

IMPROVEMENT THE BEHAVIOR OF REGION OF REINFORCED CONCRETE BEAM-COLUMN CONNECTION SUBJECTED TO SEISMIC LOADS: ROLES OF CARBON FIBER REINFORCED POLYMER

Noor Alhuda Sami Aljabbri^{1*}, Fareed Hameed Majeed², Abdulamir Atalla Karim³

Abstract: This study focuses on investigating the seismic behaviors of non-seismic joints, intermediate design joints, and the strengthening of non-seismic joints in frame buildings. For this purpose, a six-story frame building was designed according to the research objectives. The first frame assumed that the building was constructed with non-seismic joints lacking transverse reinforcement in the joint panel. According to ACI 318-19, the second building utilized the reinforcement detailing requirements for an intermediate moment frame. The third frame was strengthened utilizing carbon fiber reinforced polymer (CFRP) materials, with one layer covering the beam-column joint at a distance of 0.5 meters. The fourth model used two layers of CFRP to cover the beam-column joint of the non-seismic frame building. The final model, constructed similarly to the third model, used a CFRP length of 1.25 meters at the beam-column joint. The objective of reinforcing the frame structure in the beam-column joint area was to ensure safe seismic performance as specified in ACI 374.2R-13. Finite element analysis of the frame buildings was performed to evaluate their seismic behaviors using full-scale models. As previously indicated, following the experimental and numerical verification of the joint, the same element, material properties, and procedures were adopted to model the frame building using ABAQUS. El Centro earthquake loading was applied to the frame buildings. All frame buildings had the same number of longitudinal reinforcements and dimensional size to compare their seismic behaviors. The research variables were the types of joints used in the frame buildings. Numerical investigations revealed that strengthening the beam-column joint reduces the occurrence of soft story failure mechanisms related to joint strength. The joints play a pivotal role in affecting the seismic behavior of reinforced concrete frame buildings. Strengthening and seismic joints limit lateral displacement and roof displacement, reducing the lateral drift ratio demand and ensuring the frame building meets life safety and immediate occupancy performance levels. In contrast, inadequate structural detailing, such as a lack of transverse reinforcement in joints, causes steel yielding and concrete cracking, leading to the collapse of the frame building.

Introduction

Nowadays, numerous of experimental and analytical studies have been focused to gain a thorough understanding of the behavior of reinforced concrete beam-column (RCBC) joints under seismic loads, as their high strength is crucial for preventing the collapse of civil construction foundations. Most of these studies primarily focused on

¹ Department of Civil Engineering, Faculty of Engineering, University of Basrah, 61004, Basrah, Iraq.
Email: noorsami738@gmail.com

² Department of Civil Engineering, Faculty of Engineering, University of Basrah, 61004, Basrah, Iraq.
Email: fareed.majeed@uobasrah.edu.iq

³ Department of Civil Engineering, Faculty of Engineering, University of Basrah, 61004, Basrah, Iraq.
Email: abdulamir.karim@uobasrah.edu.iq

*Correspondence: noorsami738@gmail.com

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the construction and testing of joint of beam-column sub-assemblies to identify the factors influencing their behavior. Characteristics such as joint shear strength (JSS), reinforcement details, connection geometry, and axial loading were assessed [2, 11, 14]. Given that different types of connections—interior, exterior, and corner (knee)—exhibit distinct performance, it was important to analyze their individual attributes. Additionally, the seismic behavior of these connections was assessed using various analytical methods. Different parameters in the analytical models were adjusted to simulate the factors responsible for the failure of RCBC joints under seismic loading [37].

To improve the structural integrity of reinforced concrete beam-column (RCBC) connections, methods such as steel caging, fiber-reinforced polymers (FRPs), and concrete jacketing have been employed [4]. Additionally, recent studies have explored the use of hybrid elements and materials to strengthen RCBC linkages [9, 16]. However, in instances where enhancing a structure's ability to resist horizontal forces is necessary, reinforcing the columns should suffice [21]. It is crucial to address the connection of beam-column further, as it experiences significant forces within a confined space. The behavior of these joints greatly influences the structural response, especially in structures designed to support vertical loads only and in linkages lacking transverse reinforcement [6]. These joints are considered among the weakest components of the RCBC frame under seismic stress. Various strategies have been developed for reinforcing these beam-column joints, involving the insertion of concrete, composite materials, and steel plates [25, 27, 29, 34].

Joints are located within the column at the deepest part of the framing beam. Moment-resistant frames consist of internal (IJs), external (EJs), and corner joints (CJs) [22]. IJs occur when four timbers enclose the vertical sides of a column. An EJs are formed when one beam frames into a vertical column face, with two additional beams framed from vertical orientations. Researchers have long debated the factors significantly affecting the Joint Shear Strength (JSS) of Reinforced Concrete Beam-Column (RCBC) structures under loading [19, 38]. Consequently, JSS has become a critical aspect of RCBC analysis. To gain a thorough understanding, numerous scholars have developed JSS models and conducted experimental studies, highlighting their benefits and limitations. Various components have been used in empirical JSS models, and a comparison of these models indicates substantial differences in prediction accuracy. This discrepancy is primarily due to the consideration of different JSS variables, leading to varied results. The key factors determining JSS include concrete compressive strength (CS), beams-confined joints, anchorage systems for RC beam-column joints, and transverse reinforcement in joints [15].

Components of the building to exhibit a certain degree of flexibility. Seismic considerations were not integrated into construction regulations until the 1970s, which means most buildings constructed before this period are not adequately designed to withstand earthquakes [5]. The primary cause of building collapse is damage to the columns and the connections between beams and columns. Retrofitting buildings to enhance earthquake resistance has become a common practice. There is substantial knowledge on various techniques to strengthen individual elements such as beams and columns [1]. However, addressing the beam-column joint remains challenging due to the high concentration of load in a small area, which is difficult to manage in existing constructions [35]. Numerous methods exist for strengthening joints in concrete structures, including Ferrocement laminates, Jacketing [7], post-tensioning, steel plate bonding, and FRP composites. Nowadays, extensive research has been conducted to safeguard beam-column joints

(BCJs) against failure during seismic events. This research has focused on various critical factors, including the degree of steel reinforcement in different types of concrete [17], changes in longitudinal reinforcement [18], shear reinforcement [13, 31, 32], and the use of rebar with varying diameters [28]. Studies have shown that diverse strengthening methods, such as incorporating carbon fiber sheets (CFRP) [24, 33] and glass fiber-reinforced polymer (GFRP)), using steel plate jacketing [35], and applying external post-tension rods , can significantly enhance the seismic performance of BCJs. Both experimental and theoretical studies on these factors and strengthening techniques have greatly contributed to improving the anti-seismic performance of BCJs.

The Experiments conducted by Qazi, et al. [30] utilizing various types of CFRP anchoring systems to enhance the strength of RCBC joints. The study concluded that the new reinforcing procedure effectively enhances the shear strength resistance of FRP with concrete. Overall, the new model accurately predicted the shear strength (SS) of the CFRP-reinforced joints. In study by Attari, et al. [5], the authors enhanced ten BCJs using various types of fibers, assessing their impact on ductility, durability, strength performance, and energy dissipation capacity during earthquakes. Golias, et al. [15] investigated six external joints under seismic loads, with three joints reinforced using carbon fiber ropes of different configurations. Similarly, Mady [23] developed five T-shaped joints to endure seismic loads, evaluating the influence of critical factors such as carbon fiber GFRP reinforcement details on their performance. Bsisu and Hiari [8] conducted a theoretical analysis on the behavior and strength of CFRP-reinforced joints to determine their potential for performance enhancement against seismic loading. Ercan, et al. [12] employed four different strengthening patterns for joints to study their seismic response, reinforcing them internally by modifying reinforcement details and externally with CFRPCs.

