



WOLLEGA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

**BEHAVIOR OF HYBRID STEEL-FRP REINFORCED
CONCRETE BEAM-COLUMN JOINTS UNDER CYCLIC
LOADING: A FINITE ELEMENT ANALYSIS**

MSC Research

By

Gemechis Mekonnen

Advisor: Dr. Kabtamu Getachew

May 2026

Nekemte, Ethiopia



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A Thesis Submitted to the School of Graduate Studies of Wollega University in
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Structural Engineering

Advisor: Dr. Kabtamu Getachew

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I declare that this thesis entitled “**Behavior of Hybrid Steel-FRP Reinforced Concrete Beam-Column Joints under Cyclic Loading: A Finite Element Analysis.**” is my original work and has not been submitted as a requirement for the award of any degree in Wollega University or any other university. Wherever others contribute, every effort is made to indicate this clearly, with due reference to the pieces of literature.

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ABBREVIATION AND ACRONYMS

A/S	:	Aramid Steel Ratio
ACI	:	American Concrete Institute
AFRP	:	Aramid Fiber Reinforced Polymer
AJ-25%	:	Aramid Joint Replacement 25 Percent
AJ-50%	:	Aramid Joint Replacement 50 Percent
AJ-75%	:	Aramid Joint Replacement 75 Percent
AJ-100%	:	Aramid Joint Replacement 100 Percent
CFRP	:	Carbon Fiber Reinforced Polymer
CSA	:	Canadian Standards Association
Di	:	Diameter
FE	:	Finite Element
FEA	:	Finite Element Analysis
FRP	:	Fiber Reinforced Polymer
G/S	:	Glass Steel Ratio
GFRP	:	Glass Fiber Reinforced Polymer
GJ-25%	:	Glass Joint Replacement 25 Percent
GJ-50%	:	Glass Joint Replacement 50 Percent
GJ-75%	:	Glass Joint Replacement 75 Percent
GJ-100%	:	Glass Joint Replacement 100 Percent
MRF	:	Moment Resisting Frame
NLFEA	:	Nonlinear Finite Element Analysis
RC	:	Reinforced Concrete
RJ	:	Reference Joint

ABSTRACT

FRP materials have attracted growing interest within the field of structural engineering, primarily owing to their advantageous characteristics such as lightweight composition, resistance to corrosion, and impressive strength properties. This research endeavor focuses on investigating the behavior of beam-column joints that are reinforced with Fiber Reinforced Polymer (FRP) bars under cyclic loading conditions. These joints share identical specimen geometry, material properties, and testing setups; however, they vary in the extent to which steel bars in the beams are replaced with GFRP and AFRP bars. The alteration in the GFRP or AFRP-to-steel bars ratio ranges from 0% (representing the reference specimen) to 25%, 50%, 75%, and 100%. This comparative analysis is also conducted to assess and contrast the performance of GFRP and AFRP. The primary test outputs encompass the examination of crack propagation patterns and the hysteresis curves illustrating the crack propagation and relationship between forces - displacement. Furthermore, several seismic parameters, including displacement ductility, absorbed energy, and stiffness, will be comprehensively compared and discussed to provide insights into the behavior and potential advantages of those FRP-reinforced beam-column joints in seismic scenario. The results revealed that the type and percentage of FRP reinforcement significantly influenced the cyclic response of the beam-column joints. The hybrid AFRP-steel and GFRP-steel reinforced specimens with 25% and 50% FRP replacement ratios exhibited improved cyclic performance, stable hysteresis behavior, enhanced ductility, and higher energy dissipation capacity compared to specimens with higher FRP content. A comparison between the two FRP types indicated that AFRP-reinforced joints generally demonstrated better seismic performance than GFRP-reinforced joints due to the superior toughness and deformation capacity of aramid fibers. AFRP specimens exhibited wider hysteresis loops, slower stiffness degradation, and greater displacement capacity under cyclic loading. In contrast, GFRP-reinforced joints showed relatively lower ductility and energy dissipation, particularly at higher replacement ratios, because of the more brittle behavior of glass fibers.

Keywords: Reinforced concrete, Beam-column joints, finite element analysis, Hybrid reinforcement (GFRP and AFRP), Hysteresis response, ABAQUS

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CHAPTER ONE

1 INTRODUCTION

1.1 Background

Reinforced concrete (RC) structures built in earthquake-prone areas and designed to resist gravity loads only or before the introduction of modern seismic codes (pre-1970s or 1980s) typically display several deficiencies, resulting in inadequate behavior under seismic loading. (Pohoryles DA, *et al* 2019)

Earthquake-induced damage to reinforced concrete structures has demonstrated the critical role of beam–column joints in maintaining structural integrity. According to global seismic records, earthquakes cause significant human and economic losses each year, with many failures attributed to inadequate detailing and poor seismic performance of beam–column joints. For example, the 1995 Kobe earthquake in Japan (Mw 6.9) resulted in more than 6,400 fatalities and caused severe damage to reinforced concrete buildings due to joint shear failures and insufficient ductile detailing. Similarly, the 1999 Kocaeli earthquake in Turkey (Mw 7.6) caused over 17,000 deaths and extensive collapse of reinforced concrete frame structures, while the 2008 Wenchuan earthquake in China (Mw 7.9) led to approximately 87,000 fatalities and widespread structural damage. More recently, the 2023 Türkiye–Syria earthquakes (Mw 7.8 and 7.5) caused more than 59,000 deaths and the collapse or severe damage of hundreds of thousands of buildings, highlighting the vulnerability of inadequately detailed reinforced concrete structures to seismic loading. These observations demonstrate the need for improving the seismic performance, ductility, and energy dissipation capacity of reinforced concrete beam–column joints through advanced reinforcement strategies such as hybrid FRP–steel systems (Mohamed H *et al.*, 2024).

Recent developments in concrete composites have resulted in several new products which aim to improve the strength, stability and service ability of the concrete structures. The function of the structural elements is to resist efficiently the action of gravity and environmental loads, and the service ability of the structure without significantly disturbing the geometry and integrity. A few structural elements such as beam-column junctions, perforated shear walls may require more rigorous analysis. (Balamuralikrishnan R., *et al.*, 2019). Because of the mentioned importance of RC joints and their reinforcement detailing, many studies have either investigated performance of joints with different reinforcement or proposed novel materials which improve their seismic response. The application of Ferro cement layers for joints' retrofitting, as an example, can enhance joints' performance in terms of ultimate capacity, ultimate displacement and ductility. (Javan, *et al.*, 2022).

Beam-column joints are among the most critical regions in reinforced concrete (RC) structures because they are responsible for transferring forces between beams and columns, particularly during seismic events. Failure of these joints can significantly reduce the structural integrity of a building and may lead to severe damage or even collapse. Many existing RC structures were designed using conventional steel reinforcement, which is susceptible to corrosion and deterioration over time, resulting in reduced durability and structural performance. To address these challenges, the use of fiber-reinforced polymer (FRP) bars has emerged as a promising alternative due to their high tensile strength, corrosion resistance, and lightweight characteristics. However, the relatively low modulus of elasticity and brittle behavior of FRP bars may limit their structural efficiency when used alone. Therefore, the hybrid application of FRP and steel reinforcement can provide an effective solution by combining the advantages of both materials (Peizhou Zhang, 2016).

The techniques of using fiber reinforced polymer for reinforcing the beam column joints have benefits such as high strength to weight ratio, protection against corrosion, easy installation, quick and simple tender (Sinaei *et al.*, 2011). FRP has also the advantages of being lightweight, easy to construct and having a high specific strength. It can also be used in the repair of structures affected by seismic damage or vulnerable or substandard reinforced structures. Different FRP types that

are used to enhance RC structures includes carbon-fiber-reinforced polymer (CFRP), glass-fiber-reinforced polymer (GFRP), aramid-fiber-reinforced polymer (AFRP) and basalt-fiber-reinforced polymer (BFRP). Hybrid reinforcement could increase stiffness and absorbed energy of RC joints based on the conclusions of the relevant studies. (Javan, 2022).

Earthquake forces are known to be linearly dependent on the self-weight of built structures; thus, the impact of an earthquake is reduced when this self-weight decreases (Ibrahim Almeshala *et al.*, 2020).

In order to reach proper conclusions on the application of FRP bars, several experimental and numerical studies have been conducted so far. The enhanced response of joints with hybrid steel and GFRP bars has proven the influence of incorporating GFRP bars in RC joints under seismic loads. The complete replacement of steel bars with GFRP and AFRP bars, however, is not recommended due to its shortcomings which are observed in previous studies. In terms of stiffness, for instance, the joints with GFRP and AFRP bars possess lower initial stiffness in comparison to those with steel bars because of lower elasticity modulus of GFRP and AFRP bars. A lower dissipated energy is also reported for the joints with FRP bars compared to those with conventional steel reinforcement. This could be due to linear behavior of FRP bars. On the other hand, the application of FRP bars could decrease base shear forces, improve moment capacity of RC sections, increase load carrying capacity of RC frames and decrease drift ratio of moment frames. Moreover, presence of FRP bars might move the plastic hinge of beam-column joints away from the column face (unlike the steel reinforced joints with plastic hinge at the beam- column interface) which could be due to the large elastic deformation of FRP bars. In the joints with hybrid steel-GFRP reinforcement, the reserved strength is increased by increasing the number of steel bars. (Javan, 2022).

The joint is defined as the portion of the column within the depth of the deepest beam that frames in to the column. In a moment resisting frame, three types of joints can be identified (i) Interior joint (ii) Exterior joint (iii) Corner joint.

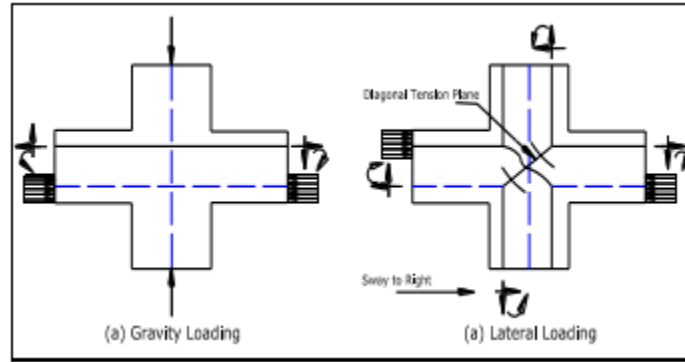


Figure 1.1 Interior joint (Balamuralikrishnan R., 2019)

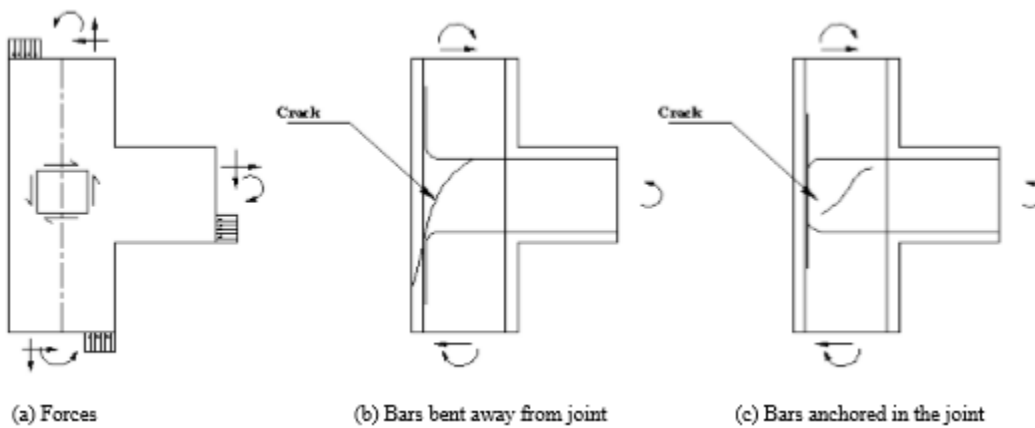


Figure 1.2 Exterior joint (Balamuralikrishnan R., 2019)

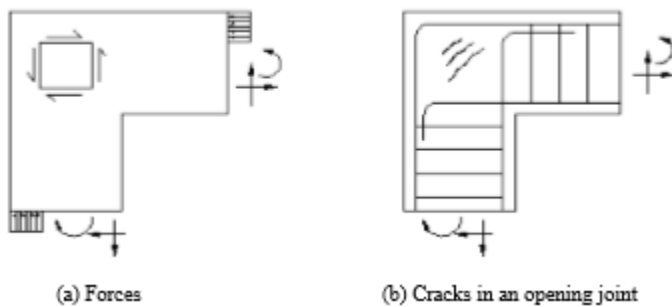


Figure 1.3 Knee joint subjected to 'Opening' moment (Balamuralikrishnan R., 2019)

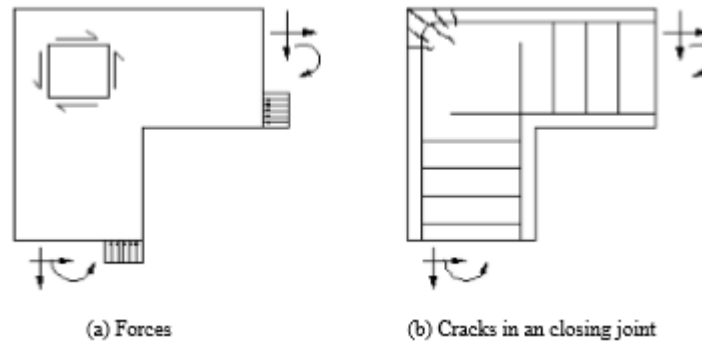


Figure 1.4 Knee joint subjected to ‘Closing’ moment (Balamuralikrishnan R., 2019)

There has been a growing interest to investigate the performance of mixed steel-FRP as well as steel-free FRP-RC structures. However, research in this area has been generally limited to some beam and column testing. Most of the newly adopted specifications for the design of FRP-reinforced concrete are not comprehensive, often do not include detailed seismic provisions, and do not cover hybrid FRP-steel RC systems. Therefore, research is needed to investigate the performance of FRP and hybrid FRP-steel-reinforced concrete systems under cyclic loading in order to form the basis for future design code provisions for FRP-reinforced concrete in seismic zones. In this study, full-scale steel reinforced, steel-free GFRP-reinforced, and hybrid GFRP-steel-reinforced beam-column joints were tested under cyclic loading.

1.2 Statement of the Problem

The durability and seismic performance of reinforced concrete (RC) structures are major concerns in structural engineering. Conventional steel reinforcement, although widely used, is highly susceptible to corrosion in aggressive environments such as marine and industrial regions. Corrosion of steel reinforcement leads to cracking, spalling of concrete cover, reduction of bond strength, and deterioration of the load-carrying capacity of RC structures, resulting in increased maintenance costs and reduced service life. To overcome these durability problems, Fiber Reinforced Polymer (FRP) bars have been introduced as an alternative to steel reinforcement because of their excellent corrosion resistance, high tensile strength, lightweight nature, and high strength-to-weight ratio. However, previous studies have shown that FRP bars exhibit linear-elastic behavior up to failure, relatively low modulus of elasticity, limited compressive strength, and brittle failure characteristics. These properties reduce their ability to provide the ductility and

energy dissipation required for structures subjected to seismic loading, particularly in critical structural components such as beam–column joints. Several researchers have investigated the seismic performance of beam–column joints reinforced with steel, FRP, and hybrid steel–FRP reinforcement under cyclic loading. Although these studies have demonstrated that hybrid reinforcement can improve structural performance by combining the advantages of steel and FRP materials, most of the existing research has focused on individual FRP types or complete replacement of steel reinforcement. Furthermore, the available seismic design provisions for FRP-reinforced concrete structures are still limited and do not adequately address the behavior of hybrid FRP–steel reinforced beam–column joints under cyclic loading. In particular, comparative investigations of hybrid AFRP–steel and GFRP–steel reinforcement systems regarding stiffness degradation, energy dissipation, load-carrying capacity, and failure mechanisms remain limited. Therefore, there is a need for a comprehensive investigation of the cyclic behavior of RC beam–column joints reinforced with hybrid FRP–steel systems. This study aims to evaluate the structural performance of hybrid AFRP–steel and GFRP–steel reinforced beam–column joints under cyclic loading using finite element analysis, thereby contributing to a better understanding of their seismic behavior and providing information that may support the future development of design recommendations for hybrid FRP–steel reinforced concrete structures in seismic regions.

1.3 Significance of the Research

FRP rebar's show better corrosion resistance than steel rebar's. This property enables FRP rebar's suitable for use in structures located in adverse environment such as marine. One major drawback of using FRP rebar is their tendency to exhibit brittle failure. This aspect must be taken into account during the design and construction processes. The substantial deformation capabilities demonstrated by FRP materials can prove beneficial in replacing the yielding behavior of steel. Consequently, this allows FRP-RC structures to adequately dissipate seismic energy. The fundamental principle behind the design philosophy of Beam-Column joints is to ensure sufficient ductility for dissipating seismic energy. To overcome these limitations, an effort will be made in this research for a more comprehensive study to determine the optimal percentage of steel bars that should be replaced with Fiber Reinforced Polymer (Glass, Aramid) bars in the beam element of a reinforced concrete (RC) joint. The behavior of the beam column joint with steel - FRP bars

under cyclic loading will provide the insights for feasibility of using FRP bars in structures which are prone to corrosion.

1.4 Research Objective

1.4.1 General objective

This research aims to understand the behavior of beam-column joints with hybrid steel-fiber reinforced polymer (FRP) rebar's under cyclic loading using finite element analysis.

1.4.2 Specific Objectives

1. To study crack propagation, load-displacement, hysteresis curves of specimens under repeated cyclic loading
2. To study the seismic parameters such as ductility, absorbed energy and stiffness of specimens considered.
3. To evaluate the performance of different types of FRP reinforcement (e.g., glass and aramid fiber) in the beam-column joint under cyclic loading and compare their effectiveness.

