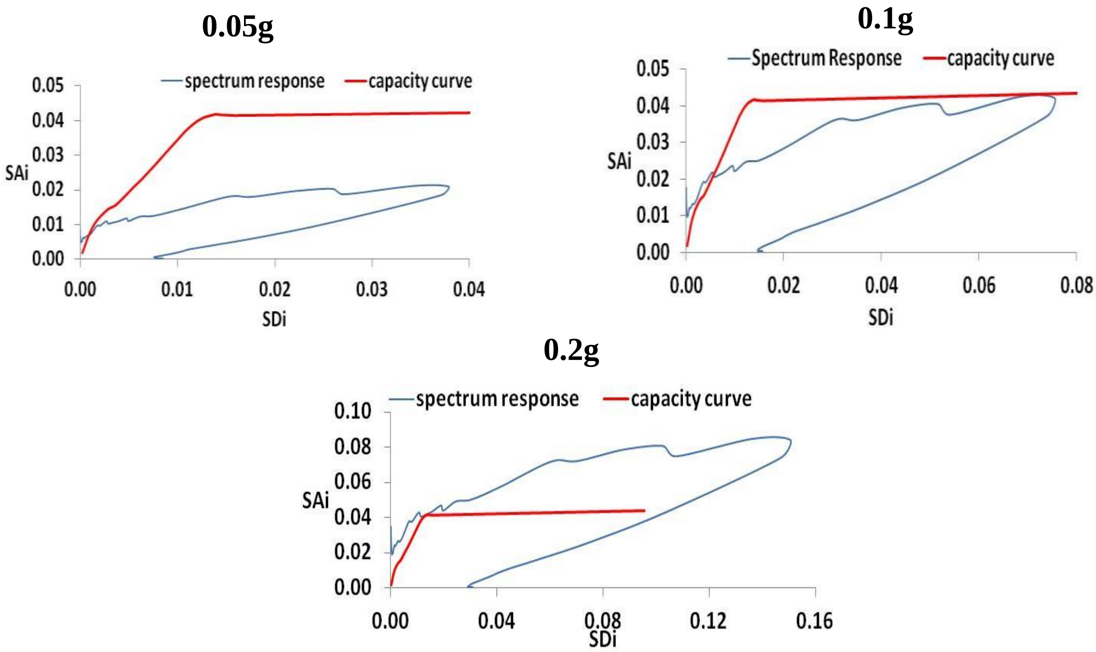


Figure 9: Capacity- Response Spectrum Curves.

5.4 Discussion

In terms of the sequence of plastic hinges, the load ratio of 2:1 shows better alignment with the dynamic analysis results. Additionally, the 2:1 load ratio produced outcomes similar to the EC8 modal pattern (1.9:1) regarding the sequence of plastic hinges and the collapse base shear force. As previously noted, the experimental results generally exceeded the analytical results, as the actual frame underwent greater degradation, which should also be accounted for in the model. Analytically, the frequency of the first mode decreased by 45%, whereas experimentally, it dropped by 64%. Furthermore, it was determined that the structure's design capacity corresponds to a PGA of 0.1g; however, at higher PGA levels of 0.3g and 0.4g, the structure would sustain severe damage.

6 ANALYTICAL MODEL (CASE 2)

6.1 Geometry

The new model represents a modified version of the previous one. In this updated model, the same beam-column element (Type 15) was used to simulate both the structural elements and the joints. As illustrated in Figure 10, additional nodes were incorporated into the columns to accurately represent the beam-column joints. According to Powell and Campbell [18], connection hinges can be defined at the ends of elements to model beam-column joint deformations. These hinges are zero-length fiber hinges, and for each fiber type, the properties can be configured to account for pullout and crack opening at the connection interface.

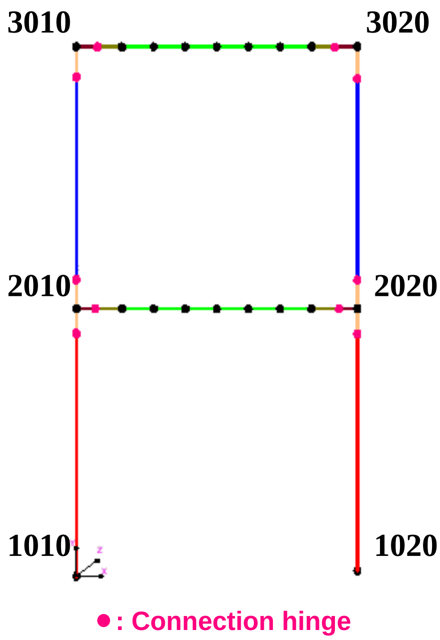
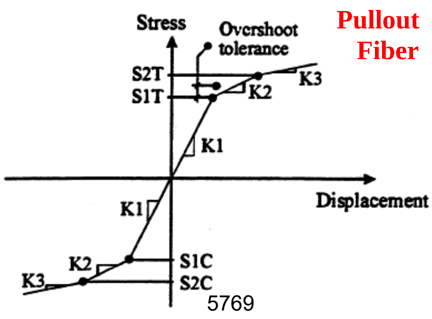


Figure 10: Geometry of the Frame in DRAIN-3DX (New Model).

6.2 Pullout and Gap Fiber Property

Two types of fibers can be utilized in connection hinges: pullout fibers and gap fibers. As outlined by Powell and Campbell [18], pullout fibers are employed to model bar deformations within the connection region, such as bond-slip failures, while gap fibers are used to represent concrete deformations at the joint interface, including concrete cracking. The fundamental properties of pullout and gap fibers are illustrated in Figure 11.