Considering the significance CBCJs with high performance, the novelty and aims of this study to investigate the seismic behavior of non-seismic joints, intermediate design joints, and the reinforcement of non-seismic joints in frame buildings. For this purpose, a six-story frame building was designed according to the research objectives. The first model assumed the building was constructed with non-seismic joints lacking transverse reinforcement in the joint panel. The second model followed ACI 318-19 guidelines for intermediate moment frame reinforcement detailing. The third model was reinforced using carbon fiber reinforced polymer (CFRP) materials, with one layer covering the beam-column joint extending 0.5 meters. The fourth model applied two layers of CFRP to the beam-column joint of the non-seismic frame building. The fifth model, similar to the third, used a CFRP length of 1.25 meters at the beam-column joint. The goal of reinforcing the beam-column joint area was to ensure safe seismic performance as specified in ACI 374.2R-13. Finite element analysis of the frame buildings was conducted using full-scale models to evaluate their seismic behavior.

Experimental Work and Model Simulation Using ABACUS

To evaluate the BCJs performance and according to previous studies conducted by Le-Trung, et al. [20], two types of reinforced BCJs are considered included non-seismic (NS) as first design and seismic design (SD) as second design. The reinforcement details of both designed BCJs of NS and SD presented in Figure 1. The NS and SD specimens were designed with identical dimensions and the same number of longitudinal reinforcements. Compared to BCJs of SD, the specimens

of NS differed in several aspects such as it lacked transverse reinforcements in the BCJs region, had larger stirrup spacing in the beam, and featured beam bar anchors bending downward away from the joints. Conversely, the SD specimen adhered to the ACI 318-02 Code [3] or an intermediate moment frame, incorporating confinement reinforcement in the BCJs region and smaller stirrup spacing in the beam. Analyzing the behaviors of these two specimens under cyclic loading can demonstrate the effects of adequate transverse reinforcements on the joints' shear capacity and ductility.

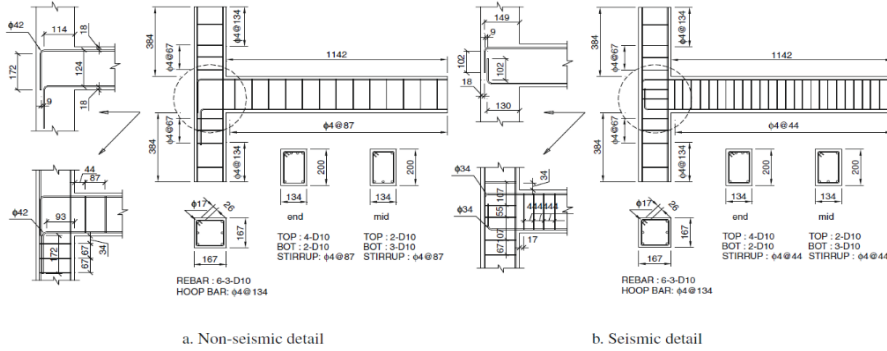


Figure 1: Details of designed (a) non-seismic BCJs (b) seismic BCJs [20].

In retrofitted CBCJs, the main components include concrete, steel reinforcement bars, and external CFRP sheets. To create an accurate model under cyclic forces, it is crucial to replicate the actual material characteristics of each component. The computer software of ABAQUS-19 offers effective material models for three-dimensional (3D) continuum elements, simulating the real behavior of each component with acceptable accuracy. Various geometries were modeled utilizing solid, shell, and link as three different elements as displayed in Figure 2. For the solid sections like concrete, a 3D eight-node linear brick element with reduced integration and hourglass control (C3D8R) was used (Fig. 2a). Linear brick components were chosen because they are compatible with contact modeling, unlike quadratic brick elements that require more computation time for constant nodal loads over the surface. The truss elements T3D2 (Fig. 2b) used for the steel bars were embedded in the concrete. The discrete reinforcement bars in the CBCJ were modeled as T3D2 elements. Four-node, doubly curved, linear, three-dimensional general-purpose shell elements with reduced integration and hourglass control (S4R5) were used for the CFRP plate (Fig. 2c).

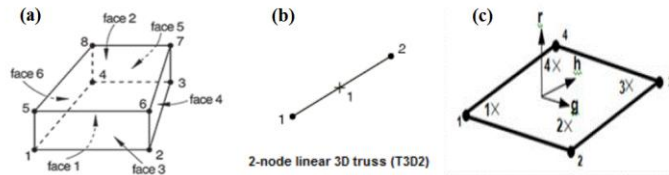


Figure 2: The Adopted Three Types of Elements in ABAQUS Model.

Table 1 summarizes the properties of materials utilized in this study such concrete'

compressive (CS) and splitting tensile strengths (TS), steel bars' yield strength, CFRP' tensile and elastic modulus (EMs) as well as the epoxy coat and primer' EMs and TS. Concrete is well known for its high CS but low TS and its tendency to fracture under tensile loads. This is primarily because the fine and coarse aggregates in concrete can withstand compressive stress, allowing it to bear compressive loads. Furthermore, the tensile stresses generate cracks that separate the cement particles in the aggregates, leading to structural failure as the cracks propagate. This issue can be mitigated by reinforcing concrete with elements such as metallic bars or fibers, which provide a framework to support the aggregates under tensile forces. This system is known as concrete reinforcement.

Concrete is considered a brittle material. Unlike ductile materials like steel, concrete responds differently to loads. Brittle materials tend to develop tensile fractures perpendicular to the direction of the greatest tensile strain. Therefore, when specimens of concrete are subjected to a uniaxial compressive load, the cracks develop parallel to the maximum compressive stress. Under compression, the stress-strain curve of concrete is initially elastic, gradually reaching the maximum CS, followed by a softening region, and eventually crushing failure at an ultimate strain. The normal concrete stress-strain relationship has been modeled by Tao and Chen [36] and Chen, et al. [10]. Unlike, in the concrete tension case it's found the stress-strain curve is approximately linearly elastic up to the maximum TS. Beyond this point, cracks form and the concrete' strength of slightly decreases to zero.

Table 1: Properties of Materials Used in This Study Included Concrete, Steel Bars, CFRP and Epoxy Properties.

Materials properties		
Concrete	Water curing' CS, MPa	33.8
	Water curing' TS, MPa	4.0
	Air curing' CS, MPa	36.5
	Air curing' TS, MPa	3.8
Steel bars	Yield strength of D10, MPa	324
	Yield strength of Ø4	459
	TS at 0°, MPa	4965.8
	EMs at 0°, GP	240.5
	EMs at 90°, GP	10
	In-plane shear modulus, GPa	5
CFRP type CF720	TS at 90°, MPa	50
	CS at 0°, MPa	1200
	CS at 90°, MPa	250
	In-plane shear strength, MPa	70
	Sheet thickness, mm	0.33
Epoxy topcoat (CLR67)	Major Poisson's ratio	0.3
	Density, g/cm ³	1.6
	Value of TS, MPa	59.5
Epoxy primer (CLR67)	Value of EMs, GP	3.7
	Value of TS, MPa	56.8
	Value of EMs, GP	3.7

A linear isotropic and bilinear kinematic model was applied to simulate the elastic and inelastic behavior of the steel components in the reinforcement bar. The ABAQUS material model used a Young's modulus of 200,000 MPa and a Poisson's ratio of 0.3 to accurately represent steel behaviour for both of D10 and Ø4 bars. According to Narayanan and James [26], at strain of 0, 0.00162 and 0.12 of D10 the stress adopted was 0, 324, 420 MPa, respectively. Likewise, for the Ø4 and at strain of 0, 0.0022 and 0.008 the considered stress was 0, 459, and 620 MPa, respectively. Based on the tensile test reported by Le-Trung, et al. [20], the steel material

parameters used in the finite element models were derived. These properties were then incorporated into the model. An orthotropic elastic material model was used to represent CFRPCs. The model assumed full bonding between CFRP and concrete.