1.5 Research Question

1. What will be the behavior beam-column joints with FRP bars under cyclic loading?
2. How the experimental can be validated using computer analysis?
3. How do different types of FRP reinforcement, affect the cyclic performance of reinforced concrete beam-column joints?

1.6 Delimitation of the study

The main scope of this study will conduct the behavior of beam-column joints with hybrid steel-fiber reinforced polymer (FRP) rebar's under cyclic loading using finite element analysis method which include; effects of various parameters, evaluation of ultimate load and failure mode

regarding to repeated cyclic loading and the scope will tend to cover the analysis only by using FEM method.

1.7 Organization of the Thesis

The present thesis is organized into five chapters which are arranged as follows: Chapter one deals with introductory parts which include background, statement of the problem, the significance of the study, existing research gap, objective of the study, research question, delimitation of the Study and thesis organization. Chapter two briefly describes the previous work on the behavior of beam-column joints with hybrid steel-fiber reinforced polymer (FRP) rebar's under cyclic loading.

Chapter three mainly focuses on the validation work, and modeling input data, and describes the analysis method and a detailed procedure of modeling. Chapter four presents the analysis result of all modeled. Finally, Chapter Five is about the conclusion and recommendations based on the analysis result.

CHAPTER TWO

2 LITREATURE REVIEW

2.1 General

Much research has been conducted on the behavior of beam-column joints with hybrid steel-FRP rebar's under cyclic loading, focusing on various key design parameters. Different studies have evaluated the impact of combining steel and FRP reinforcement on the joint's ability to resist cyclic stresses, particularly under seismic conditions. Previous experimental and numerical investigations have been carried out to enhance design recommendations by assessing critical factors that influence joint performance, such as ductility, energy dissipation, stiffness degradation, and failure modes. These studies aim to bridge the performance gap between traditional steel and FRP systems by leveraging the strengths of both materials. This chapter will provide a comprehensive understanding of the cyclic behavior of beam-column joints reinforced with hybrid steel-FRP rebar's and contribute to the development of improved structural design approaches for earthquake-resistant construction.

2.2 Beam Column joint under cyclic loading

A beam column joint is defined as the portion of a column within the depth of the beams that frame into it. Formerly the design of monolithic joints was limited to providing adequate anchorage for the reinforcement. However the increasing use of high strength concrete resulting in smaller member cross sections and the use of larger diameter and higher strength reinforcing bars now require that greater attention be given to joint design and detailing. The function of a beam-column joint in a frame is to transfer the loads and moments at the ends of the beams into the columns. (H., Darwin, & Dalon, 2010).

The behavior of beam-column joints under cyclic loading is pivotal in determining the seismic resilience of reinforced concrete (RC) structures. Traditional RC joints reinforced with steel rebar, often face challenges such as reinforcement congestion, leading to difficulties in concrete placement and potential structural vulnerabilities. To address these issues, the integration of Fiber Reinforced Polymer (FRP) materials, known for their high strength-to-weight ratio and corrosion

resistance, has been explored. However, the inherent brittleness of FRP and its lower bond strength with concrete necessitate innovative solutions.

Hybrid reinforcement systems, combining steel and FRP rebar, have emerged as a promising approach to enhance the ductility and energy dissipation of beam-column joints under cyclic loads. Numerical modeling, particularly through Non-Linear Finite Element Analysis (NLFEA), has been instrumental in evaluating the performance of these hybrid systems. For instance, studies have demonstrated that incorporating steel fibers into the joint core can significantly improve post-cracking behavior, promoting ductile shear failure and increasing joint toughness. Specifically, a 2% volume fraction of steel fibers was found to enhance the joint's load-bearing capacity and stiffness under cyclic loading. (Umar Ahmad Noor 1, *et al* 2024)

Moreover, research has indicated that hybrid joints, which utilize both bolting and adhesive bonding techniques, exhibit higher rotational stiffness and moment capacity compared to solely bolted joints. This combination effectively mitigates issues related to reinforcement congestion and enhances the overall structural integrity of the joints under cyclic loading conditions.

2.3 Challenges in Conventional Steel Reinforced Beam-Column Joints

Steel reinforcement has long been the standard for reinforced concrete (RC) beam-column joints due to its high tensile strength and ductility. However, several challenges arise, particularly under cyclic loading and seismic conditions. One of the major issues is reinforcement congestion, which occurs due to the high reinforcement ratio required in beam-column joints. This congestion makes concrete placement difficult, leading to voids, improper compaction, and reduced bond strength, which can contribute to premature cracking and failure (Hakuto *et al.*, 2000; Hwang & Lee, 1999). Another significant challenge is the corrosion of steel reinforcement, which affects the durability of structures exposed to harsh environmental conditions. Chloride penetration and moisture infiltration accelerate steel deterioration, causing expansion, cracking, and a loss of structural integrity over time (Broomfield, 2007; Cairns *et al.*, 2008). Although protective coatings such as epoxy can mitigate corrosion effects, they do not provide a permanent solution (Berke & Hicks, 1992).

Under cyclic loading, steel-reinforced beam-column joints also experience stiffness degradation, leading to reduced energy dissipation capacity and potential structural failure during seismic events (Pantelides *et al.*, 2014). The hysteresis behavior of steel-reinforced joints exhibits significant pinching; indicating a decline in energy absorption and increased vulnerability to earthquake forces (Xiao & Wu, 2003). Additionally, conventional beam-column joints are susceptible to brittle failure modes, particularly shear failure, which compromises overall ductility and structural resilience (Sharma *et al.*, 2019). Limited confinement within the joint region further exacerbates this issue, necessitating additional stirrups or alternative reinforcement materials to enhance seismic performance (Parra-Montesinos, 2005; Kwak & Kim, 2013). These challenges highlight the need for innovative reinforcement strategies, such as hybrid systems incorporating Fiber Reinforced Polymer (FRP) materials, to improve durability, reduce congestion, and enhance cyclic performance in beam-column joints.

2.4 Fiber Reinforced Polymer (FRP) as an Alternative to Steel Reinforcement

Fiber Reinforced Polymer (FRP) has emerged as a promising alternative to conventional steel reinforcement in reinforced concrete structures due to its excellent corrosion resistance, high tensile strength, lightweight nature, and high strength-to-weight ratio. The most commonly used FRP reinforcement materials in structural engineering are Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), and Aramid Fiber Reinforced Polymer (AFRP). Each type possesses distinct mechanical properties that influence its structural performance and suitability for different applications (Nanni, 1993; Benmokrane *et al.*, 2007). Unlike steel reinforcement, FRP bars are immune to corrosion caused by moisture, chlorides, and aggressive environmental conditions, making them particularly suitable for marine structures and other harsh environments. In addition, their low density facilitates transportation and installation while reducing the dead load of structures (ACI 440.1R-15, 2015). Table 2.1 presents a comparison of the typical mechanical properties of the commonly used FRP reinforcement materials and conventional steel reinforcement.

Table 2.1 Typical mechanical properties of steel and FRP reinforcing bars (Nanni, 1993; Benmokrane *et al.*, 2007).

Property	Steel	GFRP	AFRP	CFRP
Density (g/cm ³)	7.85	1.9–2.1	1.25–1.40	1.5–1.8
Tensile strength (MPa)	400–600	600–1500	1000–2000	1200–3000
Elastic modulus (GPa)	200	40–60	60–125	120–300
Ultimate strain (%)	8–15	1.5–3.0	1.9–4.5	0.5–1.7
Corrosion resistance	Moderate	Excellent	Excellent	Excellent
Fatigue resistance	Good	Good	Very good	Excellent
Electrical conductivity	High	Non-conductive	Non-conductive	Conductive
Relative cost	Low	Moderate	High	Very high

It can be observed from Table 2.1 that CFRP possesses the highest stiffness and tensile strength among the FRP materials but is associated with a relatively high cost. GFRP offers a cost-effective solution with excellent corrosion resistance but has a lower modulus of elasticity, while AFRP provides an intermediate alternative with high tensile strength and superior impact resistance. Compared with steel, all FRP materials exhibit lower density and better corrosion resistance but generally lack the ductile yielding behavior required for effective seismic energy dissipation.

Despite these advantages, FRP reinforcement presents several challenges. The brittle linear-elastic behavior of FRP bars results in sudden failure without yielding, unlike conventional steel reinforcement (Harries and Rizos, 2007). This characteristic limits the ductility and energy dissipation capacity of FRP-reinforced beam-column joints subjected to cyclic and seismic loading (Xiao and Wu, 2003). Furthermore, the bond characteristics between FRP bars and concrete differ from those of steel, requiring appropriate anchorage and detailing to ensure adequate load transfer (El-Safty *et al.*, 2014).

To overcome these limitations, researchers have investigated hybrid reinforcement systems that combine FRP and steel bars to exploit the corrosion resistance and high tensile strength of FRP while maintaining the ductility and energy dissipation capacity provided by steel reinforcement. Various studies have also explored the use of fiber-reinforced concrete and improved joint detailing to enhance the seismic performance of FRP-reinforced beam-column joints (Fawzia *et*

al., 2017). Nevertheless, the brittle behavior and bond-related issues of FRP reinforcement continue to present challenges, highlighting the need for further research on hybrid FRP-steel beam-column joints under cyclic loading conditions.

2.4.1 Justification for the Selection of GFRP and AFRP Reinforcement

Glass Fiber Reinforced Polymer (GFRP) and Aramid Fiber Reinforced Polymer (AFRP) were selected for this study because they provide a practical balance between mechanical performance, durability, and cost for reinforced concrete structures subjected to cyclic loading. GFRP offers high tensile strength, excellent corrosion resistance, low weight, and relatively low cost, making it suitable for widespread structural applications. AFRP, on the other hand, possesses higher tensile strength, better fatigue resistance, and improved impact performance than GFRP, which can enhance the seismic behavior of beam-column joints. Although Carbon Fiber Reinforced Polymer (CFRP) exhibits superior stiffness and strength, its high cost limits its practical use in many engineering applications. Furthermore, previous studies on hybrid GFRP-steel and AFRP-steel reinforced beam-column joints under cyclic loading are limited, justifying the selection of these materials to investigate their influence on the seismic performance of reinforced concrete beam-column joints.

2.5 Advantages and Disadvantages of Fiber Reinforced Polymer (FRP) Bars in Concrete

2.5.1 Advantages of FRP Bars in Concrete

1. Corrosion Resistance

One of the most significant advantages of FRP bars is their excellent resistance to corrosion. Unlike steel, FRP does not rust when exposed to moisture, chloride, or aggressive chemical environments, making it ideal for marine structures, bridges, and wastewater treatment plants (Benmokrane *et al.*, 2007; Nanni, 1993).

2. High Strength-to-Weight Ratio

FRP bars offer higher tensile strength than steel while being significantly lighter. This

reduces the overall dead load of structures and facilitates easier transportation and installation (ACI 440.1R-15, 2015).

3. Electromagnetic Neutrality

FRP bars are non-conductive and non-magnetic, making them suitable for applications in structures where electromagnetic interference needs to be minimized, such as hospitals, research facilities, and electrical substations (El-Safty *et al.*, 2014).

4. Fatigue and Impact Resistance

FRP bars exhibit superior fatigue resistance compared to steel, making them more durable under repeated loading conditions, such as in bridges and seismic applications (Harries & Rizos, 2007).

5. Low Maintenance Costs

Due to their corrosion resistance and long-term durability, FRP-reinforced structures require less maintenance, leading to reduced lifecycle costs compared to steel-reinforced structures (Cairns *et al.*, 2008).

2.5.2 Disadvantages of FRP Bars in Concrete

1. Brittle Failure and Lack of Ductility

Unlike steel, FRP bars exhibit linear-elastic behavior until failure, meaning they do not yield before breaking. This brittle nature poses a risk of sudden failure without warning, which is a significant concern in seismic applications (Pantelides *et al.*, 2014).

2. Lower Modulus of Elasticity

FRP bars have a lower modulus of elasticity compared to steel, leading to higher deflections in reinforced concrete structures. This requires careful design considerations, such as increased reinforcement ratios or additional stiffness-enhancing measures (Xiao & Wu, 2003).

3. Bonding and Anchorage Challenges

The bond strength between FRP bars and concrete is generally lower than that of steel, requiring specialized surface treatments, mechanical anchoring, or additional confinement to ensure proper load transfer (El-Gawady & Shaheen, 2017).

4. High Initial Cost

Although FRP reduces long-term maintenance costs, its initial cost is significantly higher

than traditional steel reinforcement. This limits its widespread use in cost-sensitive construction projects (Ascione et al., 2011).

5. Limited Design Codes and Guidelines

while progress has been made in developing design standards for FRP-reinforced structures, existing building codes are primarily focused on steel reinforcement. Engineers must rely on experimental data and evolving guidelines to ensure proper design and implementation (ACI 440.1R-15, 2015).

6. Temperature Sensitivity

FRP materials are sensitive to high temperatures and their mechanical properties can degrade when exposed to extreme heat. Fireproof coatings or additional protective measures may be necessary in high-temperature environments (Fawzia et al., 2017)

2.6 Structural Behavior

2.6.1 Ductility

Ductility is the capability to deform beyond the initial yield point without any remarkable loss in strength. (Saha, Behavior of reinforced concrete, 2020).

Ductility is the structural member's capacity to afford inelastic distortions beyond yield distortion without a significant load in its load-carrying capability. The ductility index (μ) can be determined from the curve that connects between the load and deflection by dividing the maximum deflection (Δ_u) on the yield deflection (Δ_y). (Hamsa M. Adnan1, 2020).

The ductility y index:

$$(\mu\Delta) = \Delta_u/\Delta_y \quad \text{eq 2.1}$$

Where;

Δ_u = maximum deflection

Δ_y = yield deflection

2.6.2 Secant Stiffness

Secant stiffness is another notable factor for evaluating performance of structures under cyclic load. It is worth mentioning that stiffness degradation during a cyclic loading is mainly due to flexural and shears cracks deformations in joints' core, inelastic deformation of concrete, concrete cover spilling and rebar sliding.(D. Javan *et al*, 2022).

$$K = \frac{P}{\delta} \quad \text{eq 2.2}$$

Where p = load, KN and δ = deformation, mm

2.6.3 Absorbed Energy

Absorbed energy, also referred to as energy dissipation, is the total amount of energy dissipated by a structural component under cyclic loading before failure. It is an important parameter for evaluating the seismic performance of reinforced concrete (RC) beam–column joints because it reflects the ability of a structure to withstand earthquake-induced loading through inelastic deformation (Pantelides *et al.*, 2014; Xiao & Wu, 2003). In hybrid steel–FRP reinforced joints, steel bars contribute to energy dissipation through yielding and plastic deformation, while FRP reinforcement contributes through its high tensile strength and elastic behavior. The combination of these materials can improve the overall seismic performance of the joint (Harries & Rizos, 2007). The absorbed energy is determined from the load–displacement hysteresis response obtained during cyclic loading. It is equal to the area enclosed by the hysteresis loops and can be calculated as

$$E_d = \oint F d\Delta \quad \text{eq 2.3}$$

where (E_d) is the dissipated energy, (F) is the applied load, and (Δ) is the corresponding displacement. For discrete experimental or numerical data, the dissipated energy for one loading cycle can be approximated by

$$E_d = \sum_{i=1}^{n-1} \frac{(F_{i+1} + F_i)}{2} (\Delta_{i+1} - \Delta_i) \quad \text{eq 2.4}$$

Where (F_i) and (Δ_i) are the load and displacement values at the (i^{th}) data point. The cumulative absorbed energy is obtained by summing the energy dissipated over all loading cycles. A larger hysteresis loop area indicates greater energy dissipation capacity and better seismic performance of the beam-column joint (Fawzia *et al.*, 2017).

2.6.4 Failure Mode and Crack Propagation in Beam-Column Joints

2.6.4.1 Failure Mode in Beam-Column Joints

Failure modes in beam-column joints reinforced with hybrid steel-FRP bars depend on material properties, reinforcement configuration, joint detailing, and applied loading conditions. These joints experience different failure mechanisms under cyclic or seismic loading, which affect their structural performance. The most common failure modes include:

1. Flexural Failure:

- Occurs when the beam section yields due to excessive bending moments, leading to plastic hinges.
- Steel-reinforced joints exhibit ductile behavior, while FRP-reinforced joints experience brittle failure due to lower strain capacity (Kassem *et al.*, 2011).

2. Shear Failure of the Joint Core:

- A critical failure mode in poorly detailed joints where diagonal cracks form in the joint region.
- Occurs due to insufficient confinement, leading to abrupt degradation of strength (Pantelides *et al.*, 2014).

3. Bond Failure and De bonding:

- FRP bars are prone to bond-slip failure, especially at anchorage points, due to their smooth surface and lower bond strength compared to steel.
- Hybrid reinforcement systems use mechanical anchoring or special surface treatments to improve bond behavior (El-Gawady & Shaheen, 2017).

4. Concrete Crushing and Spilling:

- Concrete failure occurs at high compression zones, particularly near the beam-column interface.
- Hybrid steel-FRP systems help delay this failure mode by improving confinement using FRP wraps or fiber-reinforced concrete (Benmokrane *et al.*, 2007).

2.6.4.2 Crack Propagation in Beam-Column Joints

Crack propagation in beam-column joints follows a progressive failure pattern under cyclic loading, starting with micro cracks and expanding into larger cracks leading to structural failure.

The stages of crack development are:

1. Initiation Phase:

- Micro cracks develop due to initial stress concentrations at rebar-concrete interfaces.
- Steel reinforcement delays crack formation through yielding, whereas FRP reinforcement has a lower crack resistance due to its brittle nature (Harries & Rizos, 2007).