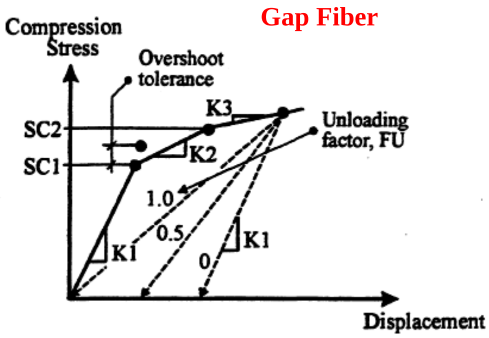


Figure 11: Gap and Pullout Basic Properties [18].

6.3 Analysis Results

The updated model of the frame was subjected to the same set of ground motions to evaluate its performance. Figure 12 presents a comparison between the analytical results from the new model and the experimental data at node 3010. Results for 0.05g and 0.1g PGA levels are not displayed, as the initial model already demonstrated a satisfactory representation of the structural response at these lower intensities. However, at higher PGA levels, the new model exhibits a significant improvement, with a 15% enhancement in accuracy compared to the previous model. This improvement highlights the effectiveness of the modifications, particularly in capturing the complex behavior of beam-column joints and their influence on the overall structural response under seismic loading. The refined model better aligns with experimental observations, demonstrating its capability to more accurately predict the frame's performance under dynamic conditions.

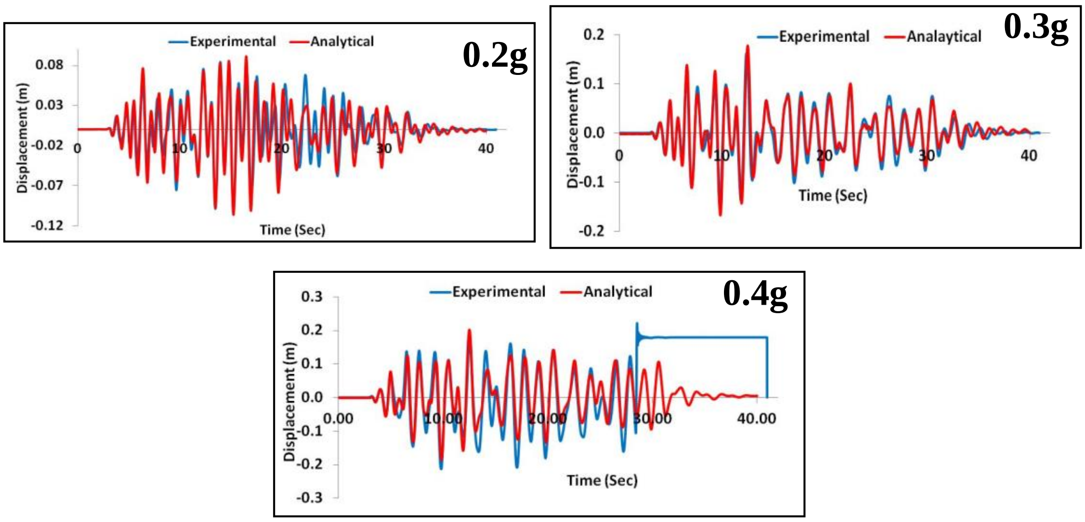


Figure 12: Displacement Time-Histories.

6.4 Discussion

As demonstrated earlier, the updated model accurately captures the actual behavior of the frame with greater precision. The analytical frequency decreased by 54%, representing a more significant reduction compared to the initial model and aligning more closely with the experimental degradation. This improvement underscores the enhanced capability of the new model to replicate the structural response under seismic conditions. Figure 13 illustrates a comparison between the analytical and experimental strain time-history under PGA levels of 0.3g and

0.4g. As evident from the figure, the analytical strain values are lower than the experimental ones, suggesting that bar slippage has occurred in the actual structure. This discrepancy highlights the importance of accounting for bond-slip effects in the model to better simulate real-world behavior, particularly under higher seismic intensities. The refined model's ability to more closely match experimental data demonstrates its potential for improving the accuracy of seismic performance assessments.

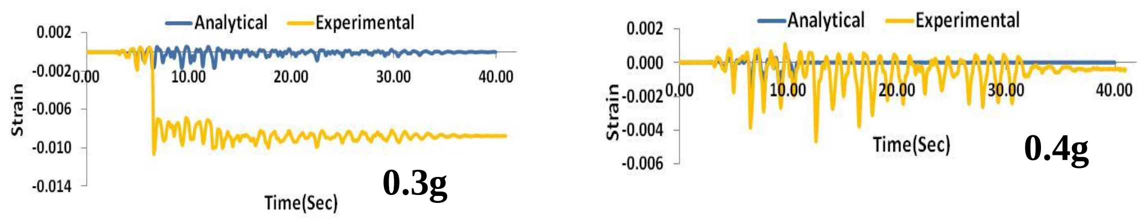


Figure 13: Strain Time-Histories.

7 CONCLUSIONS

In conclusion, deficiencies in structural joints significantly amplify the vulnerability of both the joints and the overall structure, leading to a substantial reduction in the performance level. The seismic behavior of a deficient joint can be effectively modeled using appropriate techniques, such as pullout and gap fibers, to simulate the damage and response under seismic loading. The DRAIN-3DX model has proven to accurately capture the degradation of deficient joints, with an accuracy of up to 85% when compared to actual observed degradation. This level of precision makes the model an invaluable tool for further research aimed at developing improved joint strengthening methods and refining design approaches. By leveraging this model, future studies can contribute to enhancing the resilience and safety of structures subject to seismic events.

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