Geometry and Boundary Condition

Additional numerical investigation is required to accurately demonstrate the full scale of the individual joints in reinforced concrete frames and subjected to seismic reversed cyclic loads. It is crucial to recognize that these joints play a vital role in maintaining the integrity of the frames. These concerns arise regarding their suitability for earthquake-resistant constructions that meet the seismic criteria of ACI 374-05 [6]. The specimens were joints consisting of two columns and two beams representing half of the second floor of reinforced concrete frame for the corner joint and joints consisting of two columns and three beams representing half of the second floor of reinforced concrete frame for the exterior joints. The purpose of this investigation was to assess the performance of the exterior and corner beam-column connections, which simulate the behavior of the connections in the modelled buildings. The frame which subassemblies were designed to meet the requirements of non-seismic details joints done by Trung as well as seismic design of the joints satisfy the intermediate moment frame, and the strengthening of non-seismic joint with the objective to satisfy the seismic performance. Figures 3, 4 and 5 illustrated the configuration of the beam-column joints. The joints were scaled using the full-scale factor. The beams were 2500 mm in length and 400 mm by 500 mm in cross-section. They were reinforced at each beam with longitudinal bars of 4-20 mm in length, placed at the bottom for positive reinforcement and at the top for negative reinforcement. Due to the occurrence of both positive and negative bending forces on the beams during the seismic activity, longitudinal reinforcing was required on both the upper and lower sides of the beams. Therefore, the longitudinal reinforcement had an even distribution on both the top and bottom of the beams. There were two columns positioned above and below the joint, each with a length of 3000 mm and a cross-section measuring 400 mm by 400 mm. The columns have reinforcement by longitudinal bars of 12-25 mm in diameter. At the tips of each column, lateral loads were applied to the structural members. The beams and columns' flexural and shear reinforcement ratios corresponded to those in the original frame. Ten classes of joints were performed, two joints with same dimensions, one of NS (non-seismic) frame, the second is SD (seismic design) frame. Third frame great by strengthen non-seismic frame by the Carbon Fiber Reinforced Polymer (CFRP) materials using one layer of CFRP covering the beam column joint with distance of 0.5m.

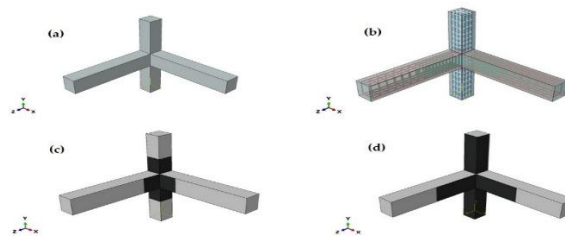


Figure 3: Illustrates the Configuration of the two BCJs; (a) Model of Full-Scale Joints (b) Model Longitudinal and Transverse Reinforcement for Seismic Joints (c) Model of Strengthened by one and two Layers of CFRP Joint with Distance of 0.5 m (d) Model of Strengthened by one layer of CFRP with Distance of 1.25 m.

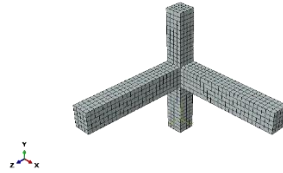


Figure 4: Mesh size of all BCJs' Models.

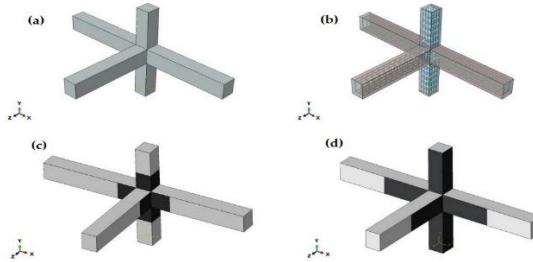


Figure 5: Illustrates the Configuration of the three BCJs; (a) Model of Full-Scale Joints (b) Model Longitudinal and Transverse Reinforcement for Seismic Joints (c) Model of Strengthened by one and two Layers of CFRP Joint with Distance of 0.5 m (d) Model of Strengthened by one Layer of CFRP with Distance of 1.25 m.

The fourth model using two layers of CFRP to cover the beam column joint of the non-seismic frame building. Last model created same as the third model but using the length of CFRP in the beam column joint with a distance of 1.25 m. Only the transverse reinforcements in the joint, column, and beam were different between the NS and SD. The SD specimen was specifically built to meet the requirements of the intermediate moment frame as specified in the ACI 318-19 code. The CFRP joints were constructed using the NS specimen as a basis, employing methods of wrapping CFRP sheets at the joints. The joints have same number of longitudinal reinforcements and dimensional size with the objective to compare the seismic behavior. The beam-column joint indicated above is analyzed using ABAQUS/Standard through nonlinear finite element analysis. In order accurately replicate the behavior of connections used in the construction of frame buildings, both geometrical and material nonlinearities are taken into account. Using Trung's verified modelling, the development of models encompasses the specification of geometry and boundary conditions, selection of element types, determination of material properties, and implementation of nonlinear analysis solution. The numerical modelling is initially validated using the experimental findings of cyclic tests conducted on exterior beam-column joints, as previously conducted by Trung et al. Subsequently, the model is applied to a full-scale reinforced concrete beam-column joint in a frame building, which is subjected to cyclic loading. The finite element simulation of reinforced concrete structures and its components is challenged by the complex behavior of concrete, which is non-homogeneous and anisotropic. As granted by Trung's verified model, Concrete Damage Plasticity is used in the numerical model. An orthotropic elastic material was used to represent CFRP used as the properties of the verified model. Behavior of the reinforcement under uniaxial tensile stress was considered to be elastic. The typical values of Young's modulus and Poisson's ratio were used. Additionally, the yield stress and related plastic strain are modelled, as well as the plastic behavior. The plastic phase properties are defined in the model using a bilinear behavior. The strain -stress values for concrete and steel reinforcement have been changed as was followed in the building design.

The modelling of concrete elements with reduced integration (C3D8R) utilizes 3D hexahedral (brick) elements with 8 nodes. Each node has 3 degrees of freedom, allowing for translations in the X, Y, and Z directions. To model reinforcements, two-nodes truss elements (T3D2) with three degrees of freedom in each node (translations in the X, Y, and Z directions of the global coordinate system) are used. The full bond approach is utilized to accurately replicate the interaction between the concrete and reinforcement. Full bond is used to model the effects of CFRP and the concrete interface.

The joints are analyzed using finite element analysis in a nonlinear manner. Both material and geometric nonlinearities are taken into consideration during the analytical procedure. The entire specified loads applied to a finite element body will be divided into multiple load increments during a nonlinear analysis. The structure reaches an approximate state of equilibrium at the end of each increment, and its stiffness matrix is adjusted to account for nonlinear changes in the stiffness of the structure.

The boundary conditions established on the exterior and corner joints of the specimen involved a simply supported column at its bottom end, with a cyclic load applied to the top of the column. The beam ends were joined by a roller support, allowing them to move freely in a horizontal direction while being constrained in a vertical one. The beam-column connections have the same boundary condition and loading procedure of the verified modeling used the experimental work done by Trung. The column was not subjected to any axial force during the test, as per Trung's instructions so in the finite element the axial force not applied. Figure 6 displays the specimen's boundary condition in the finite element.