2. Propagation Phase:

- Cracks extend diagonally from the beam to the column joint, increasing in width.
- In shear-dominated joints, diagonal cracks become primary failure indicators (Fawzia *et al.*, 2017).

3. Final Failure Stage:

- Fracture or excessive spilling occurs, leading to joint collapse.

In hybrid reinforcement systems, the failure pattern is influenced by the steel-to-FRP ratio. Higher steel content results in ductile yielding, while higher FRP content increases brittle fracture risk (Pantelides *et al.*, 2014)

2.7 Review of Previous Experimental and Analytical Investigations

Pang, Qu, et al., (2015) studied delves into the characteristics of hybrid FRP-RC beams, particularly focusing on an under-reinforced configuration adhering to appropriate reinforcement ratio constraints. Additionally, they analyze the ductility of hybrid-RC elements. The pivotal factors examined in their research paper include the ultimate strength and ductility index of under-reinforced hybrid-RC beams. Their findings suggest that various parameters such as concrete strength, steel strength, FRP type, effective longitudinal reinforcement stiffness, and ultimate compressive strain significantly influence ductility. Similar to conventional steel-RC beams, they

observe that higher concrete strength and ultimate compressive strain correlate with enhanced ductility in hybrid-RC beams.

Mady et al., (2011) examined the seismic performance of concrete beam-column joints fortified with glass fiber reinforced polymer (GFRP) bars and stirrups. Five full-scale exterior T-shaped beam-column joint prototypes were meticulously constructed and subjected to simulated seismic loads. The primary parameters under investigation are the types and ratios of longitudinal and transversal reinforcement. Their experimental findings demonstrate that joints reinforced with GFRP can effectively withstand a 4.0% drift ratio without experiencing notable residual deformation. Consequently, they affirm the viability of employing GFRP bars and stirrups as reinforcements in beam-column joints subjected to seismic loading conditions.

Mahmoud, et al., (2022) they conducted research on the cyclic behavior of exterior beam-column connections made of high-strength lightweight concrete (HSLWC) reinforced with glass fiber reinforced polymer (GFRP). They tested twelve full-scale joints, comprising normal-strength concrete (NC with $f_c' = 32$ MPa) and HSLWC (with $f_c' = 42, 49$, and 52 MPa), under cyclic loading conditions. The beams were reinforced with either conventional steel bars (CS) or GFRP combined with steel fibers (SF). Three main parameters were investigated: (1) HSLWC, (2) GFRP ratios of 0.70%, 1.03%, and 1.37%, and (3) SF ratios of 0.0%, 0.75%, and 1.50%.

Their findings revealed that increasing the concrete strength from NC with conventional steel bars to HSLWC ($f_c' = 42$ MPa) with the same GFRP ratio enhanced the first cracking load by approximately 25%. Furthermore, increasing the SF ratio to 1.50% improved the failure load by 18–24% compared to specimens without fibers. Overall, incorporating GFRP bars in the exterior beam-column joints as flexural reinforcement in the connected beam augmented the ultimate strength and ductility of the joint compared to conventional steel reinforcement bars. Additionally, introducing SF in specimens with GFRP bars enhanced the deformability factor compared to specimens without SF.

Javan, et al., (2022) conducted a study on the performance of reinforced concrete (RC) beam-column joints utilizing hybrid GFRP-steel reinforcement under cyclic and axial loads. Their aim was to assess how replacing steel bars with GFRP bars influences the behavior of these joints. They fabricated and tested five half-scale joints under cyclic and axial loading conditions. In their

investigation, all joints had identical geometry, material properties, and test setups, differing only in the number of steel bars in the beams replaced with GFRP bars.

Their findings suggest that incorporating GFRP bars, up to a ratio of less than 50%, could improve the cyclic response of joints in terms of ductility, absorbed energy, and equivalent damping ratio. This indicates a positive impact of GFRP reinforcement on the performance of RC beam-column joints under cyclic and axial loading.

Bing Li, et, al., (2009) conducted a study on enhancing the seismic performance of reinforced concrete beam-column joints using fiber-reinforced polymer (FRP) composites. Three non-seismically detailed interior reinforced concrete beam-column joints, including one eccentric and two concentric joints were strengthened with various configurations of FRP wrapping using glass fiber-reinforced polymer and carbon fiber-reinforced polymer strips and sheets. These joints were then subjected to constant axial compression load and reversed cyclic loading to simulate low to moderate earthquake forces.

The investigation focused on evaluating the seismic performance of the strengthened beam-column joints in terms of their hysteresis response, stiffness, and energy dissipation capacity compared to the original and un-strengthened joints. Their findings suggest that applying strips at a 45-degree angle on a flushed eccentric joint core, along with cross-bracing on the beam and confinement around the column, proved to be highly effective. All specimens exhibited gradual strength deterioration, with observed phenomena such as bond degradation and de bonding of FRP sheets near the joint core.

Overall, the proposed strengthening schemes were deemed efficient and cost-effective for the mass repair or upgrading of non-seismically detailed structures, offering promising prospects for enhancing their seismic resilience.

Nehdi, et, ,al (2016) conducted an investigation into the behavior of hybrid GFRP-steel RC beam-column joints under reversed cyclic loading conditions. Three full-scale beam-column joint specimens were utilized, each reinforced with either steel, GFRP, or a hybrid GFRP-steel configuration, to assess their performance in seismic scenarios.

Their findings indicated that the GFRP-reinforced beam-column joint exhibited limited plasticity characteristics when subjected to reverse cyclic loading. This led to reduced energy dissipation compared to the steel and hybrid reinforced specimens. Additionally, they suggested a need for re-evaluation of design code provisions originally developed for ductile steel reinforcement in the context of FRP-RC structures. This underscores the importance of adapting seismic design guidelines to suit the unique properties and behaviors of FRP reinforcements in reinforced concrete structures.

Griira and Saatcioglu investigated the use of both steel grids and CFRP grids as stirrups for confinement of concrete columns having longitudinal steel reinforcement. Several grid configurations were used and column specimens were tested under cyclic loading. They concluded that the performance of columns reinforced with CFRP stirrups was comparable to that of columns reinforced with steel stirrups. They also argued that the use of grids whether made of steel or CFRP provides ease of construction and a near-uniform distribution of the confinement pressure along the column, without congesting the reinforcement cage. They reported that the NEFMAC grid-based stirrups failed at their nodes, which is the common

Mohamed, (2017) Study proposes both steel and fiber-reinforced polymer (FRP) composites as main reinforcement for modern moment-resisting frame structures. The design concept of the proposed reinforcement detailing is stated based on the available provisions of the current seismic-design codes. A very detailed 3D FEM model, which takes into account the material and geometric nonlinearity and bond behavior of the steel and glass FRP (GFRP) reinforcement, was created and validated against the available experimental results. 54 cases covering all possible combinations of steel-to-GFRP reinforcements (both under and over reinforced design scenarios) were studied. The analysis results of SFRC joints pointed to the ratio between the effective FRP reinforcement ratio and the balanced FRP reinforcement ratio (the normalized reinforcement ratio) as the main design tool that can be adopted to achieve the required seismic behavior; and a definition is given to the lower and upper limits of the normalized ratio. Design recommendations regarding the controllability of the serviceability state, the post-yielding state, the residual strength, and the ultimate state of SFRC joints through an appropriate design for the steel-to-FRP reinforcement ratio are drawn. Finally, a mechanical model describing the behavior of SFRC joints with different

steel-to-FRP reinforcement ratios is introduced based on the general behaviors of the simulated joints.

Peizhou Zhang, et al., (2016) Earthquake reconnaissance and laboratory tests reveal that the beam-column joints of existing RC frame structures in China are susceptible to failure, leading to severe structural damage. However, the inelastic response of joint elements is rarely considered in structural analysis or design. A new joint element considering shear deformation and bar-slip behavior was proposed and verified using an extensive experimental data set. Two RC frame specimens with different details were modeled with the joint element and their simulated seismic responses were compared with experimental results in terms of global and local performance. Based on the simulation, the joint element proved to be reliable and suitable for 2D structural modeling. Finally, two reinforced concrete frame structures with the same dimensions and reinforcement ratios but different ductility are modeled with and without the proposed joint elements. The proposed joint element was shown to accurately predict the mechanical behavior of such structures and their components, especially the hysteresis behavior. Analysis shows that joint failure tends to happen in low-ductility structures and will reduce the ductility and the energy dissipation ability of the structure, even cause structural collapse. Compared with the new designed structures, seismic performance of the low-ductility ones is worse, with poor energy dissipation, weak collapse resistance and brittle failure modes.

Wentong Zhaoa, et, al., (2018) the proposed macro beam-column joint was developed based on the force transfer mechanisms and inelastic response mechanisms, using axial springs representing bar-slip mechanism of longitudinal reinforcement, concrete and reinforcement in the joint core and interface-shear. In the joint core, eight concrete components and eight reinforcement components worked together to contribute to the effect of joint shear deformation. Constitutive relationship was developed to define the response of proposed joint model based on the dimensions, geometric, and material properties. An applicable model was used for simulating strength reduction of confined concrete strut due to joint damage and cyclic load history. Modifications were made to provide a more reasonable simulation of the anchorage zone response. The numerical analysis results were compared with experimental data of six beam-column sub assemblages to validate the proposed macro beam-column joint element model. The comparison between the simulated and

the test results shows that the proposed joint model is able to simulate the hysteretic response, joint shear strength and joint shear deformation of the beam-column sub assemblages. Additionally, the comparison of the simulated results between proposed joint model and available joint model indicates that the proposed joint model is more accurate and efficient.

Costas P. et, al., (2002) Analytical models are presented in this study for the analysis of reinforced concrete joints strengthened with composite materials in the form of externally bonded reinforcement comprising unidirectional strips or flexible fabrics. The models provide equations for stresses and strains at various stages of the response ~before or after yielding of the beam or column reinforcement! Until the ultimate capacity is reached, defined by concrete crushing or fiber-reinforced polymer (FRP) failure due to fracture or de bonding. Solutions to these equations are obtained numerically. The models provide useful information on the shear capacity of FRP-strengthened joints in terms of the quantity and configuration of the externally bonded reinforcement and may be used to design FRP patching for inadequately detailed beam-column joints. A number of case studies are examined in this article, indicating that even low quantities of FRP materials may provide significant enhancement of the shear capacity. The effectiveness of external reinforcement increases considerably if de bonding is suppressed and depends heavily on the distribution of layers in the beam and column. The latter depends on the relative quantities of steel reinforcement crossing the joint panel and the level of axial load in the column. Analytical shear strength predictions were in good agreement with test results found in the literature, thus adding confidence to the validity of the proposed models.

Mohamed H. et, al., (2024) provide a thorough understanding of the performance of GFRP-RC MRFs in seismic regions, the challenges and the potential advantages and disadvantages. The design parameters governing the connection response were identified and evaluated to help in the appropriate design of the connections of MRFs. This state-of-the-art review found that the GFRP-RC beam-column sub-assemblages can reach a 4 % drift without strength reduction, resulting in a pseudo-ductile behavior that provides warnings of impending failure. However, at the drift allowance of 2.5 % for conventional RC structures, it was recognized that the design capacity may not always be reached. Additionally, the GFRP-RC beam-column subassembly can demonstrate

minimal damage after earthquakes and can withstand repeated earthquake loads without requiring repair, thereby minimizing repair costs. However, this resilience comes at the expense of ductility and energy dissipation capacity reduction. Therefore, it is advisable to prevent joint failure and employ well-over reinforced structural elements to facilitate a more gradual failure by keeping the reinforcement's stress of the beams well below its capacity. Besides, incorporating replaceable external damping systems can enhance the energy dissipation capacity, especially considering the nearly elastic behavior of GFRP-RC and their low level of damage. The study also outlined design guidelines for beam-column connections, including joint shear strength, anchorage details, and the column-to-beam flexural capacity ratio. This synthesis of existing literature points to the potential use of GFRP-RC MRFs in seismic regions and highlights their shortcomings, current issues, the gaps regarding the better understanding of GFRP-RC MRFs performance as well as guiding future research toward establishing seismic provisions for GFRP-RC MRFs.

Jianchun Li, et, al., (2002) Conducted through a comprehensive experimental work, investigates the behavior of reinforced concrete frame specimens designed to represent the column-beam connections in plane frames. As a follow-up to the previous reported work, it focuses on details of experimental analyses, in particular, a comprehensive strain analysis. Results of the analysis show that designed hybrid FRP reinforcement greatly improve the stiffness and load carrying capacity of its concrete counterpart. It also delays the crack initiation at the joint through confinement due to FRP reinforcement.

M. Nehdia, et, al., (2010) Studied, a SMA-FRP hybrid RC beam-column joint has been proposed to address not only corrosion resistance, but also seismic related problems. This joint is reinforced with a super-elastic Ni-Ti SMA bar at the plastic hinge regions of the beam and FRP in the other regions of the beam and column. To validate the proposed joint, an experimental investigation has been carried out to develop such a joint and test it under reversed cyclic loading. The results are compared in terms of load-story drift, moment-rotation and energy dissipation capacity to those of a similar RC beam-column joint specimen reinforced with conventional steel. The SMA-FRP beam-column joint proved to have adequate energy dissipation under earthquake type loading.

Arindom Bora, et, al., (2018) Studied, the beam-column joint analysis is done using ANSYS. The design is first carried out in ETABS and using the design data it is analysed in ANSYS. The equivalent stresses and the total deformation generated in the beam-column joint is calculated. Due to the bad effects of environmental changes, pollution, carbonation, corrosion occurring in a structural element due to which the building is likely to collapse. The failure in the beam-column joint can occur due to these reasons and also due to lack of proper reinforcement in the joint region. While experiencing seismic activity with inadequate reinforcement the beam-column joint will fail. This project aims in introducing FRP in the beam column joints which are likely to fail by retrofitting it. The failure can be identified by observing cracks or carrying out NDT tests to find out the region of cracks and the amount of reinforcement corroded. In this study different types of FRP is introduced to the beam-column joint in ANSYS. It is analysed and then the equivalent stresses and total deformations generated are compared with each other whichever will be more effective to be used in the field of construction.

Hamid Sinaei, et, al., (2011) the effectiveness of composite fiber reinforced polymer (CFRP) layers for exterior beam-column connections was studied through a finite element model (FEM). ABAQUS environment (Hibbitt et al., 1988) was used for finite element analysis and a model based on a previous experimental test was made. The FEM results were validated by comparing with previous experimental test results. This model was developed to analyse rehabilitation of exterior beam-column connection. Five exterior reinforced concrete beam-column joint specimens, including a control specimen (non-retrofitted) and four retrofitted specimens with altered arrangements of CFRP were developed. From the realistic nonlinear analysis of reinforced concrete (RC) connections with FRP overlays, it was determined that L shape overlays from FRP composites at the beam-column, is an appropriate usage to increase ductility. In addition, U shape overlays under the beam and the use of FRP on both lateral sides of the beam are very good strengthening strategies for strength and ductility enhancement of the RC joints. However, FRP only on the top and bottom of the beam decreases the ductility.

Haitham A. Ibrahima, et, al., (2018) Proposed both steel and fiber-reinforced polymer (FRP) composites as main reinforcement for modern reinforced concrete (RC) moment-resisting frame (MRF) structures. A detailed three-dimensional finite element model (3D FEM), which takes into

account the material and geometric nonlinearity and the bond behavior of steel and glass FRP (GFRP) reinforcement, was created and validated against the available experimental results. 54 cases covering several combinations of steel-to-GFRP reinforcements and design scenarios (under and over reinforced design scenarios) were studied. The analysis results of steel-FRP reinforced concrete (SFRC) joints pointed to the ratio between the effective FRP reinforcement ratio and the balanced FRP reinforcement ratio (the normalized reinforcement ratio) as the main design tool that can be adopted to achieve a predefined seismic behavior. Moreover, a definition is given to the lower and upper limits of the normalized ratio. Design recommendations regarding the controllability of the serviceability state, the post-yielding state, the ultimate state, and the residual strength of SFRC joints through an appropriate design for the steel-to-FRP mixing ratio are drawn. Ultimately, a mechanical model describing the behavior of SFRC joints with different steel-to FRP reinforcement ratios is introduced based on the general behaviors of the simulated joints.

El-Salakawy, et, al., (2018) four full-scale specimens were constructed and tested under reversal cyclic loading to study the seismic behavior of exterior glass fiber-reinforced polymer (GFRP)-reinforced concrete (RC) beam-column joints with lateral beams. The test variables were joint shear stress (0.85, 1.0, and 1.1 times the square root of the concrete compressive strength) and type of reinforcement (steel or GFRP). Test results indicated that well-designed exterior GFRP-RC beam-column joints confined with lateral beams exhibit linear behavior with minimum residual damage up to 5% drift ratio. Specialized software was used to construct a finite elements model, capable of simulating hysteresis behavior of reinforced concrete beam-column joints under seismic loading by taking into account the nonlinear behavior of concrete, confinement provided by the internal reinforcement, and the effect of cracks and bond-slip relationship between reinforcing bars and surrounding concrete. The model was used to investigate the effect of joint shear stress, size of lateral beams, reinforcement material, column axial load, and geometrical configuration on the joints' behavior.

Balamuralikrishnan R. et, al., (2019) conducted a Finite Element Analysis (FEA) study on exterior beam-column joints reinforced with GFRP reinforcements, aiming to assess their behavior numerically using ABAQUS software under various material properties, loading conditions, and

support conditions. The analysis and design of these joints were carried out using a strut and tie model.

Their study involved predicting the behavior of GFRP-reinforced beam-column joints using ABAQUS and validating these predictions with experimental results. They concluded that the developed strut and tie model accurately predicts joint shear strength for different variations in beam longitudinal reinforcement ratio, joint aspect ratio, and stirrup ratio.

Additionally, their findings suggested that the performance of GFRP-reinforced specimens is inferior to those reinforced with conventional steel. However, they noted that hybrid reinforcements combining GFRP and steel could yield similar results to steel reinforcement due to the high elastic modulus of the hybrid reinforcements. This highlights the potential of hybrid reinforcement systems in achieving comparable performance to traditional steel reinforcements in structural applications.

Shervin K., et, al., (2019) conducted an investigation on the seismic behavior of exterior glass fiber-reinforced polymer (GFRP)-reinforced concrete (RC) beam-column connections, utilizing four full-scale specimens tested under reversal cyclic loading. The study examined the performance of these joints with lateral beams, focusing on varying joint shear stress levels (0.85, 1.0, and 1.1 times the square root of the concrete compressive strength) and types of reinforcement (steel or GFRP).

Their test results demonstrated that well-designed exterior GFRP-RC beam-column joints, confined with lateral beams, exhibit linear behavior with minimal residual damage up to a 5% drift ratio. Additionally, they employed specialized software to construct a finite element model capable of simulating the hysteresis behavior of reinforced concrete beam-column joints under seismic loading. This model accounted for the nonlinear behavior of concrete, confinement provided by internal reinforcement, and the effects of cracks and bond-slip relationships between reinforcing bars and surrounding concrete.

Using this model, they investigated the influence of various factors such as joint shear stress, size of lateral beams, reinforcement material, column axial load, and geometrical configuration on the behavior of the joints. This comprehensive approach allowed for a deeper understanding of the

seismic performance of exterior GFRP-RC beam-column connections and provided valuable insights for optimizing their design and behavior under seismic loading conditions.

M. A. Rashid., et al., (2005) Conducted flexural test outcomes of ten high-strength concrete beams reinforced with aramid fiber-reinforced polymer (AFRP) bars, along with a steel-reinforced control beam, are presented and analyzed. All specimens were subjected to third-point loading during testing. The results indicate that AFRP-reinforced concrete beams exhibit greater flexibility in the post-cracking stage compared to comparable steel-reinforced beams. They also develop wider cracks that are mainly vertical, including within the shear span, and may experience an atypical flexure-shear failure mode. Key challenges related to the flexural design of AFRP-reinforced beams are examined in relation to existing code provisions, and appropriate practical design recommendations are proposed. In addition, a method for meaningfully quantifying ductility in FRP-reinforced beams is introduced. The study further highlights the necessity of reducing the maximum stirrup spacing specified in current codes for members subjected to high shear combined with significant bending moments, and corresponding recommendations are provided.

Hui Yang., et al., (2015) examined the behavior of aramid fiber-reinforced polymer (AFRP) confined concrete under high strain-rate compression. A total of 71 specimens were tested under both quasi-static and dynamic axial loading conditions, using a hydraulically driven testing machine and a 100-mm-diameter Split Hopkinson Pressure Bar (SHPB) apparatus, respectively. The study considered strain rates between 80 and 170 s⁻¹ to evaluate the effect of loading rate. In addition, the level of lateral confinement was varied by changing the number of AFRP layers and applying different strain rates.

The findings show that dynamic compressive strength, ultimate strain, and energy absorption capacity are all significantly influenced by strain rate. It was also observed that external AFRP confinement markedly enhances these mechanical properties. Furthermore, the study discusses the mechanisms responsible for the strengthening and toughening effects provided by AFRP jackets.

R. Mohanraj., et al., (2024) examines the structural behavior and failure mechanisms of beam-column joints strengthened with aramid fiber-reinforced polymer (AFRP) in order to improve the

durability and seismic performance of concrete structures. The materials were carefully selected and proportioned, including Ordinary Portland Cement Grade 53, fine and coarse aggregates complying with IS: 383–1970, and water conforming to IS: 456–2000. Experimental verification confirmed the suitability of the cement for achieving reliable beam–column joint performance, while fiber-reinforced polymers were noted for their high tensile strength (3800–4200 MPa) and lightweight characteristics that contribute to structural enhancement.

The failure observations showed that specimens without AFRP confinement primarily failed due to concrete crushing. In contrast, AFRP-wrapped specimens failed mainly through rupture of the composite material, indicating critical stress concentration regions within the joints. The findings highlight the importance of stress distribution in governing failure behavior and emphasize the need for effective reinforcement detailing to improve structural resilience. Overall, the study contributes to the development of improved retrofitting approaches and strengthening techniques aimed at increasing the service life and seismic resistance of concrete structures.

Table 2.1 Summary of Previous Studies on FRP and Hybrid RC Beam–Column Joints

Author	Material / System	Loading Type	Key Findings	Research Gap
Pang et al. (2015)	Hybrid FRP-RC beams	Monotonic / Analytical	Ductility influenced by reinforcement stiffness, concrete strength, and FRP type	Limited focus on joint-level seismic behavior
Mady et al. (2011)	GFRP RC beam–column joints	Cyclic loading	GFRP joints reached up to 4% drift without major damage	Lack of hybrid steel–FRP comparison
Mahmoud et al. (2022)	GFRP + steel fiber concrete joints	Cyclic loading	Strength and deformability improved with fibers and GFRP	Limited study on AFRP systems
Javan et al. (2022)	Hybrid GFRP–steel joints	Cyclic + axial loading	Up to 50% FRP replacement improved ductility and energy absorption	AFRP–steel systems not studied
Bing Li et al. (2009)	CFRP/GFRP strengthening	Cyclic loading	FRP wrapping improved stiffness	Strengthening only, not

			and energy dissipation	internal reinforcement
Nehdi et al. (2016)	Steel, GFRP, hybrid joints	Cyclic loading	GFRP joints showed low energy dissipation; hybrid improved performance	AFRP behavior not investigated
Grira & Saatcioglu	Steel/CFRP grids	Cyclic loading	CFRP grids comparable to steel stirrups	Limited application to beam-column joints
Mohamed (2017)	Steel-GFRP RC frames	Analytical / FEM	Steel-FRP ratio governs seismic performance	Lack of AFRP- based studies
Zhang et al. (2016)	RC frame joints model	Numerical simulation	Joint failure reduces ductility and energy dissipation	Limited material-level comparison
Zhao et al. (2018)	Macro joint model	Cyclic simulation	Accurate hysteresis prediction of joints	No focus on FRP hybrid reinforcement
Costas et al. (2002)	FRP- strengthened joints	Analytical	FRP increases shear capacity significantly	External strengthening only
Mohamed H. et al. (2024)	GFRP-RC MRFs	Review	GFRP shows low damage but low ductility	Hybrid AFRP systems not addressed
Jianchun Li et al. (2002)	Hybrid FRP reinforcement	Experimental	Hybrid FRP improves stiffness and crack control	Limited seismic cyclic data
Nehdi et al. (2010)	SMA-FRP hybrid joints	Cyclic loading	Good energy dissipation under earthquake loads	AFRP-specific behavior missing
Sinaei et al. (2011)	CFRP retrofitted joints	FEM + Cyclic	CFRP improves ductility and strength	Focus on retrofitting only
El-Salakawy et al. (2018)	GFRP beam- column joints	Cyclic loading	Linear behavior up to 5% drift	Lack of energy dissipation capacity
Balamuralikrishnan et al. (2019)	GFRP joints (ABAQUS)	Numerical + cyclic	Hybrid reinforcement improves performance vs GFRP alone	AFRP not considered
Shervin et al. (2019)	GFRP joints	Cyclic loading	Minimal damage up to 5% drift	Low ductility limitation

Rashid et al. (2005)	AFRP beams	Flexural testing	AFRP shows high flexibility but brittle failure	Joint behavior not studied
Hui Yang et al. (2015)	AFRP confined concrete	Dynamic loading	AFRP increases energy absorption significantly	No beam–column joint application
Mohanraj et al. (2024)	AFRP strengthened joints	Experimental	AFRP improves durability and reduces crushing failure	No hybrid AFRP–steel comparison

2.8 Gaps learnt from literature

The reviewed literature indicates that extensive research has been conducted on FRP-reinforced and FRP-strengthened reinforced concrete beam–column joints under monotonic, cyclic, and analytical loading conditions. Previous studies have demonstrated that FRP materials improve durability and strength, while hybrid steel–GFRP systems enhance ductility and energy dissipation capacity compared to FRP-only reinforcement. However, most existing research has focused primarily on GFRP and CFRP systems or external FRP strengthening techniques, with limited attention given to AFRP reinforcement in beam–column joints. In addition, comparative studies between hybrid AFRP–steel and GFRP–steel reinforcement systems under cyclic loading are still scarce. Furthermore, detailed finite element investigations using ABAQUS to evaluate stiffness degradation, energy dissipation, and failure mechanisms of hybrid FRP–steel beam–column joints remain limited. Therefore, there is a clear need for a comprehensive numerical study to evaluate and compare the seismic performance of hybrid AFRP–steel and GFRP–steel reinforced beam–column joints.

CHAPTER THREE

3 METHODOLOGY AND MATERIALS PROPERTY

3.1 General

This chapter outlines the methodologies and procedures employed to collect data and address the research problem. It covers the research design, study population, sample size and selection, sampling techniques, data collection methods, and measures taken to ensure data quality, including validity and reliability. Additionally, the chapter details the data collection process, data analysis techniques, and ethical considerations observed throughout the study.

3.2 Research Methodology

This study employs finite element analysis (FEA) using ABAQUS software to simulate the structural response of FRP-reinforced beam-column joints under cyclic loading. When conducting a study on the behavior of beam-column joints with FRP bars under cyclic loads using finite element analysis (FEA), the research process typically begins with a comprehensive literature review. Here are the subsequent steps involved in this research method:

- **Literature Review:** Conduct an extensive literature review to gather information on previous studies, research papers, and relevant publications related to the behavior of beam-column joints with FRP bars under cyclic loads. This step helps establish a solid foundation of existing knowledge, identifies research gaps, and informs the selection of appropriate FEA methods and models.
- **Problem Formulation:** Based on the literature review, clearly define the research problem, objectives, and specific research questions to be addressed. This step ensures that the study is focused and aligned with the gaps and needs identified in the literature review.
- **Model Selection:** Determine the type of FEA model to be used for the study. This includes selecting the appropriate software platform and considering factors such as the complexity of the joint, desired accuracy, computational resources, and available expertise. Commonly used FEA software packages for structural analysis include ABAQUS

- **Model Development:** Develop a detailed FEA model of the beam-column joint with FRP bars under cyclic loads based on the selected software platform. A 2100 mm-height column and a 1400 mm-length beam are the components of the T-shape joints. Cross section dimensions of both columns and beams are considered 250×250 mm. In terms of reinforcement, $8\Phi 18$ and $8 \Phi 14$ are incorporated as the longitudinal reinforcement of columns and beams, respectively. $\Phi 10 @ 60$ mm are also considered as transverse reinforcement of both beams and columns. It shall note that transverse reinforcement of columns is continuing in the joint core so that three stirrups are placed in the joint core of each specimen. The reinforcement of beams is the main variable of the present study. In other words, the specimens are the same in terms of geometry, materials and loading conditions while their G/S or A/S ratio is different. Reinforcement of the first specimen, RJ (Reference Joint), is all steel bars. The steel bars of the other four specimens, however, are replacing by GFRP or AFRP bars by 25 % (two bars), 50 % (four bars), 75 % (six bars) and 100 % (eight bars) for specimens GJ-25 or AJ-25, GJ-50 or AJ-50, GJ-75 or AJ-75, and GJ-100 or AJ-100, respectively. It is noteworthy that the number of GFRP or AFRP bars in top and bottom reinforcement layers of beam are equal (e. g., in GJ-25, one bar from the top and one bar from the bottom layer were replaced with GFRP bars)
- **Material Modeling:** Implement appropriate material models within the FEA software to accurately represent the behavior of FRP bars and concrete under cyclic loading. This may involve selecting constitutive models and assigning material properties based on the literature review findings. Calibration of material models can be performed using experimental data if available.
- **Loading Conditions:** Define the cyclic loading conditions to be applied to the FEA model. This includes selecting suitable load histories, such as earthquake ground motion records or wind-induced vibrations, and applying them as displacements or forces. Consideration should be given to the amplitude, frequency content, and duration of the cyclic loading to adequately capture the dynamic response of the joint.
- **Analysis and Results:** Perform the FEA analysis by applying the defined loading conditions to the model. Conduct iterative analyses to simulate the cyclic loading and observe the response of the beam-column joint. Monitor and record key parameters of interest such as displacements, strains, stresses, and bond behavior between FRP bars and

concrete. Ensure that an adequate number of loading cycles are simulated to capture the cyclic behavior and potential degradation.

- **Results Interpretation and Validation:** Interpret the FEA results by analyzing stress contour plots, displacement-time histories, strain distributions, and other relevant output data. Compare the obtained results with available experimental data or theoretical models from the literature to validate the FEA model. Assess the accuracy and reliability of the FEA predictions and identify any discrepancies or limitations.
- **Discussion and Conclusions:** Based on the FEA results discuss and analyze the behavior of the beam-column joint with FRP bars under cyclic loads. Address the research objectives and research questions formulated in the problem formulation stage. Draw conclusions about the observed behavior, failure modes, energy dissipation, and other relevant findings. Highlight any recommendations or areas for future research.

The literature review sets the stage for the subsequent steps in the research process, providing a basis for model development, analysis, and interpretation of results. It ensures that the study is informed by existing knowledge and contributes to the advancement of understanding in the field of beam-column joints with FRP bars under cyclic loads.

The flow chart for the whole process of this research work is shown in Figure 3.1.

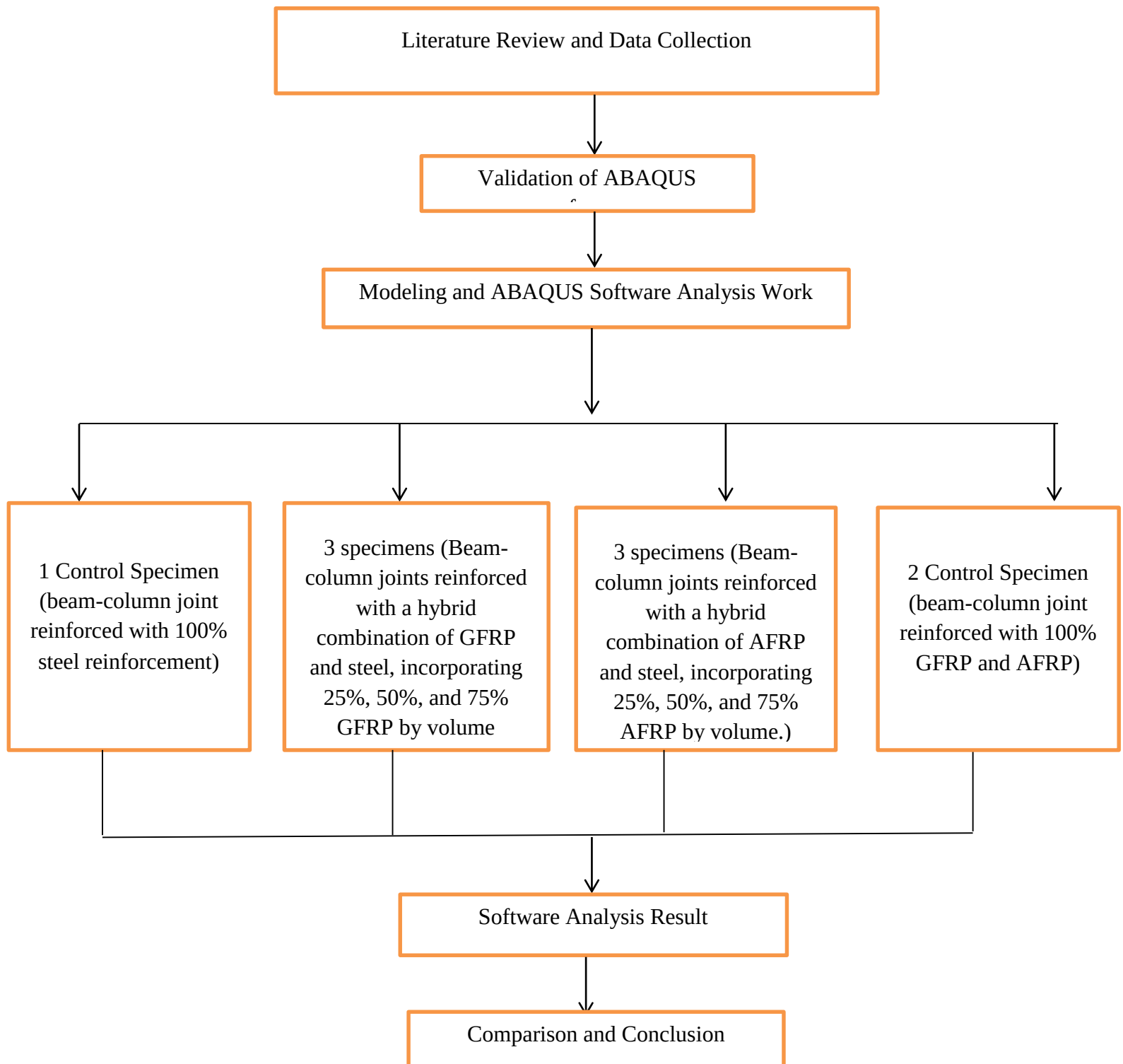


Figure 3.1 Flow chart for the whole process of this research work

3.3 Study Variables

- **Independent Variables**

An independent variable is the variable you manipulate or vary in the study to explore its effects. It's called "independent" because it's not influenced by any other variables in the study. These are:

- ✓ Types of FRP
- ✓ Percentage of FRP

- **Dependent Variables**

The dependent variables/output parameters, which were observed and determined due to the effect of independent variables, are:

- ✓ crack propagation
- ✓ load-displacement
- ✓ hysteresis curves
- ✓ ductility
- ✓ absorbed energy
- ✓ stiffness

3.4 Population and Sampling Method

In this study, the cyclic behavior of beam-column joints reinforced with hybrid steel–FRP rebar was investigated using the finite element analysis method. The analysis focused on evaluating the influence of varying hybrid reinforcement ratios (25%, 50%, and 75% GFRP and AFRP). Key parameters such as load-displacement response, ductility, stiffness degradation, energy dissipation, and crack propagation were examined to assess structural performance under cyclic loading. A total of nine (9) beam-column joint models were developed for the parametric study, incorporating appropriate material properties and boundary conditions to simulate realistic cyclic loading scenarios.