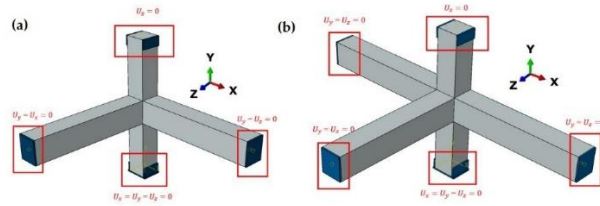


Figure 6: Illustrates Boundary Condition of (a) two BCJs (b) Three BCJs.

Results and Discussion

Force-Displacement Curves of Full-Scale Joints

The force-displacement curves of two and CBJs' NS and SD, CFRPs strengthen two and three CBJs' NS and SD in one and two layers, 0.5- and 1.25-mm distance are presented in Figures 7, 8, 9, and 10, respectively. By implementing this strengthening technique, the ultimate load carrying capacity of the strengthened joints is enhanced compared to the reference joints (non-seismic details). For joints with two and three beams, the maximum lateral load of non-seismic joints was 209.6 kN and 225.8 kN, respectively. The load begins to decrease after a displacement of 53 mm, and the weakening of the joints initiates the loss of strength. The seismic joints with two and three beams exhibit 15.7 % and 14.6% increase in load-carrying capacity with respect to non-seismic joints. Same percentage of increasing as seismic joints observed for the strengthening joint by one layer by distances of 0.5 m and 1.25 m compared non-seismic joints. The improvement occurrence in the joint observed in seismic and strengthened joints in comparison to non-seismic joints. Therefore, inserting sufficient transverse reinforcement in the joints and strengthening non-seismic joints would be a suitable approach for enhancing the strength of RC structures in

earthquake-prone areas. The load-carrying capacity is greatly improved by the presence of sufficient joint transverse reinforcement and strengthening non-seismic joints, as demonstrated by finite element studies.

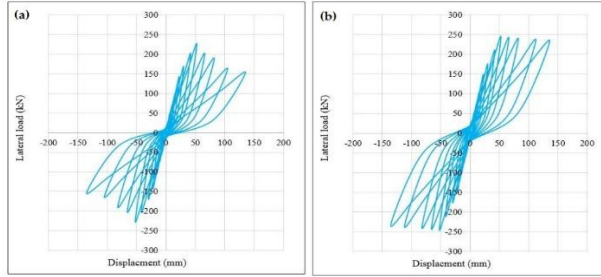


Figure 7: Force-Displacement Curves of (a) Non-Seismic Joint with two Beams (b) Seismic Joint with two Beams.

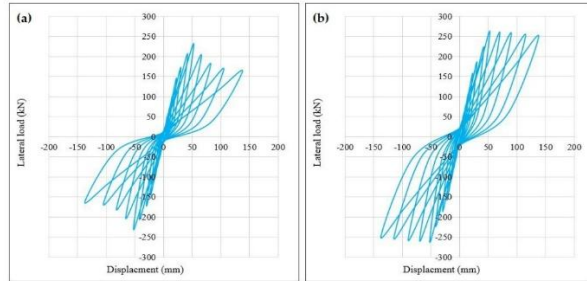


Figure 8: Force-Displacement Curves of (a) Non-Seismic Joint with Three Beams (b) Seismic Joint with three Beams.

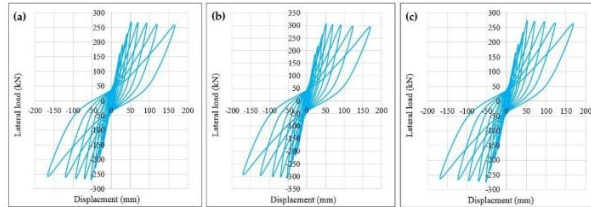


Figure 9: Force-Displacement Curves of (a) One-Layer CFRP joint with two Beams (b) Two-Layers CFRP Joint with two Beams (c) One-layer CFRP Joint with Distance 1.25 m and two Beams.

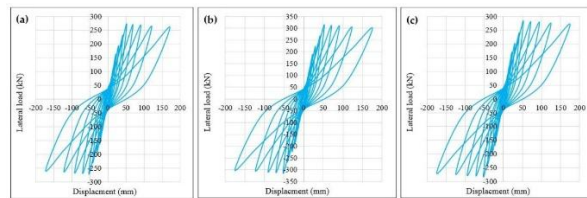


Figure 10: Force-Displacement Curves of (a) One-Layer CFRP Joint with Three Beams (b) Two-Layers CFRP Joint with three Beams (c) One-Layer CFRP Joint with Distance 1.25 m and Three Beams.

Numerical results of cyclic loading of joints that have been obtained through ABAQUS are compared with the requirement listed in ACI 374.1-05 as mentioned in section (4.2). These requirements function to guarantee the structural components can be used in areas with high seismic action. Examination of the structural response was carried out on, strength, dissipated energy, and secant stiffness from the hysteretic curve. ACI 374.1-05 requires that the lateral force resulting from experimental testing is not greater than λE_n . Table 2 displays the results of computing these criteria for two and three BCJs with different conditions.

Table 2: Checking The Maximum Lateral Load Resistance of Two and Three Bcjs.

Specimen	Type	λ	E_n (kN)	λE_n (kN)	E_{max} (kN)	Remarks
Non-seismic (NS) joints	Two Beams	2.04	226.38	461.81	223.94	Ok
	Three Beams	2.04	226.38	461.81	228.70	Ok
Seismic design (SD) joints	Two Beams	2.04	226.38	461.81	242.55	Ok
	Three Beams	2.04	226.38	461.81	259.00	Ok
Strengthened by CFRP one-layer joints (0.5m)	Two Beams	2.04	226.38	461.81	265.11	Ok
	Three Beams	2.04	226.38	461.81	269.30	Ok
Strengthened by CFRP two layers joints (0.5m)	Two Beams	2.04	226.38	461.81	302.90	Ok
	Three Beams	2.04	226.38	461.81	309.80	Ok
Strengthened by CFRP one-layer joints (1.25m)	Two Beams	2.04	226.38	461.81	269.45	Ok
	Three Beams	2.04	226.38	461.81	278.60	Ok

From the calculations above, it can be seen that all joints with meet the requirements since the column strength value which is high, so it is intended to avoid failures occurring in the column. With a high excess strength value, failure of the test object occurs in the beam area. Apart from these strength criteria, also states that the strength degradation is equal to or exceeds 3.5% must be greater than 0.75 E_{max} . Table 3 illustrated the assessment of joint strength degradation at a drift level of 3.5%. This criterion checked in one direction of loading since the lateral strength is almost same in both directions of loading. The results of the examination of these criteria can be seen below and it clearly have observed that all joints meet the required criteria except non-seismic joints which confirmed the Trung joints.

Table 3: The Assessment of Joint Strength Degradation at A Drift Level of 3.5%.