Table 3.1 Dimensions of the Beam-Column Joints and material used

Depth of column	250mm
Width of column	250mm
Length of column	2100mm
Depth of beam	250mm
Width of beam	250mm
Length of beam	1400mm
No of bars in beam	<p>8 ϕ14mm Steel bars for 0% GFRP</p> <p>6 ϕ14mm steel bars and 2 ϕ 10mm GFRP bars for 25% GFRP (GJ-25)</p> <p>4 ϕ14mm steel bars and 4 ϕ 10mm GFRP bars for 50% GFRP (GJ-50)</p> <p>2 ϕ14mm steel bars and 4 ϕ 10mm GFRP bars for 75% GFRP (GJ-75)</p> <p>0 ϕ14mm steel bars and 8 ϕ 10mm GFRP bars for 100% GFRP (GJ-100)</p> <p>6 ϕ14mm steel bars and 2 ϕ 10mm AFRP bars for 25% AFRP (AJ-25)</p> <p>4 ϕ14mm steel bars and 4ϕ 10mm AFRP bars for 25% AFRP (AJ-50)</p> <p>2 ϕ14mm steel bars and 6ϕ 10mm AFRP bars for 25% AFRP (AJ-75)</p> <p>0 ϕ14mm steel bars and 8ϕ 10mm AFRP bars for 25% AFRP (AJ-100)</p>
No of bars in Column	8 ϕ 14mm steel bars
Column transverse reinforcement	Φ 10@60 mm
Beam transverse reinforcement	Φ 10@60 mm

Arrangement of Beam longitudinal reinforcement	number of GFRP or AFRP bars in top and bottom reinforcement layers of beam are equal (e. g., in GJ-25, one bar from the top and one bar from the bottom layer were replaced with GFRP bars)
Concrete cover for column	25mm
Concrete cover for beam	25mm

Table 3.2 Naming of Assembled Beam-Column Joints Specimens

S. No	Specimens ID	Remark
1	RJ	Conventional Beam-column Joints(100% steel reinforced)
2	GJ-25%	Beam-column Joints with: ✓ Two number of GFRP and Six number of steel bars
3	GJ-50%	Beam-column Joints with: ✓ Four number of GFRP and Four number of steel bars
4	GJ-75%	Beam-column Joints with: ✓ Six number of GFRP and Two number of steel bars
5	GJ-100%	Beam-column Joints with: ✓ Eight number of GFRP and Zero number of steel bars
6	AJ-25%	Beam-column Joints with: ✓ Two number of AFRP and Six number of steel bars
7	AJ-50%	Beam-column Joints with: ✓ Four number of AFRP and Four number of steel bars
8	AJ-75%	Beam-column Joints with: ✓ Six number of AFRP and Two number of steel bars
9	AJ-100%	Beam-column Joints with: ✓ Eight number of GFRP and Zero number of steel bars

3.5 Sources of Data

The primary data (the first-hand information) was extracted from ABAQUS results and secondary data from different journals including published research papers

3.6 Data Collection Procedure

For this research, data was collected from a variety of credible sources, including peer-reviewed journal articles, ongoing studies, textbooks, and structural design codes related to beam-column joint performance and FRP reinforcement. Additional resources such as videos and case studies focusing on the cyclic behavior of RC beam-column joints were also reviewed. Particular attention was given to comparative studies involving hybrid reinforcement systems and their behavior under seismic loads. The research approach involved conducting several Finite Element Analyses to examine the performance of beam-column joints reinforced with different ratios of hybrid steel–FRP rebar.

3.7 Model Samples Used in Finite Element Analysis

In the present study, nine (9) reinforced beam-column joint models with varying configurations of hybrid steel–FRP reinforcement were developed using finite element analysis. All joints featured square cross-sections and were modeled with high-strength concrete to ensure structural integrity. The models were subjected to cyclic loading to evaluate key performance indicators, including load-deflection behavior, energy absorption capacity, ductility, stiffness degradation, and crack propagation.

Specimen's Description

In total, 9 reinforced beam-column joints were analyzed for the parametric study. The first letter in specimen RJ refers Reference joint. The second specimen GJ refers Glass joint and the Third specimen AJ refers to Aramid joints.

3.8 Finite Element Method

Finite Element Analysis (FEA) is a commonly used computational technique for numerically solving a variety of boundary value problems. In this approach, a continuous domain is divided

into a set of discrete, interconnected elements at specific points called nodes—a process referred to as discretization. Field variables such as displacement or temperature are represented by their values at these nodes, while values between nodes are estimated through polynomial interpolation. The nodal values are calculated by solving a system of simultaneous equations using matrix-based computational methods. The precision of FEA results depends on the quality of discretization, the form of interpolation used, and the accuracy of the numerical solution techniques. Its widespread use today stems from its versatility in handling complex geometries, diverse boundary conditions, and varied loading scenarios (Ashcroft & Mubashar, 2018).

3.9 Data Presentation and Analysis

Finite Element Analysis (FEA) of reinforced concrete beam-column joints was carried out using a nonlinear static analysis approach, accounting for both material and geometric nonlinearities. In this analysis, the total applied cyclic loads were incrementally applied, and at the end of each increment, the structure reached an approximate state of equilibrium. The stiffness matrix was updated to capture nonlinear changes in the joint's structural behavior. The general-purpose FEA software ABAQUS®CAE was employed to evaluate the impact of different hybrid reinforcement ratios, combining steel and FRP rebars, on the seismic performance of beam-column joints. A comprehensive three-dimensional finite element model was developed to simulate the nonlinear response of the joints under reversed cyclic loading, incorporating accurate geometric representations and material behaviors.

Every complete finite-element analysis consists of three separate stages:

- ❖ Pre-processing involves defining the geometry of the structure, selecting appropriate material properties, assigning boundary conditions and loads, and discretizing the model into finite elements (meshing).
- ❖ Solution refers to the process of solving the system of equations generated by the finite element model to obtain results such as displacements, stresses, or internal forces.
- ❖ Post-processing includes interpreting and visualizing the results through graphs, contour plots, or animations to evaluate the structural behavior and draw conclusions.

3.10 Finite Element Modeling of Reinforced Concrete Beam-Column Joints

Beam-Column Joints

The beam-column joint concrete of 2100 mm in length, 250 mm in width, and 250 mm in depth of column and a square beam concrete of 1400 mm extended from the face of column, 250mm in width and 250mm depth and surface were modeled using ABAQUS/Explicit using C3D8R elements. ABAQUS/Explicit is a finite element analysis product that is particularly well-suited to simulate brief thermal analysis.

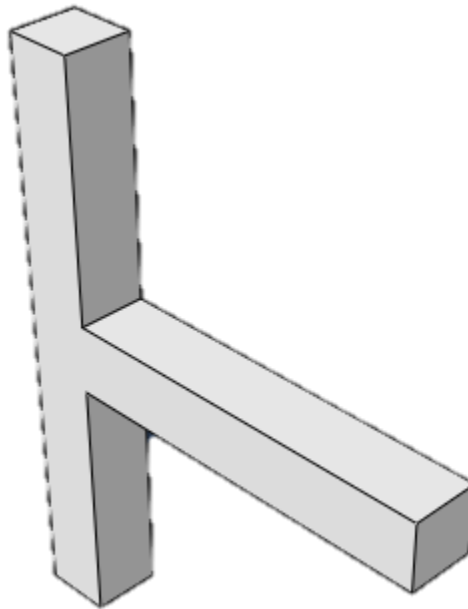


Figure 3.2 Beam-Column joint Concrete Parts

Longitudinal Reinforcement Bars (Steel)

The steel reinforcement was modeled on 3D modeling space as a deformable type with wire shape and planer base feature. 18mm diameter for the column and 14mm diameter for the beam were used for longitudinal reinforcement as shown in Figure 3.3. The steel mechanical properties included modulus of elasticity, Poisson's ratio, and yield stress in tension and compression.

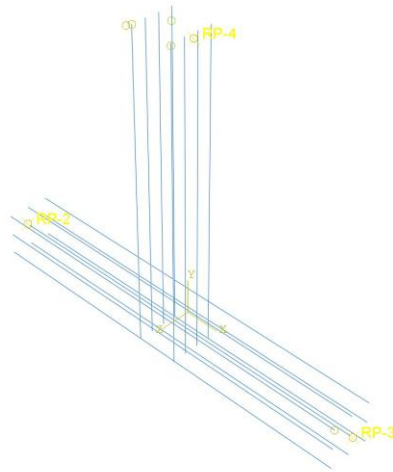


Figure 3.3 Longitudinal steel Reinforcement Bar for Beam-Column joint

Transverse Reinforcement Bars

The steel reinforcement was modeled on 3D modeling space as a deformable type with wire shape and planer base feature. 10mm diameter for the column and the beam were used for transverse reinforcement as shown in Figure 3.3. The steel mechanical properties included modulus of elasticity, Poisson's ratio, and yield stress in tension and compression.

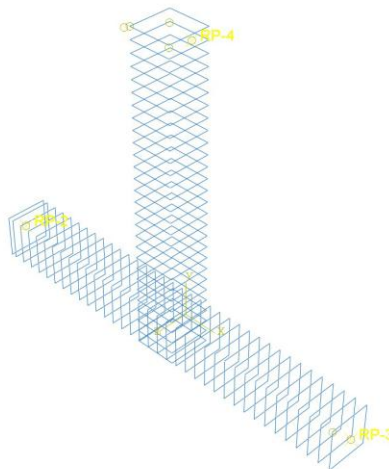


Figure 3.4 Transverse Reinforcement Bar (Stirrup) for beam-column

Longitudinal Reinforcement Bars (GFRP and AFRP)

The GFRP and AFRP reinforcement was modeled on 3D modeling space as a deformable type with wire shape and planer base feature. 10mm diameters for the beam were used for longitudinal reinforcement as shown in Figure 3.3. The characteristics of FRP bars varied in the transverse direction because of their fibrous nature, and it would be more appropriate to simulate them as anisotropic materials. However, for the sake of computational simplicity, an isotropic material assumption is used. The model's accuracy in the current case is unaffected by this supposition as the beam-column joints investigated in the present study are designed not to fail in shear; the contribution of the FRP reinforcement's shear dowel action is presumed to be minimal. Consequently, the shear failure of the FRP bars is not included in this work. The longitudinal beam reinforcement mostly contributes by transmitting axial tensile force, and hence, FRP bars contribute in the fiber direction. The modulus of elasticity and ultimate strength are the mechanical properties necessary to define the FRP material within the FE model. (Violetta K. Kytiou, *et, al.*, 2022)

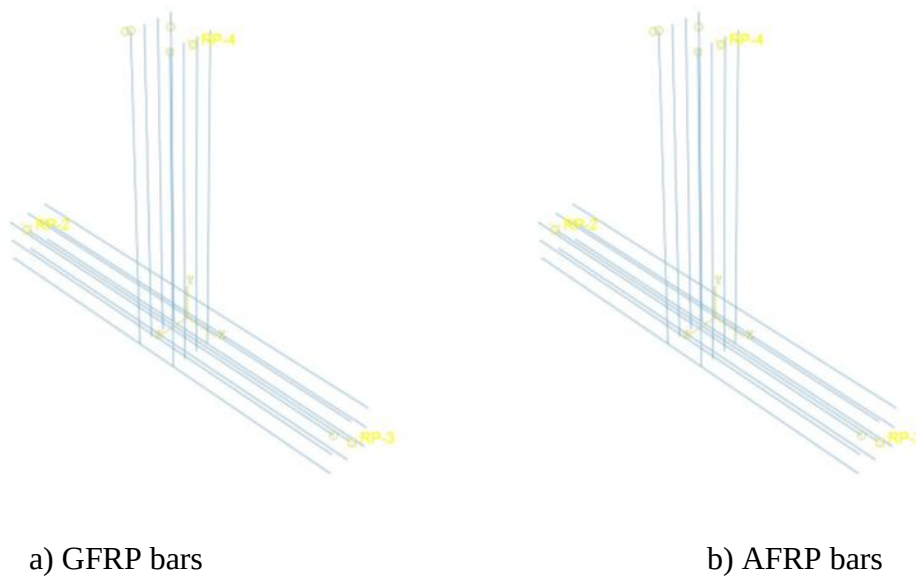


Figure 3.5 Longitudinal GFRP and AFRP Reinforcement Bar for Beam-Column joint

3.11 FEA Geometry Element Types

The beam–column joints studied in this research consist of three key components: the concrete section, longitudinal reinforcement, and transverse reinforcement. In finite element analysis, the model is discretized into smaller parts called finite elements, which are connected at nodes. The accuracy of the numerical simulation depends significantly on the appropriate selection of element types. In this study, 3D solid elements (C3D8R) were used to model the concrete due to their suitability for capturing nonlinear material behavior, cracking, and crushing under cyclic loading. The reinforcing steel and FRP bars (AFRP and GFRP) were modeled using two-node truss elements (T3D2), which are appropriate for representing axial behavior of reinforcement embedded within concrete. The interaction between reinforcement and concrete was defined using the embedded region constraint to ensure perfect bond behavior. The ABAQUS/CAE software provides a wide range of element types, which can generally be classified into 2D line elements, 2D planar elements, 3D solid elements (used for geometry definition), and special elements used for boundary conditions and interactions such as spring, gap, and rigid elements. Although different finite element packages provide similar element formulations, their implementation and numerical integration schemes may vary slightly.

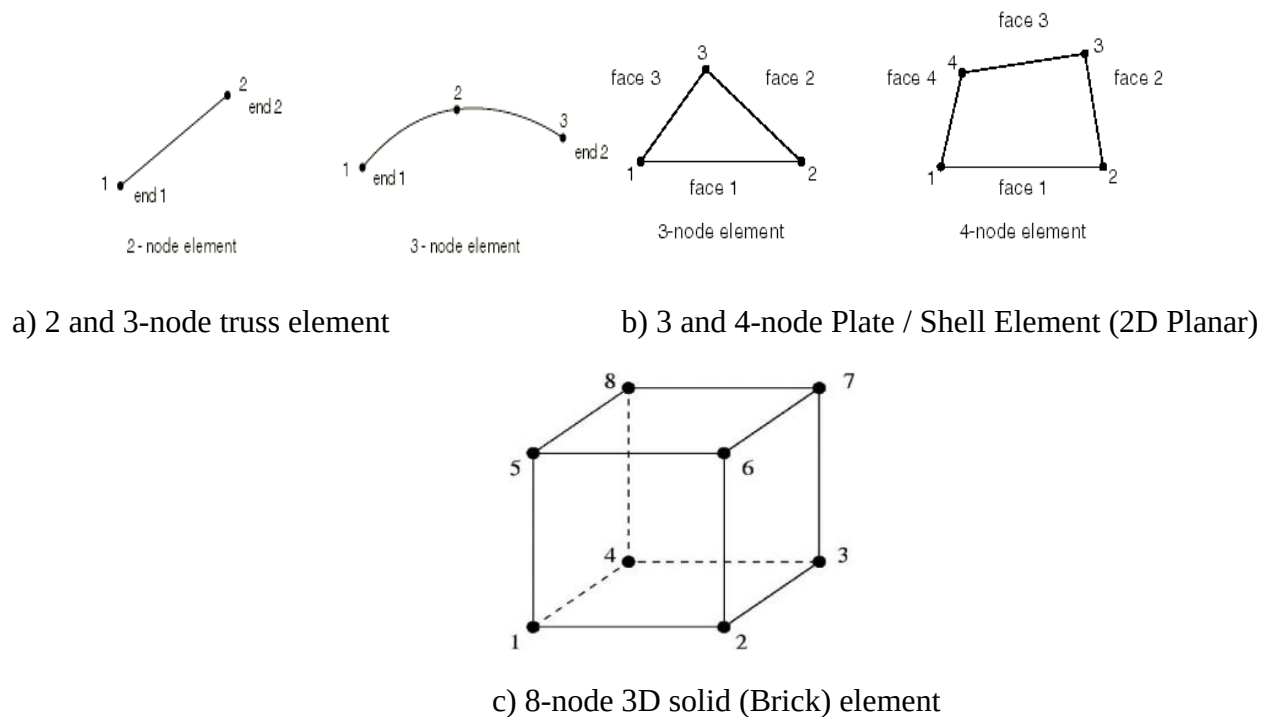


Figure 3.6 Various Elements Used in ABAQUS© (ABAQUS, 2014)

3.12 Meshing

In Finite Element Analysis, the objective is to numerically simulate real-world physical phenomena using the Finite Element Method. To achieve this, mathematical equations are necessary to quantify these phenomena. Partial Differential Equations (PDEs) can be used to solve most physical problems, but this approach is often impractical for real-world applications due to the infinite degrees of freedom of continuous objects. To overcome this limitation, the Finite Element Method discretizes the problem domain into smaller elements, allowing for approximate solutions to be calculated and interpolated across the entire domain. A crucial step in Finite Element Analysis is creating a mesh that accurately captures the physical phenomena being simulated. The mesh elements must carefully consider various factors to effectively discretize stress gradients. Generally, smaller mesh sizes result in more accurate solutions, as they provide a better sampling of the physical domain. However, this increased accuracy comes at the cost of longer simulation times. To strike a balance between accuracy and computational efficiency, engineers often conduct convergence studies to determine the optimal mesh density for their specific problem.