Specimen	Type	Ultimate lateral force in (kN)	3.5% (drift ratio)	
			Force in kN	Ratio of the strength > 0.75
Non-seismic (NS) joints	Two Beams	223.94	162.15	0.72*
	Three Beams	228.70	168.00	0.73*
Seismic design (SD) joints	Two Beams	242.55	235.20	0.97
	Three Beams	259	251.23	0.97
Strengthened by CFRP one-layer joints (0.5m)	Two Beams	265.11	257.05	0.97
	Three Beams	269.30	260.93	0.97
Strengthened by CFRP two layers joints (0.5m)	Two Beams	302.90	291.97	0.96
	Three Beams	309.80	300.70	0.97
Strengthened by CFRP one-layer joints (1.25m)	Two Beams	269.45	261.90	0.97
	Three Beams	278.60	270.63	0.97

The ideal energy ratio is one of the parameters required in ACI 374.1-05. The results of the examination of these criteria can be seen in Table 4. From this table it can be seen that all the energy ratios of the joints exceed 0.125, which means they meet the ideal energy ratio criteria.

Table 4: Relative Energy Dissipation Ratio Checking of two and Three Bcjs.

Specimen	Type	Parallelograms area	Area of hysteretic loop	Relative energy dissipation ratio β	Check to meet the criteria ≥ 0.125
Non-seismic (NS) joints	Two Beams	1366.20	314.22	0.23	Ok
	Three Beams	1493.10	300.74	0.20	Ok
Seismic design (SD) joints	Two Beams	2116.80	910.22	0.43	Ok
	Three Beams	2261.07	1040.10	0.46	Ok
Strengthened by CFRP one-layer joints (0.5m)	Two Beams	2112.66	845.06	0.40	Ok
	Three Beams	2348.37	986.31	0.42	Ok
Strengthened by CFRP two layers joints (0.5m)	Two Beams	2470.59	1309.42	0.53	Ok
	Three Beams	2278.53	1298.76	0.57	Ok
Strengthened by CFRP one-layer joints (1.25m)	Two Beams	2138.85	962.48	0.45	Ok
	Three Beams	2374.56	1163.53	0.49	Ok

ACI 374.1-05 requires that the slope of the line connecting two points with a drift of -0.35% and 0.35% must exceed 0.05 of initial stiffness value. Initial stiffness of the test object in this study was calculated on a cycle with a drift of 0.2%, where the positive and negative loading directions had different initial stiffness values. This criterion only needs to be checked in the third cycle for a drift level of 3.5% or more. The upper and lower reinforcement are equal, so the strength of the beam in both directions is almost equal, so the stiffness criteria was applied to one direction. Examination of the secant stiffness criteria aims to ensure that the structure has sufficient stiffness after a large earthquake. If the stiffness value at the specified drift is too small, the structure will be susceptible to large displacements due to small lateral forces. The results of checks against these criteria were carried out at a drift of 3.5% and can be seen in Table 5. All test objects met the stiffness criteria in the required drift range.

Table 5: Two and Three Bcjs' Secant Stiffness Checking.

Specimen	Type	Secant stiffness (kN/mm)	Initial stiffness (kN/mm)	Ratio between secant stiffness and initial stiffness	Check to meet the criteria ≥ 0.05
Non-seismic (NS) joints	Two Beams	1.54	7.83	0.20	Ok
	Three Beams	1.60	8.00	0.2	Ok
Seismic design (SD) joints	Two Beams	2.10	8.16	0.25	Ok
	Three Beams	2.18	8.63	0.25	Ok
Strengthened by CFRP one-layer joints (0.5m)	Two Beams	2.12	8.83	0.24	Ok
	Three Beams	2.14	8.97	0.23	Ok
Strengthened by CFRP two layers joints (0.5m)	Two Beams	2.35	10.03	0.23	Ok
	Three Beams	2.44	10.33	0.24	Ok
Strengthened by CFRP one-layer joints (1.25m)	Two Beams	2.13	9.00	0.23	Ok
	Three Beams	2.17	9.30	0.23	Ok

Remark obtained from the analysis of the data is as follow: (1) Specimens strengthened by CFRP have increasing the lateral resisting force same as the verified numerical modeling and Trung experimental test. The general behavior of specimens done by Trung is almost same as the full-scale joint. The difference in the values of strength energy dissipation and stiffness occur between Trung models and the full-scale models is due the dimension size and reinforcement size and details. (2) Compared to NS specimens, all strengthen specimens dissipated a good amount of energy. (3) From the comparison of the acceptance criteria of ACI 374-05, all detail specimen proves good seismic performances except the non- seismic joint fails to satisfy the strength criteria.

Building Performance Level

The seismic investigation of five types of reinforced concrete buildings consists of non-seismic, seismic, strengthen non-seismic frame using one layer and two layers of CFRP with distance of 0.5 m, and strengthen non-seismic frame using one layer of CFRP with distance of 1.25 m were considered in this study. The reinforced concrete buildings are subjected to El Centro earthquake with the main objective is to investigate the seismic behavior of each type of building mentioned above and checking the strengthened frame building satisfies the performance level. The frame structural performance level confirms the degrees of reparability, serviceability, and safety. Safety level of frame building is important since it's based on the possibility of the life people danger to inside and outside the frame building, frame building should not collapse and able to sustain the column axial compression load. The furniture and the equipment inside the frame building must not be scattered or move. The reparability of a frame building depends on the degree of damage, so the structural element can be repaired easily. Serviceability can be established based on the comfort and functions of the frame building. The deformation of the structural element should not prevent the building from being used.

Suitable strengthen improves the non-seismic frame to be the ductile behavior which practically done by confining the joint with the beam and column area near the joint. If joint has sufficient strength, the plastic hinges are considered to be evolve in the strengthening the beam and column area near the joint. The strengthening of frame building by CFRP is provided in the case of the capacity assessment results of those frames cannot resist the expected intensity of lateral load and meet the damage limitation. To assess the level of performance, finite element is modeled use the validated model of the beam-column joint. Comparison between the different strengthening techniques provide to the frames is performed to choose the best strengthening techniques option. Furthermore, comparison included the seismic details frame to study the performance level. After the comparison, the most practical option capable of achieving good seismic behavior can be chosen. The performance level of non-seismic reinforced concrete building is assessed before and after using the strengthening techniques. Figures 11 to 20 presented the distribution of stress and plastic strain as a result of the six story frames' finite element analysis at different conditions of BCJs' NS and SD or strengthen layers and distance.

Typically, the strain of concrete and stress in the reinforcement of the beam column junction is greater at the top two floors of reinforced concrete frame buildings compared to other levels. Maximum plastic strain of the concrete has occurred in the part of column near the joint and the beam with the joint. The damage is in the beam due to beam flexural hinging since the building designed with the criteria of weak beam/ strong column, so the plastic hinge is expected to be occurred in the beams near joint. Non-seismic detail frame showed the maximum plastic strain compared to others frame buildings. At this level, the joint regions with lack of transverse reinforcement were subjected to maximum lateral load resulting in increased the joint deformation and the cracks (lack of joint transverse reinforcement leading to weak joint). At the joints, the yielding of the longitudinal reinforcement is observed, Tensile failure has occurred when the reinforcement reaches the limit state of 420 MPa. Some beam locations near the joints is showed yielding of the longitudinal reinforcement since those location of the plastic hinges. It should be noted that the non-seismic building has reached the maximum value of yielding the reinforcement. From the comparing of the seismic and non-seismic