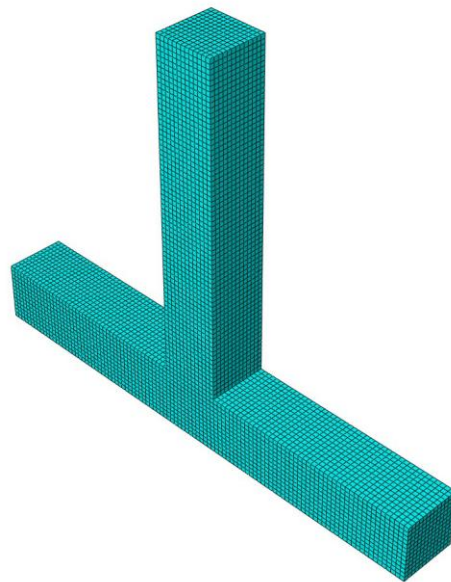


Figure 3.7 Meshed Beam Column Joints

3.12.1 Mesh Convergence Analysis

To ensure the accuracy and reliability of the finite element model, a mesh convergence study was performed before conducting the final numerical simulations. Three different mesh densities, namely coarse, medium, and fine meshes, were considered for the reinforced concrete beam–column joint model. The ultimate load capacity was selected as the convergence criterion because it is one of the primary parameters used to evaluate the structural performance of the joint under cyclic loading.

The mesh size was gradually refined, and the corresponding ultimate loads were compared. It was observed that the variation in ultimate load decreased with mesh refinement, indicating convergence of the numerical solution. The coarse mesh required less computational time but produced less accurate results, whereas the fine mesh provided only a marginal improvement in accuracy at the expense of significantly increased computational cost. Therefore, the medium mesh was selected for the final analysis as it provided a satisfactory balance between computational efficiency and prediction accuracy. The convergence criterion was considered satisfied when the difference in ultimate load between successive mesh refinements became negligible, demonstrating that the selected mesh density was sufficient to accurately capture the structural response of the beam–column joint.

3.13 Interactions and Kinematic Constraints between Components

To accurately model the behavior of interconnected bodies, it is necessary to define interactions that allow for simultaneous deformation under equal and opposite loading conditions. In this study, two types of interactions were employed: embedded constraints and coupling constraints.

a) Embedded Region Constraint Type

The embedded region constraint is a technique used to define a specific relationship between elements, where one or more elements are embedded within a host element. This method is particularly useful for modeling rebar reinforcement in concrete structures. In this study, the embedded element option in ABAQUS/Standard was utilized to define the elements representing both the rebar and concrete in the reinforced concrete beam-column joints, as illustrated in Figure

3.9. This allowed for the creation of a constraint between the concrete and rebar, enabling the simulation of their interaction.

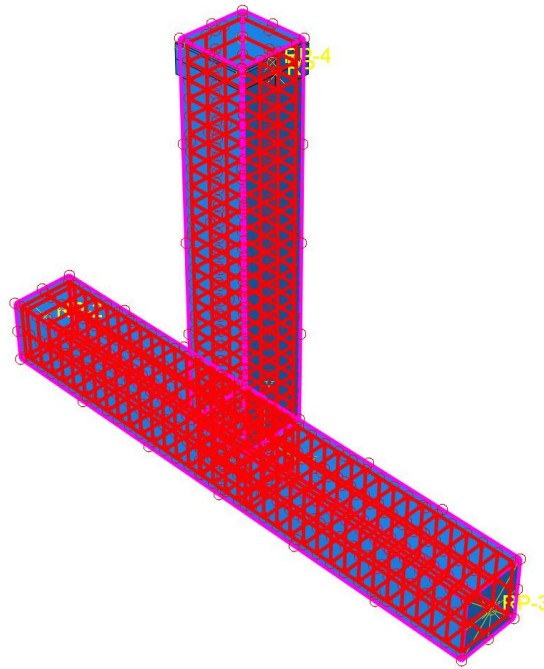


Figure 3.8 Embedded Region Constraint for Beam column joints with Reinforcement bar

b) Coupling Constraint Type

ABAQUS's coupling constraint allows for the creation of a connection between a reference node and a set of nodes, known as coupling nodes. This feature offers similar functionality to kinematic coupling constraints and distributing coupling elements in ABAQUS/Standard, but with a more user-friendly surface-based interface.

To define a coupling constraint, the reference node, coupling nodes, and constraint type must be specified. This constraint links the reference node to the coupling nodes, enabling the coordination of their motion. A name must be assigned to the constraint, which can be used in post-processing with ABAQUS/CAE. The reference node can be defined by a node number or node set name, and must contain exactly one node. The coupling constraint is particularly useful in various applications, including:

- Applying loads or boundary conditions to a model

- Distributing loads across a model
- Modeling end conditions

In essence, the coupling constraint provides a powerful tool for simulating complex interactions between different model parts.

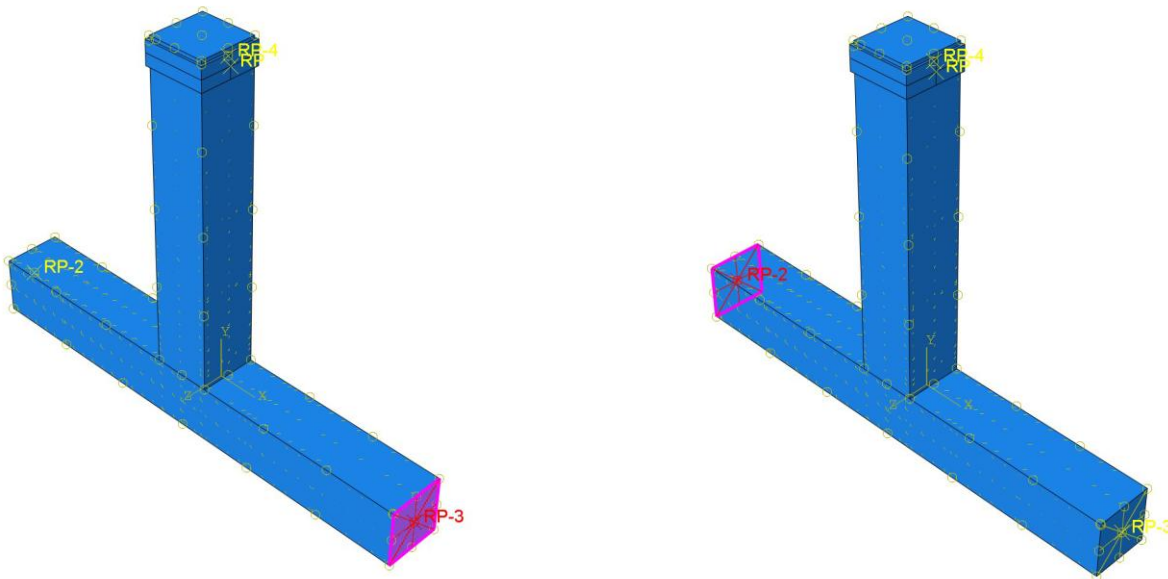


Figure 3.9 Coupling Constraints of Column on top and bottom

3.14 Boundary Conditions and Loading

In finite element analysis, boundary conditions and loading are critical for accurately simulating the structural response under applied actions. Boundary conditions define the constraints imposed on the model, while the loading conditions represent the external forces acting on the structure. In ABAQUS, boundary conditions can be prescribed as fixed or variable displacements and rotations, and loads may be applied as concentrated forces or prescribed displacements. In the present study, the adopted boundary conditions were selected to replicate the experimental setups commonly used for reinforced concrete beam–column joint testing under seismic loading (Javan *et al.*, 2022). The top and bottom ends of the column were restrained using fixed supports to represent the boundary restraints of a beam–column subassembly, while a reversed seismic load was applied at the free end of the beam to simulate earthquake-induced lateral actions. This loading arrangement enables the development of realistic joint shear stresses, flexural actions, and hysteretic behavior,

and has been widely adopted in previous experimental and numerical studies for evaluating the seismic performance of reinforced concrete beam–column joints. Therefore, the selected boundary conditions provide a realistic representation of the structural behavior and facilitate direct comparison between the finite element results and available experimental observations.

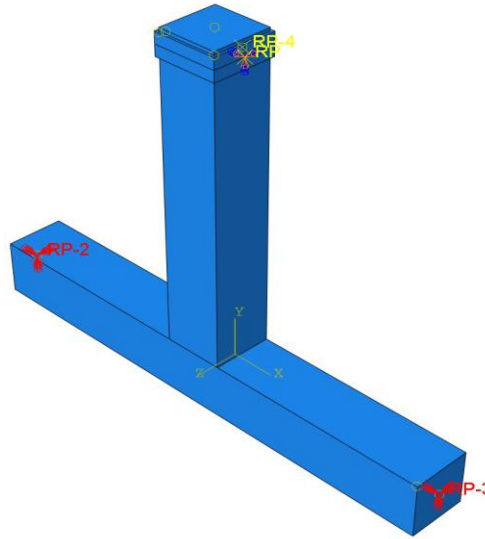


Figure 3.10 Boundary Conditions and Loading

3.15 Material Modeling

In finite element analysis, defining materials is a crucial step that involves selecting and characterizing material behaviors. ABAQUS provides a comprehensive material library that covers a wide range of linear and nonlinear, isotropic and anisotropic material behaviors. The library allows for the analysis of complex composite structures by using numerical integration in elements, including across the cross-sections of shells and beams. Material behaviors can be categorized into several groups, including:

- General properties (e.g., material damping, density, thermal expansion)
- Elastic mechanical properties
- Inelastic mechanical properties
- Thermal properties
- Mass diffusion properties

In this study, the main materials used in ABAQUS are concrete, reinforcement steel, GFRP and AFRP bars. To achieve accurate predictions in the parametric study of the reinforced concrete column-beam joints, the mechanical properties of the component materials are required for the analysis. The table below provides a listing of mechanical properties of the concrete and rebar, including concrete compressive damage, concrete failure under biaxial compression, concrete tensile damage, elastic modulus, density, and plasticity.

Table 3.3 Plasticity Properties of Concrete (Li Qingfu et al., 2020).

Parameters	Dilation angle	Eccentricity	fb0/fc0	k	viscosity parameter
Value	30	0.1	1.16	0.6667	0.0005

Table 3.4 Elastic Properties of Unidirectional Glass Fiber Reinforced Polymer Composite.

Density (kg/m3)	E_{11}	E_{22}	E_{33}	V_{12}	V_{13}	V_{23}	G_{12}	G_{13}	G_{23}
1230	44870	12130	12130	0.3	0.3	0.5	3380	3380	3380

Table 3.5 Elastic Properties of Unidirectional Aramid Fiber Reinforced Polymer Composite

Density (kg/m3)	E_{11}	E_{22}	E_{33}	V_{12}	V_{13}	V_{23}	G_{12}	G_{13}	G_{23}
1440	76000	5500	5500	0.34	0.34	0.4	2300	2300	2300

Table 3.6 Mechanical properties of concrete and Reinforcement Bars used for this study.

Reinforcement bars for column		Yield stress (N/mm2)	Ultimate stress (N/mm2)	Density (Kg/m3)	Young's modulus (N/mm2)	Poisson ratio
	Rebar	400	600	7850	200000	0.3
	Stirrup	400	600	7850	200000	0.3
Reinforcement bars for beam (steel)	Rebar	400	600	7850	200000	0.3
	Stirrup for all sample of beam	400	600	7850	200000	0.3
Concrete		32.85		2400		0.15

Table 3.7 Compressive Behavior of Concrete in the CDP Model (Li Qingfu 2020)

Compressive behavior		
Yield stress	Inelastic stress	Damage parameter
25	0	0
28.69445	0.000004	0
32.306528	0.000011	0
35.788877	0.000024	0
39.07904	0.000045	0
42.099602	0.000079	0
44.760825	0.000128	0
46.966482	0.000197	0
48.623061	0.00029	0
49.65157	0.000411	0
50	0.000562	0
49.653598	0.000743	0.006928
48.640084	0.000953	0.027198
47.028019	0.00119	0.05944
44.918499	0.001449	0.10163
42.432283	0.001724	0.15134
39.695559	0.002011	0.206089
36.82741	0.002303	0.263452
33.93093	0.002596	0.321381
31.088567	0.002887	0.378229

28.361177	0.003173	0.432776
25.78968	0.003452	0.484206
23.398168	0.003723	0.532037
21.197516	0.003986	0.57605
19.188864	0.004241	0.616223
17.366625	0.004487	0.655668
15.720901	0.004725	0.685582
15	0.004838	0.7

Table 3.8 Tensile Behavior of Concrete in the CDP Model (Li Qingfu 2020)

Tensile behavior		
Yield stress	Cracking strain	Damage parameter
3.328708	0.000381	0.445216
2.358295	0.000688	0.606951
1.846717	0.000974	0.692214
1.52766	0.001252	0.74539
1.308346	0.001525	0.781942
1.147672	0.001796	0.808721
1.02453	0.002065	0.829245
0.926926	0.002333	0.845512
0.847523	0.0026	0.858746

3.16 Verification of Finite Element Modeling

The proposed finite element method was verified by comparing the finite element model solution with the experimental results of the specimens done by (Davoud J., et, al., (2022) The comparison between the outcomes of the experiment and the finite element analysis in terms of damage, was done.

3.16.1 Geometric Properties of the Specimens

The experimental investigation was conducted on reinforced concrete beam–column joint specimens reinforced with GFRP and AFRP bars in the beam section. The specimens consisted of a vertical column and a horizontal beam forming an exterior beam–column connection.

The column had a square cross-section of 250 mm × 250 mm and a total height of 2100 mm. The longitudinal reinforcement of the column consisted of 8 bars of 18 mm diameter, uniformly distributed within the cross-section. The transverse reinforcement was provided by 10 mm diameter stirrups spaced at 60 mm along the column height to ensure adequate confinement.

The beam also had a square cross-section of 250 mm × 250 mm and a total length of 1400 mm measured from the column face. In the reference specimen (RJ), the flexural reinforcement consisted of four 14 mm diameter bars placed at the top and bottom of the beam section. Similar to the column, the beam was confined using 10 mm diameter stirrups spaced at 60 mm.

To evaluate the effect of Glass Fiber Reinforced Polymer (GFRP) and of Aramid Fiber Reinforced Polymer (AFRP) reinforcement, several beam specimens were prepared with different reinforcement ratios while maintaining the same geometric dimensions. The beam specimens were designated as GJ-25, GJ-50, GJ-75, and GJ-100 depending on the percentage of GFRP reinforcement used. In these specimens, part or all of the conventional steel reinforcement was replaced with 10 mm diameter GFRP and AFRP bars arranged symmetrically at the top and bottom of the beam section.