details frame building, seismic building showed less plastic strain distribution in the concrete, moreover, seismic building showed lower value of yielding reinforcement with the yielding has occurred in lesser some locations. In the strengthened frame building by one and two layers of CFRP is showed the plastic strain distribution of concrete is lower than the non-seismic building because of the CFRP contribution to the stress of concrete resulting in reducing the cracks and the deformation of the joints. For the same reason of the contribution of CFRP to the stress, the yield of the reinforcement showed lower. The behavior of the strengthened frame building at the distance 1.25 m from the face of the joint same as the building strengthened using two CFRP layers of regarding the concrete strain and stress in the steel reinforcement. At the two mid-height floors of reinforced concrete frame buildings, failure has occurred in the joint area because of yielding of the reinforcement and concrete cracking. Considering the two top floors, the plastic strain in the concrete has almost same values in comparing to the two mid-height floors. As a result of the beams reaching their maximum flexural strength, the joints are highly stressed. When comparing the load on the columns of the lower floors to the highest level, axial comparison in high levels is lower, joint cracks are increased. At the two lower floors of reinforced concrete frame buildings, flexural plastic hinges occurred in the beams. The strain of concrete in these floors was less since the joint confinement increases as it is a part of the column, and column axial compression higher. The stress of the reinforcement in the base of the column at the ground floor reaches the yield in the non-seismic, seismic detail and strengthened by one layer of CFRP frame building while not reaching the yield in the strengthened by two layers and building strengthened with distance of 1.25 m, since this location has the maximum axial compression due to the highest dead, live, and lateral load affected on it so the strengthened CFRP makes the structural elements sharing the stress from the concrete resulting in reducing the stress on the reinforcement. The stress of the reinforcement in the building strengthened by one layer of CFRP has the maximum value of 433.736 MPa which is not much higher than the yield strength of 420 MPa.

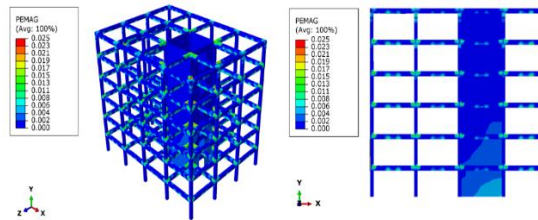


Figure 11: Plastic Strain Distribution for Non-Seismic Frame Building.

Concrete strain and stress of reinforcing bar explained the level of performance for seismic evaluation of reinforced concrete frame are stipulated by American Concrete Institute (ACI 374.2R-13) as below: (1) Operational is defined by no enduring deformation and no damage in the concrete such as crushing and slight hairline cracks. The frame building remains in the elastic range during the seismic action. (2) Immediate occupancy allows possibly of limited yielding of reinforcing bar in a few structural element locations with no damage in the concrete such as crushing and slight hairline cracks. (3) Life safety is denoted by the severe damage occur in the beams and spalling of concrete. The width of cracks should be less than 3.2 mm in joint and beam. However, damage that is expected to occur has a low impact on life. (4) The presence of severe spalling of the concrete cover in the

columns and beams indicates the collapse prevention. The joint experiences significant structural harm due to the deformation and failure of some compression reinforcing bars at the plastic hinge point. The frame building is deemed unsafe for reoccupation and irreparable.

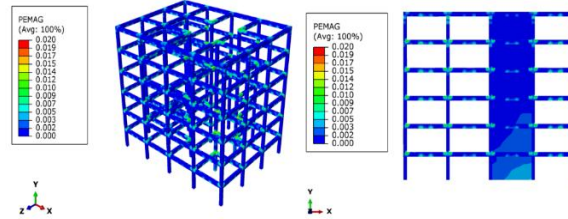


Figure 12: Plastic Strain Distribution for Seismic Frame Building.

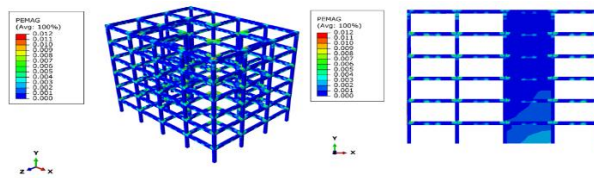


Figure 13: Plastic Strain Distribution for Strengthened Frame Building by One Layer of CFRP with Distance of 0.5 M.

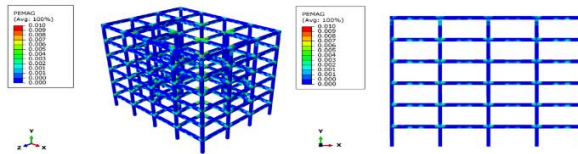


Figure 14: Plastic Strain Distribution for Strengthened Frame Building by Two Layers of CFRP with Distance of 0.5 M.

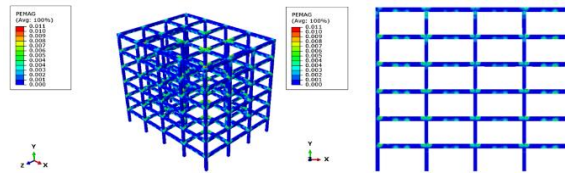


Figure 15: Plastic Strain Distribution for Strengthened Frame Building by one Layer of CFRP With Distance of 1.25 M.

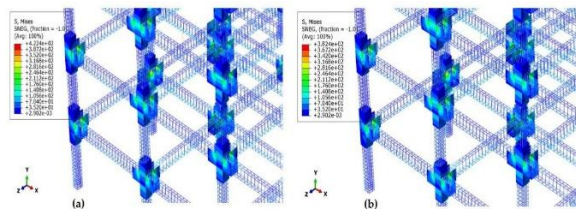


Figure 16:(A) Stress Distribution in CFRP For Strengthened Frame Building by One Layer of CFRP With Distance of 0.5. (B) Stress Distribution in CFRP For Strengthened Frame Building by two Layers of CFRP With Distance of 0.5 M.

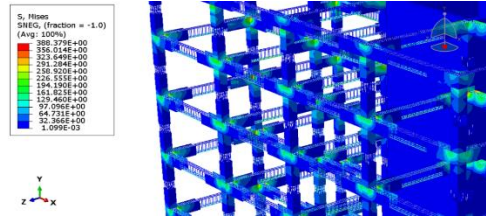


Figure 17: Stress Distribution in CFRP For Strengthened Frame Building by One Layer of CFRP with Distance of 1.25 M.

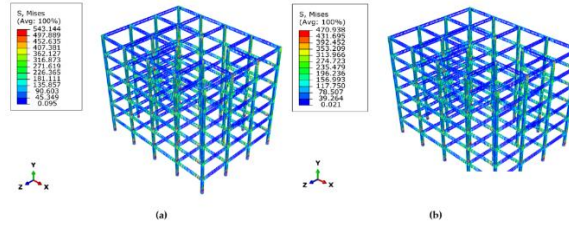


Figure 18: (A) Stress Distribution in the Reinforcement Bar for Non-Seismic Frame Building. (B) Stress Distribution in the Reinforcement Bar for Seismic Frame Building.

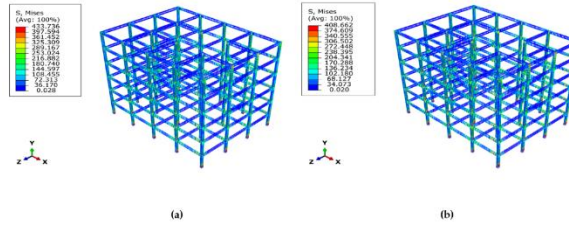


Figure 19: (A) Stress Distribution in the Reinforcement Bar for Strengthened Frame Building by One Layer of CFRP With Distance of 0.5 M. (B) Stress Distribution in The Reinforcement Bar for Strengthened Frame Building by Two Layers of CFRP With Distance of 0.5 M.

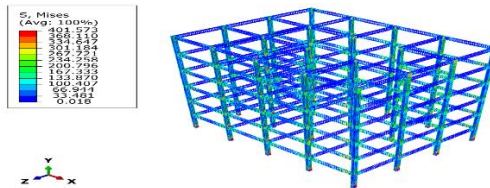


Figure 20: Stress Distribution in the Reinforcement Bar for Strengthened Frame Building by one Layer of CFRP With Distance of 1.25 M.

For the non-seismic frame building, the maximum stress value in the reinforcing bars of 543.144 MPa which is higher than the yield strength of 420 MPa. The damage had occurred in the joints and beams; the most width of concrete crack is 3.4 mm except some beams location near the joint has a crack with around 5 mm. Therefore, the non-seismic frame building satisfied the required of collapse prevention performance, indicating high damage state. In contrast, the seismic frame building showed the less probability of collapse, much lower than the non-seismic frame building. The stress of reinforcing bar is 470.938 MPa which cross

the limit yield strength in most joint location. Maximum strain occurred in the beam and joint. Generally, the width of concrete crack is around 2.8 mm. This confirms that the seismic details frame building, which is designed according to the requirement of the intermediate moment frame is satisfying the life safety level of performance. Strain distribution for strengthened frame building by one layer of CFRP with distance of 0.5 m showed that the damage of concrete is reduces compared to non-seismic details ones. Most of concrete crack's width in the beams and joints is 1.6 mm, few locations in the beams showed increased the crack width to 2.4 mm. The stress in the reinforcing bar is almost same (433.736 MPa) as the yield strength of 420MPa, and hence, the building achieved the life safety level of performance. In the strengthened frame building by two CFRP layers, the concrete crack width in beams and joints is 1.2 mm, with a few locations in the beam reaching a crack width of approximately 2 mm. The stress in the reinforcing bar below the yield strength, therefore, this building is satisfying the level of performance of the immediate occupancy. Finally, the strengthened frame building by one layer of CFRP with distance of 1.25 m showed the width of cracks is 1.2 mm in the beams and joints with some beam location in the beam reach a crack with of 2.2 mm. The stress in the reinforcing bar below the yield strength, therefore, this building is satisfying the level of performance of the immediate occupancy. Based on the probability of collapse, the strengthened frame building was preferable than the non-seismic frame building. Thus, in order to achieve the required level of performance, i.e., immediate occupancy or life safety, a step to strengthen the beam column joints should have conducted to non-seismic details building. It is clear from the results that the numbers of CFRP layer and distance of the strengthened is affect the satisfy performance level of the building. The strengthened frame building by two layers and one layer of CFRP with a distance of 1.25m achieved the better level of performance. The numerical investigations of the frame building confirm the previous considerations based on numerical and experimental analyses of cycle load of the beam column joints. The joint concrete cracks and stress in the reinforcing bar are reduced by strengthening the structure element by CFRP. The design of frame building according to the seismic resistance requirement of the ACI 318-19 safe it from the collapse by satisfy the level of performance. Design the frame building following criteria of weak beam and strong column reduce the brittle behavior resulting in a higher displacement capacity. The presence of the plastic hinge in the frame structure at the end of the beam near the joint, confirms the same location in the experimental work by Le-Trung, et al. [20]. The effects on a predominantly weak joint system due to lack of transverse reinforcement is leading the collapse of frame building during earthquake.

Lateral Displacement

Displacement at the roof of the frame buildings is show in Figure 21 when subjected to El Centro earthquake. According to the response results which indicate that the collapse is probably occurring at maximum acceleration ground levels. For the non-seismic frame building underwent maximum roof displacement of 146.27 mm in 3 s which is larger of the seismic frame building of 65.13 mm at about 29 s. This is mostly because there is insufficient transverse reinforcement in the joints, which increases joint distortion. The strengthened frame by one layer of CFRP showed low deformation compared to non-seismic ones since the maximum roof displacement is 69.67 mm at about 5 s. The frame reinforced with two layers of CFRP exhibited the maximum displacement of 32.22 mm approximately 5 seconds into the

recording. The strengthened frame by one layer of CFRP with distance of 1.25 m was displaced the maximum displacement of 33.56 mm approximately 5 seconds into the recording. The strengthened frame by two layers of CFRP and at distance of 0.5 m was showed elastic response throughout the El Centro ground motion. All strengthened frames response duration the input of ground motion was reduced the roof displacement compered to non-seismic frame. Frame strengthened with one, two layers and one layer with distance of 1.25 m exhibited 47.63%, 22.02% and 22.94% decrease in the roof displacement when compared to non-seismic details frame for the respectively. Consequently, the earthquake impacted all structures, resulting in the formation of plastic hinges at the beam column connection of the frames.

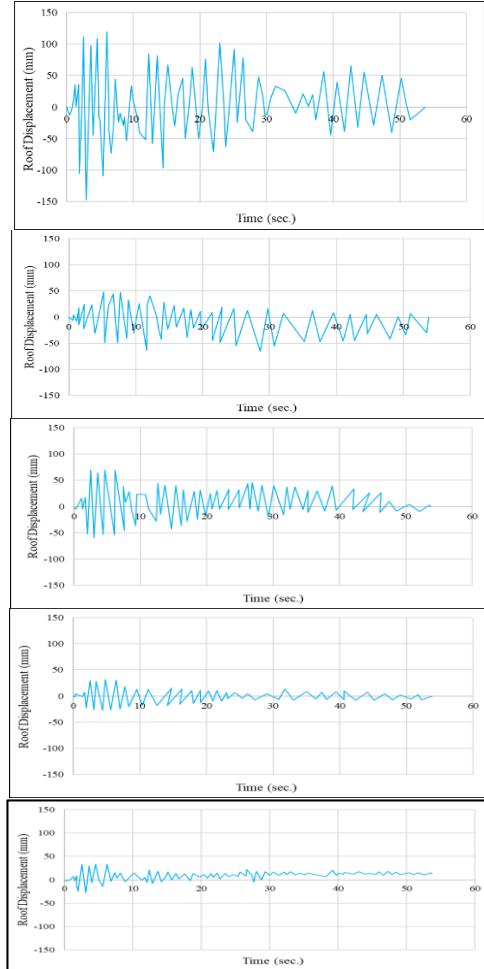


Figure 21: Variation In the Roof Displacement (A) Roof Displacement for the Non-Seismic Detail Frame Building (B) Roof Displacement for the Seismic Detail Frame Building (C) Roof Displacement for the Strengthened Frame Building By One Layer of CFRP with Distance of 0.5 M (D) Roof Displacement for the Strengthened Frame Building By Two Layers Of CFRP with Distance of 0.5 M (E) Roof Displacement for the Strengthened Frame Building By one Layer Of CFRP With Distance of 1.25 M.

The Figure 22 illustrated the envelopes representing the maximum lateral

displacement for all frames of the building. The figure displays a variation in the lateral displacements of the envelopes between the frames. The figure demonstrates that non-seismic frame buildings have greater lateral displacement within the frame as a result of insufficient transverse reinforcement in the joint. The study of the lateral displacement proves the response of the frame building is distributed damage type. The distributed damage response type corresponds to the plastic hinge occurred in the beams which distribution most of the deformation in the frame building height. The soft story response type corresponds to the plastic hinge occurred in the columns, which leading to destroy the frame building. Figure 23 shows the difference between the two response types. The two classes of buildings may be simply divided based on the knowing the design details were implemented, in the most straightforward scenario, where no inspection of the buildings is anticipated. The effects of non-seismic, seismic, and strengthened beam column joint on roof displacements, lateral drift ratio and envelope of maximum lateral displacements are significant. The strengthened beam column joint slightly reduces the lateral drift ratio demand, preventing soft story mechanisms, while the lateral displacement demand is reduced.