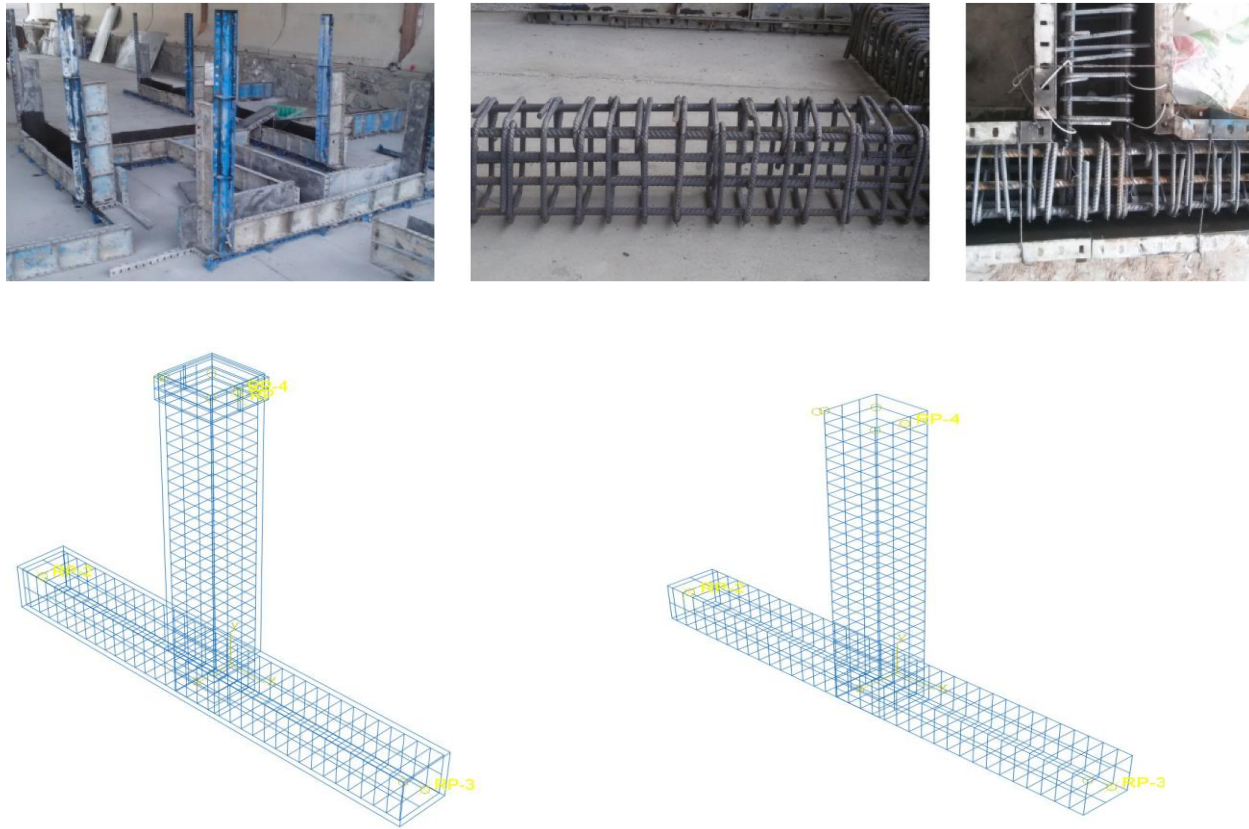


Figure 3.11 Reinforcement Detail of Specimen from the Experiment and ABAQUS

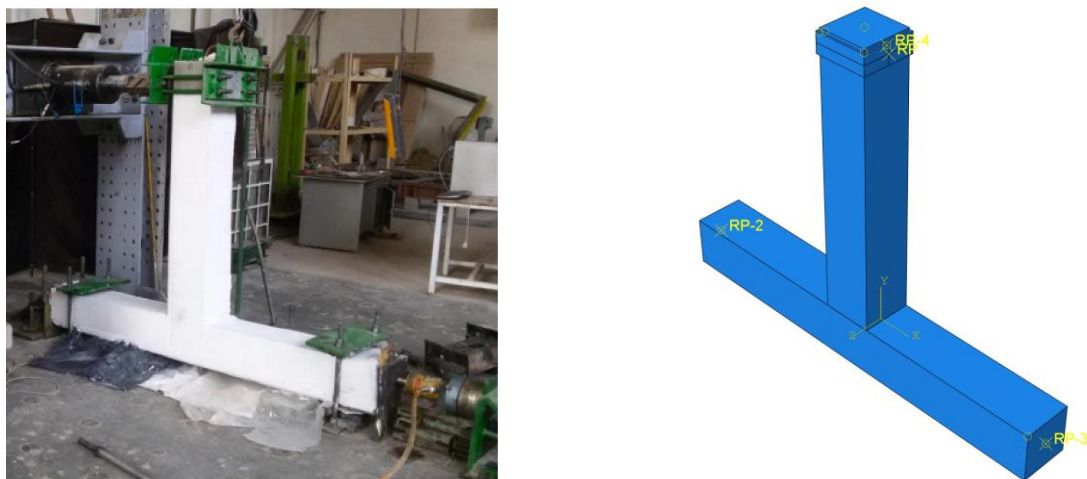


Figure 3.12 Experimental and ABAQUS Test Setup

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 General

This research investigates the behavior of reinforced concrete beam–column joints reinforced with hybrid steel and fiber reinforced polymer (FRP) rebar when subjected to repeat cyclic loading. A comprehensive finite element analysis was carried out to simulate the nonlinear response of the beam–column joint and to understand the influence of hybrid reinforcement on the structural performance of the joint region. The study focused on evaluating the crack propagation, load–displacement relationships, and hysteresis behavior of the specimens under cyclic loading. Furthermore, important seismic performance parameters, including ductility, energy absorption capacity, stiffness degradation, and equivalent damping ratio, were examined to assess the structural response during cyclic loading. The research also compared the effectiveness of different types of FRP reinforcement, particularly glass fiber reinforced polymer (GFRP) and aramid fiber reinforced polymer (AFRP), when used in combination with conventional steel reinforcement in the beam–column joint. Based on the numerical results obtained from the finite element simulations, the study provides insights and design recommendations for the application of hybrid FRP reinforcement in beam–column joints to enhance the seismic performance and durability of reinforced concrete structures.

4.2 Verification of the Finite Element Model

The verification work was conducted to demonstrate the validity and reliability of the developed finite element model used to study the behavior of beam–column joints with hybrid steel–FRP reinforcement under cyclic loading. For this purpose, a reinforced concrete beam–column joint specimen from previous experimental research was modeled using the same finite element modeling procedures described in Chapter Three. The geometry, material properties, reinforcement configuration, boundary conditions, and loading protocol were defined in the numerical model to closely replicate the experimental conditions.

The analysis was performed under cyclic loading, and the structural response of the specimen was obtained from the simulation. From the numerical results, the load–displacement relationship, hysteresis curves, and damage patterns of the specimen were recorded and analyzed. These results were then compared with the corresponding experimental results reported in the literature.

The comparison between the finite element analysis results and the experimental findings, particularly in terms of load–displacement response, hysteresis behavior, and failure patterns, was used to evaluate the accuracy of the developed numerical model. A good agreement between the numerical and experimental results indicates that the finite element modeling approach adopted in this study can reliably predict the behavior of reinforced concrete beam–column joints under cyclic loading and can therefore be used for further investigation in this research.

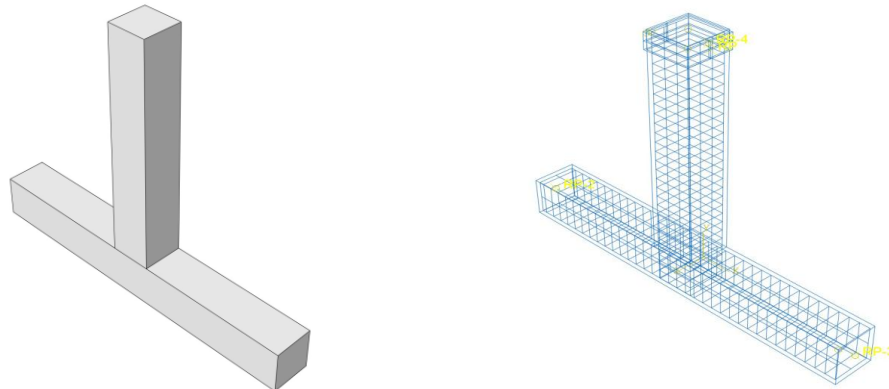


Figure 4.1 Isometric View of beam-column joints



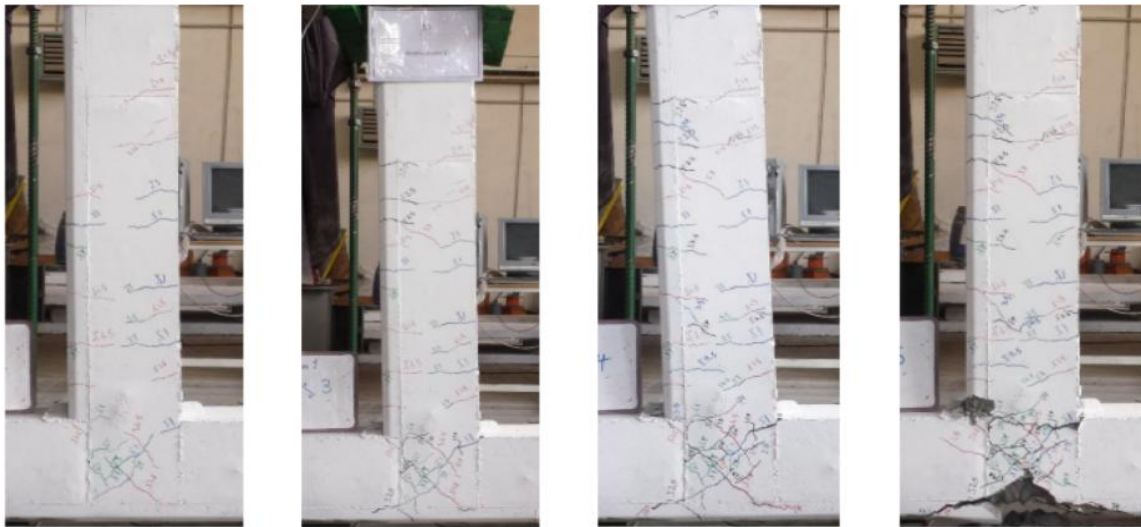
Figure 4.2 Assembled and Meshed View of beam-column joints

4.2.1 Experimental Results

Cracking initiated at the base (tension zone) and propagated upward with increasing load, leading to widened diagonal and vertical cracks and eventual crushing and spalling of concrete at the lower region. The failure mode was governed by combined compression–shear action due to high stress concentration and limited confinement. The hysteresis response shows progressive stiffness degradation, pinching effects, and energy dissipation, while the envelope curve indicates nonlinear behavior up to peak load followed by strength degradation, reflecting moderate ductility and damage accumulation.

4.2.2 Finite Element Analysis Results for Verification

For verification, finite element analysis was conducted, and the load–deflection response along with the failure mode of the specimen was obtained. These analytical results were then compared with the corresponding experimental findings to evaluate the accuracy and reliability of the numerical model.



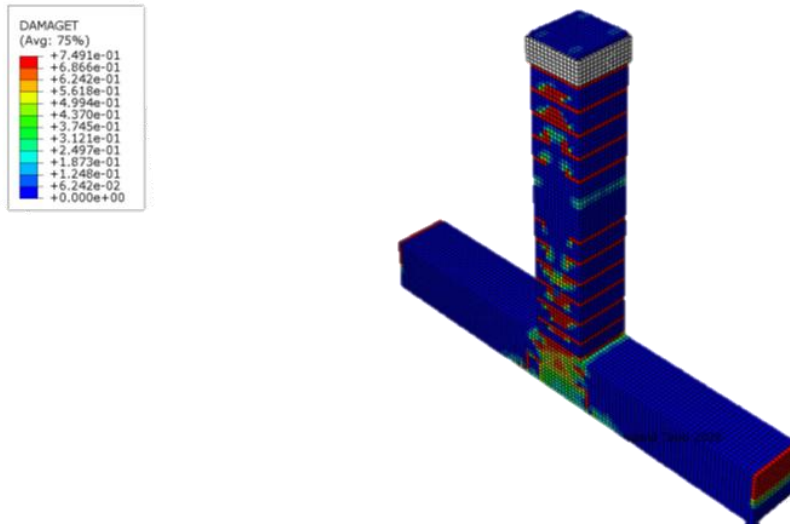


Figure 4.3 Experimental and ABAQUS Crack Pattern on Beam-Column Tension Side

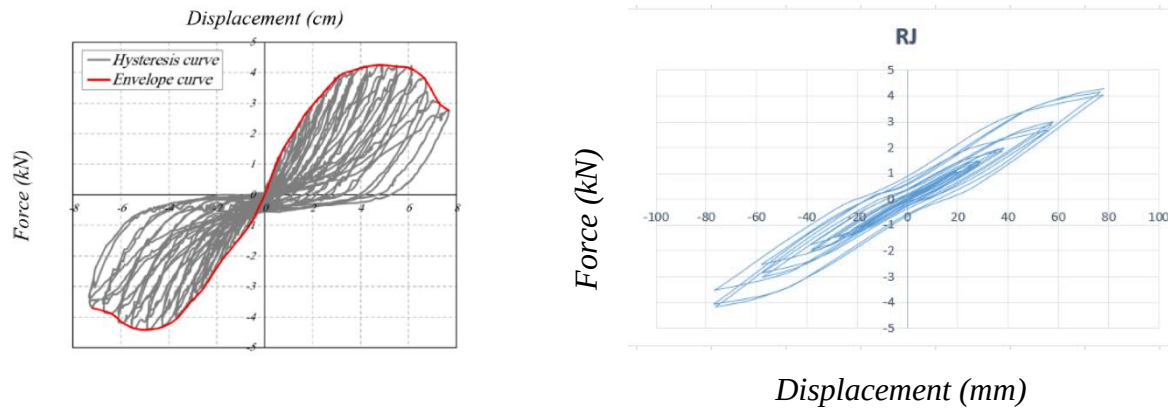


Figure 4.4 Experimental and ABAQUS on the Hysteresis Curves

The load–deflection response and failure mode predicted by **ABAQUS** show close agreement with the experimental results. Therefore, the software can be reliably used to analyze flat slab–column connections.

Table 4.1 Validation summary

Specimen	Experimental Displacement (mm)	ABAQUS Displacement (mm)	Error (%)	Experimental Load (kN)	ABAQUS Load (kN)	Error (%)
RJ	78.0	77.77	0.29	4.30	4.27	0.70
G/S-25%	78.2	78.00	0.26	4.40	4.30	2.27
G/S-50%	80.0	78.00	2.50	4.20	4.10	2.38
G/S-75%	77.0	76.00	1.30	3.90	3.74	4.10
G/S-100%	70.0	70.00	0.00	3.30	3.27	0.91

$$R^2 = \frac{[n\sum xy - (\sum x)(\sum y)]^2}{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]} \quad \text{eq 4.1}$$

Where:

- ✓ x = experimental values,
- ✓ y = ABAQUS values,
- ✓ n= number of specimens,
- ✓ $\sum x$ = sum of experimental values,
- ✓ $\sum y$ = sum of ABAQUS values,
- ✓ $\sum xy$ = sum of the products of corresponding values,
- ✓ $\sum x^2$ = sum of squares of experimental values,
- ✓ $\sum y^2$ = sum of squares of ABAQUS values.

Table 4.2 Value for calculating R2 on loading

Specimen	Experimental Load, x (kN)	ABAQUS Load, y (kN)	xy	x ²	y ²	Error (%)
RJ	4.30	4.27	18.361	18.490	18.233	0.70
G/S-25%	4.40	4.30	18.920	19.360	18.490	2.27
G/S-50%	4.20	4.10	17.220	17.640	16.810	2.38
G/S-75%	3.90	3.74	14.586	15.210	13.988	4.10

G/S-100%	3.30	3.27	10.791	10.890	10.693	0.91
Total	20.10	19.68	79.878	81.590	78.214	10.36

Table 4.3 Value for calculating R^2 Displacement

Specimen	Experimental, x (mm)	ABAQUS, y (mm)	xy	x^2	y^2	Error (%)
RJ	78.0	77.77	6066.06	6084.00	6048.17	0.29
G/S-25%	78.2	78.00	6099.60	6115.24	6084.00	0.26
G/S-50%	80.0	78.00	6240.00	6400.00	6084.00	2.50
G/S-75%	77.0	76.00	5852.00	5929.00	5776.00	1.30
G/S-100%	70.0	70.00	4900.00	4900.00	4900.00	0.00
Total	383.20	379.77	29157.66	29428.24	28892.17	4.35

Table 4.4 Validation value

Parameter	Value
Average displacement error	0.87%
Average load error	2.07%
Displacement R^2	0.915
Load R^2	0.940

A validation study was performed by comparing the experimental and ABAQUS results for ultimate displacement and ultimate load of the tested specimens. The percentage error was calculated for each specimen to quantify the accuracy of the numerical predictions. The average percentage errors were found to be 0.87% for displacement and 2.07% for ultimate load, indicating close agreement between the experimental and numerical results. In addition, the coefficient of determination (R^2) was calculated to evaluate the correlation between the two datasets. The R^2 values were 0.915 for displacement and 0.940 for ultimate load, demonstrating a strong relationship between the experimental observations and the finite element predictions. These low percentage errors and high R^2 values confirm that the developed ABAQUS model is capable of

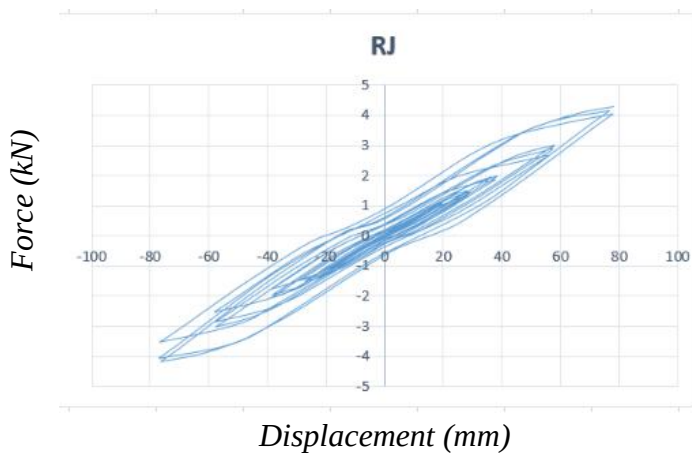
accurately predicting the behavior of the beam–column joints and can be reliably used for further analytical and parametric investigations.

4.3 Results from Analysis

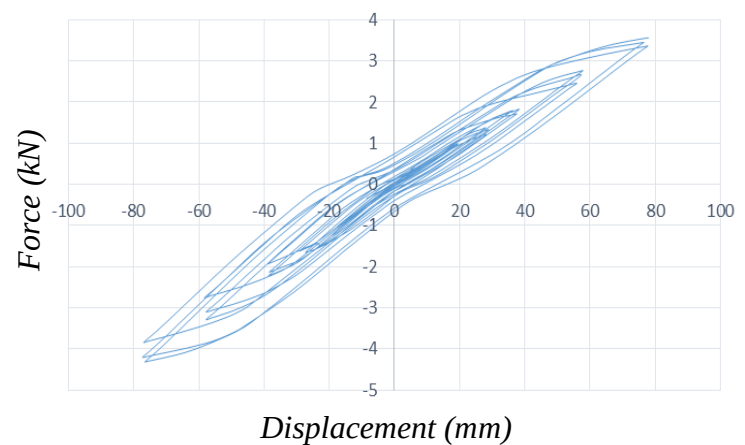
The results of this study are presented through the analysis of load–displacement hysteresis curves and crack propagation behavior. The hysteresis response illustrates cyclic performance, including stiffness degradation, strength reduction, and energy dissipation under repeated loading, while crack patterns provide insight into damage initiation and progression throughout the specimen. In addition, key seismic performance parameters such as ductility, energy absorption capacity and stiffness are evaluated to assess structural behavior, and these parameters are comparatively discussed in the following section to determine

4.3.1 Effect of FRP Type and Replacement Ratio on the Hysteresis Curves of Beam–Column Joints

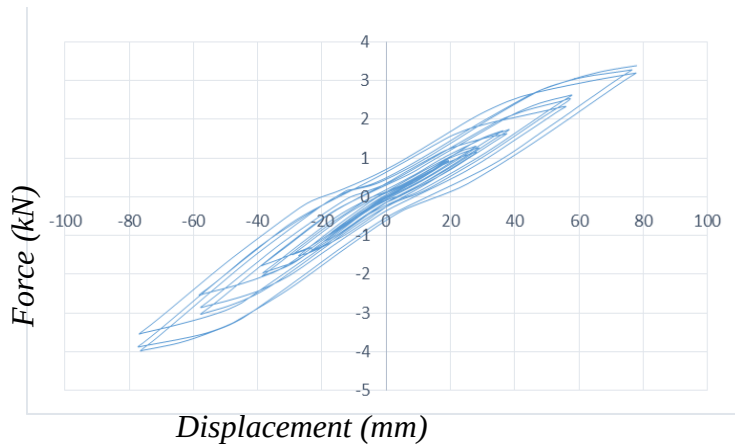
Cyclic hysteresis loops of the experimental specimens for beam column joint are presented in Fig. 4.5. The data from these hysteresis loops were utilized for investigating the cyclic characteristics, energy absorption, stiffness degradation, seismic efficiency, and load-displacement relationship of the specimens that contained varying combinations of A/S and G/S at 25%, 50%, 75%, and 100%.