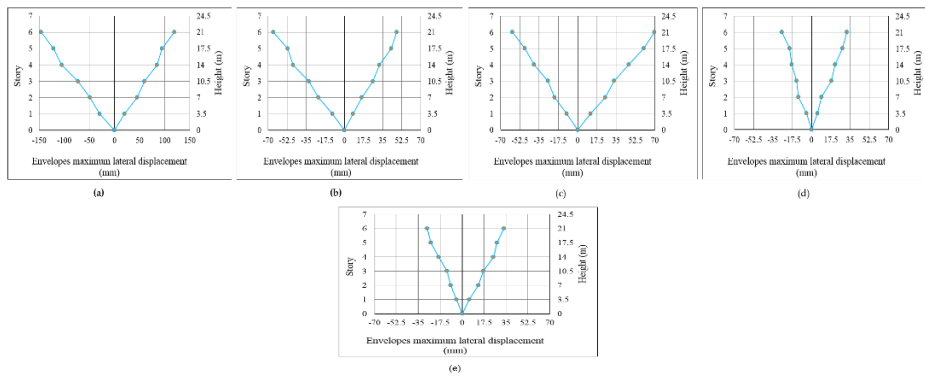


Figure 22: Comparison the Envelopes of the Maximum Lateral Displacement from All Frame Buildings (A) Non-Seismic Detail Frame Building (B) Seismic Detail Frame Building (C) Strengthened Frame Building by one Layer of CFRP with Distance of 0.5 M (D) Strengthened Frame Building by two Layers of CFRP with Distance of 0.5 (E) Strengthened Frame Building by one Layer of CFRP with Distance of 1.25 M.

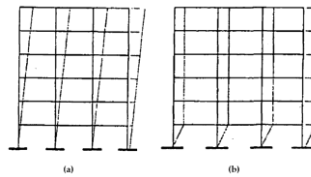


Figure 23: Show Response Mechanism of Frame Building (A) Distributed Damage Response (B) Soft Story Response.

Conclusions

The conclusions discussed in this research mainly related of considering the modeling of the joints response in modeling expected seismic behavior of a reinforced concrete frame building. Two main joints are taken into consideration in the construction of frame building, first joint is non-seismic details, which

constructed in absence of applying the seismic requirement of ACI 318 so insufficient of transverse reinforcement exists in the joint, the second joint is constructed using the seismic code provisions of the intermediate moment frame. The other joint models focus on strengthening the non-seismic joint to achieve the performance seismic requirement. The strengthen of the joint use one layer and two layers of CFRP with distance of 0.5 m from the face of joint. Last model used the strengthen of non-seismic details joints by one layer of CFRP with distance of 1.25 m from the face of joint. The strengthening strategy of non-seismic details frame building is to increase the seismic resistance capacity of the structural elements and improving the overall structure performance during the severe lateral forces. From the obtained results, the following conclusions are drawn:

- i. From study the non-seismic joint in the reinforced concrete frame building before the strengthening and after strengthening, it observed that the non-seismic details building is satisfied the collapse prevention while the strengthening building by CFRP can satisfy the required life safety and immediate occupancy depending on the strengthening strategy. The strengthening methods improve the performance level of the frame.
- ii. Strengthening is important parameter increasing the confinement of structural members of the frame building leading to enhance the lateral strength of the members to resist the deformation and maintain the integrity of frame during the seismic action. The strengthening of beam column joint help to decrease crack of concrete in the joint and making the plastic hinges location in the beam which leading to decrease the risk of building collapse. The plastic hinges formed in the frame of the reinforced concrete building in the beam near joint. Strengthening of ground story is important specialty for the columns due to the seismic load affects the first two stories of the building. The strengthening structural elements increase the capacity of the lateral displacement. However, all the strengthen joints in the frame buildings exhibited low lateral displacement under same lateral load compared to non-seismic details joint frame buildings.
- iii. The lateral displacement closes slightly between the strengthened frame building by two layers of CFRP with distance of 0.5 m and one layer of CFRP with distance of 1.25 m. The maximum lateral displacement occurs at the roof story for those two strengthening strategies which is less than that of the non-seismic details frame building. The seismic and strengthen joints have good strength, stiffness, ductility, and energy-dissipation capabilities. The seismic and strengthen joints achieved the required seismic code provisions of ACI 374.1-05. The non-seismic joint failure in satisfying the requirement of the ACI 374.1-05 because of not achieving the strength criteria.
- iv. From finite element models of full scale specimens for exterior joint with two beams, it was demonstrated an improvement in the relative energy dissipation ratio for seismic design joint, strengthening the joint by one layer at distance of 0.5 m, strengthening the joint by two layers at distance of 0.5 m, and strengthening the joint by one layer at distance of 1.25 m by 46.51%, 42.5%, 56.60% and 48.88% compared to the non-seismic joint, respectively. Furthermore, for the exterior joint with the three beams the relative energy dissipation ratio increased by 56.52%, 52.38%, 64.91% and 59.18% compared to the non-seismic joint, respectively.
- v. Finite element models of full scale specimens for exterior joint with two beams demonstrated an improvement in the maximum lateral strength for seismic design joint, strengthening the joint by one layer at distance of 0.5 m, strengthening the joint by two layers at distance of 0.5 m, and strengthening the

joint by one layer at distance of 1.25 m by 7.67%, 15.53%, 26.07% and 16.88% compared to the non-seismic joint, respectively. Furthermore, for the exterior joint with the three beams the maximum lateral strength increased by 11.69%, 15.07%, 26.17% and 17.91% compared to the non-seismic joint, respectively.

- vi. Secant stiffness of full-scale specimens for exterior joint with two beams increased for seismic design joint, strengthening the joint by one layer at distance of 0.5 m, strengthening the joint by two layers at distance of 0.5 m, and strengthening the joint by one layer at distance of 1.25 m by 26.67%, 27.35%, 34.46% and 27.69% compared to the non-seismic joint, respectively. Furthermore, for the exterior joint with the three beams the secant stiffness increased by 26.60%, 25.23%, 34.42% and 26.26% compared to the non-seismic joint, respectively. Finite element research demonstrated that utilizing two layers of CFRP and extending its length from the joint will enhance the seismic performance in the frame building. According to the above information, it can be concluded that the strengthening of the non-seismic joint can achieve good seismic performance and can potentially be used in building constructed with lack of joint transverse reinforcement.

Recommendation for Future Work

- i. Future research required to study the effect of applying the column axial compressive during the test of strengthened beam column joint. The beneficial effect of axial loading on joint seismic behavior should investigated using the experimental and numerical approach.
- ii. Additional testing of the exterior and interior joints is required to determine the joint behavior by strengthening the column and beam in a distance of 1.25 m from the face of the joint.
- iii. More studies are required to investigate the seismic behavior of frame building using different techniques to strengthen the non-seismic beam column joint such as jacketing using the steel section, external plate bonding, and ferrocement.
- iv. Experimental test using the shaking table need to conduct on the non -seismic joint of the frame building and strengthened the non-seismic joint by CFRP in the frame building to study the seismic performance of these buildings.

Supplementary Materials

No supplementary Materials.

Author Contributions

The following statements should be used “Conceptualization, N.A.S.A. and A.A.K.; methodology, N.A.S.A.; software, F.H.M.; validation, A.A.K. and F.H.M.; formal analysis, N.A.S.A.; investigation, N.A.S.A.; resources, N.A.S.A.; data curation, N.A.S.A.; writing—original draft preparation, N.A.S.A.; writing—review and editing, A.A.K.; visualization, F.H.M.; supervision, A.A.K.; project administration, N.A.S.A.; funding acquisition, A.A.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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Conflicts of Interest

The authors declare no conflicts of interest.

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