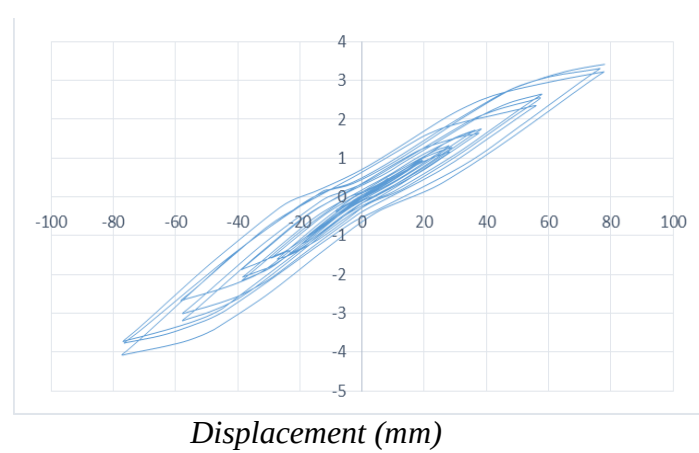
A) Hysteresis responses for RJ



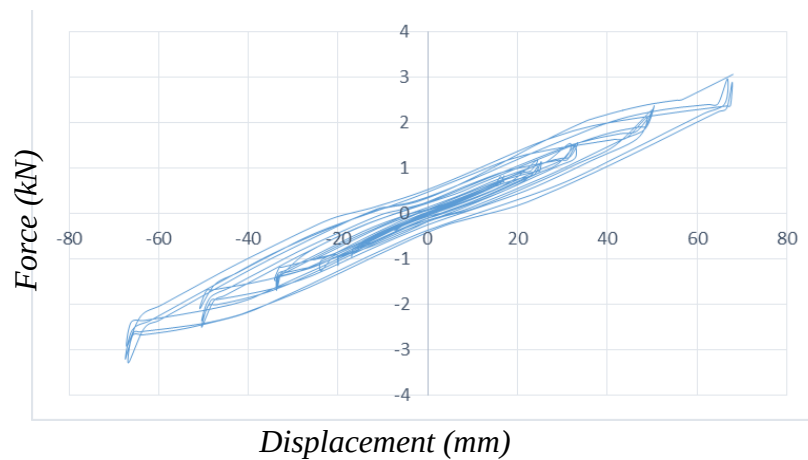
B) Hysteresis responses for GJ-25%



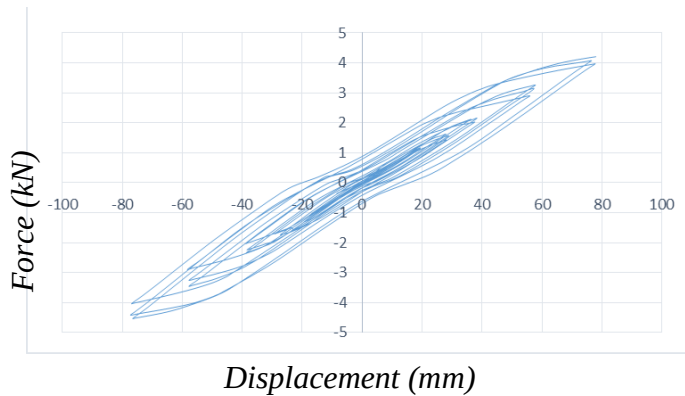
C) Hysteresis responses for GJ-50



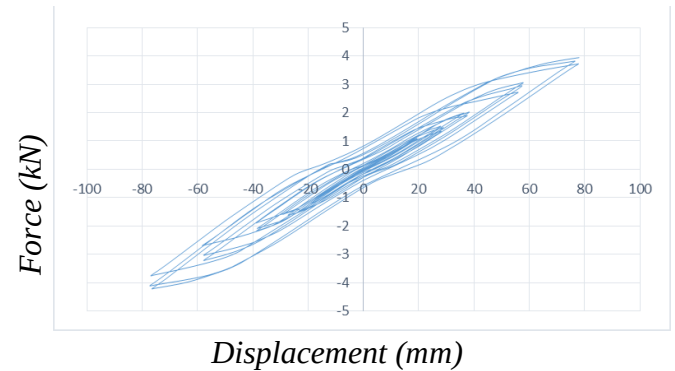
D) Hysteresis responses for GJ-75%



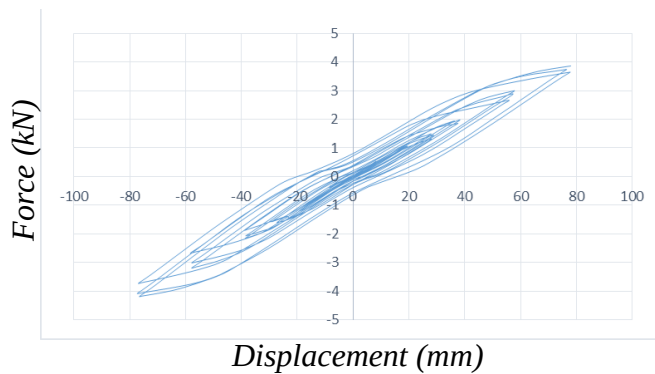
E) Hysteresis responses for GJ-100%



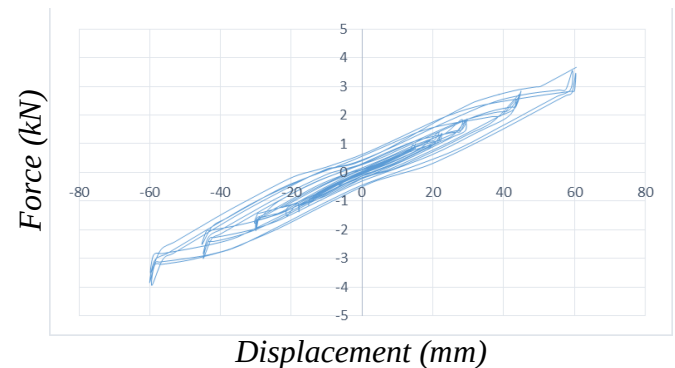
F) Hysteresis responses for AJ-25%



G) Hysteresis responses for AJ-50%



H) Hysteresis responses for AJ-75%



I) Hysteresis responses for AJ-100%

Figure 4.5 Hysteresis curves of beam-column joint specimens under cyclic loading

The hysteresis response of the beam–column joint specimens provides important information regarding their seismic performance, including strength, stiffness, ductility, energy dissipation, and damage progression under cyclic loading. Wide and stable hysteresis loops indicate good energy dissipation capacity and improved seismic resistance, whereas narrow loops and significant pinching behavior indicate stiffness degradation, bond deterioration, and reduced ability to dissipate earthquake energy.

The hysteresis curves of the G/S specimens (Figure 4.5 b–e) show that increasing the GFRP-to-steel replacement ratio generally reduced the load-carrying capacity and the area enclosed by the

hysteresis loops. The control specimen exhibited relatively stable loops with satisfactory energy dissipation, while the G/S-25% and G/S-50% specimens maintained acceptable cyclic performance. However, the G/S-75% and particularly the G/S-100% specimens developed narrower hysteresis loops accompanied by more pronounced pinching behavior, indicating reduced energy dissipation capacity and progressive stiffness degradation due to the linear-elastic behavior and lower modulus of elasticity of GFRP reinforcement.

The hysteresis curves of the A/S specimens (Figure 4.5 f–i) exhibited comparatively fuller and more stable loops throughout the loading history. The A/S-25% and A/S-50% specimens demonstrated good energy dissipation and stable cyclic behavior, while the A/S-75% and A/S-100% specimens maintained higher load-carrying capacity and less stiffness degradation than the corresponding G/S specimens. The improved performance can be attributed to the higher tensile strength and elastic modulus of AFRP reinforcement, which enhanced the overall structural response under repeated loading cycles.

Pinching behavior observed in several specimens is an important indicator of seismic performance. Pinching refers to the narrowing of the hysteresis loops during load reversals and is commonly associated with crack opening and closing, degradation of the bond between reinforcement and concrete, local concrete crushing, and stiffness deterioration. Excessive pinching reduces the area enclosed by the hysteresis loops, thereby decreasing the energy dissipation capacity of the beam–column joint and increasing its vulnerability to earthquake-induced damage. The G/S specimens exhibited more pronounced pinching than the A/S specimens, suggesting greater degradation of stiffness and bond characteristics during cyclic loading. In contrast, the A/S specimens showed relatively moderate pinching and more stable hysteretic behavior, indicating improved energy absorption and better seismic performance.

4.3.2 Effect of FRP Type and Replacement Ratio on Crack Propagation in Beam–Column Joints

The crack propagation behavior of the beam–column joints was investigated under reversed cyclic loading to evaluate the influence of FRP type and replacement ratio on structural damage. In all specimens, crack initiation occurred at the beam–column interface, where tensile stresses reached their maximum values during the early loading cycles. As the applied displacement increased,

flexural cracks developed in the beam adjacent to the column face and gradually propagated into diagonal shear cracks extending toward the joint core. This crack evolution reflects the transfer of shear and bending forces through the joint region during cyclic loading.

The finite element crack patterns shown in Figure 4.6 indicate that hybrid steel–FRP reinforcement delayed crack initiation and promoted a more uniform distribution of cracks compared with the conventional steel-reinforced specimen. The control specimen exhibited early crack formation, wider crack openings, and rapid crack propagation due to the concentration of tensile stresses near the joint region. In contrast, the hybrid specimens developed a larger number of smaller distributed cracks, indicating improved stress redistribution and enhanced crack control.

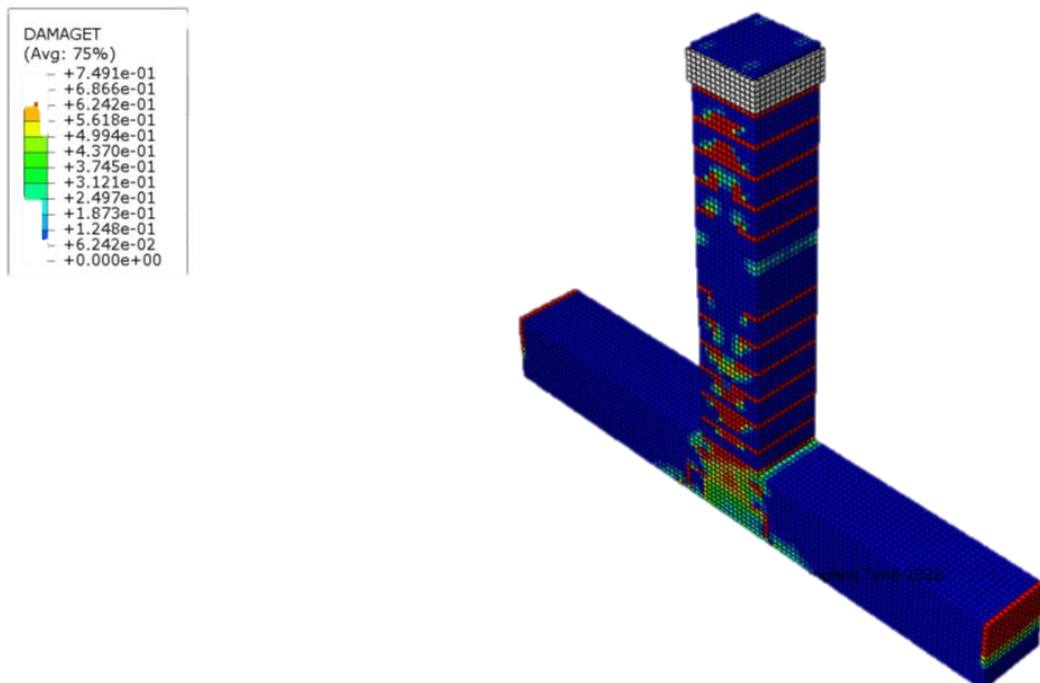
A comparison with the experimental investigation of Javan *et al.* (2022) shows good agreement between the numerical and experimental crack patterns. In the experimental specimens, initial flexural cracks formed near the beam–column interface and gradually extended into diagonal cracks within the joint core under repeated cyclic loading. The hybrid GFRP–steel specimens exhibited delayed crack development and reduced crack concentration compared with the conventional steel specimens. Similar behavior was observed in the ABAQUS simulations, where crack initiation occurred in the same critical regions and propagated along comparable stress paths. Both the numerical and experimental results indicate that the inclusion of FRP reinforcement contributes to improved crack distribution and reduced damage concentration under cyclic loading.

Among the analyzed specimens, the AFRP-reinforced joints exhibited better crack control than the corresponding GFRP-reinforced joints. The crack propagation in the AFRP specimens was slower, with smaller crack widths and less localization of damage, whereas the GFRP specimens developed relatively wider cracks at higher displacement levels. This behavior can be attributed to the superior tensile strength and mechanical properties of AFRP reinforcement, which enhance the stress transfer mechanism within the joint.

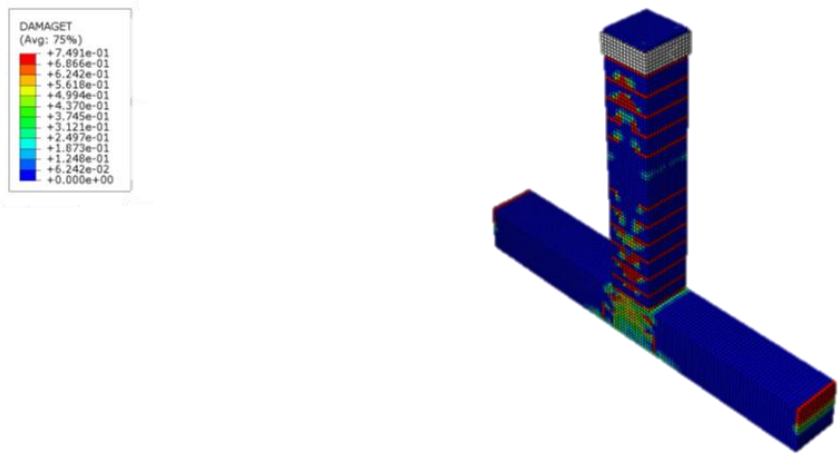
As the FRP replacement ratio increased from 25% to 100%, the crack patterns became more distributed and less concentrated around the beam–column interface. The higher reinforcement ratio improved the tensile resistance and confinement of the joint, thereby reducing stress concentrations in the surrounding concrete and slowing crack propagation. This distributed

cracking pattern is beneficial for seismic-resistant structures because it enhances energy dissipation and reduces the likelihood of sudden brittle failure.

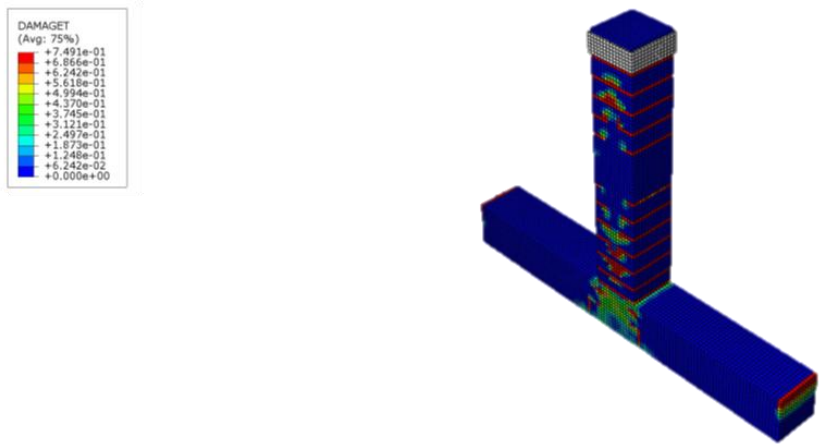
At larger displacement amplitudes, some FRP-reinforced specimens exhibited rapid crack extension near the ultimate loading stage. This behavior is associated with the linear-elastic nature of FRP reinforcement, which does not undergo yielding before failure as conventional steel does. Nevertheless, the hybrid steel–FRP reinforcement system delayed crack initiation, reduced crack widths, and improved crack distribution compared with the conventional steel specimen. The close agreement between the ABAQUS crack contours and the experimental observations reported by Javan *et al.* (2022) confirms the capability of the numerical model to accurately predict the crack initiation and propagation mechanisms of hybrid FRP–steel reinforced beam–column joints under cyclic loading.



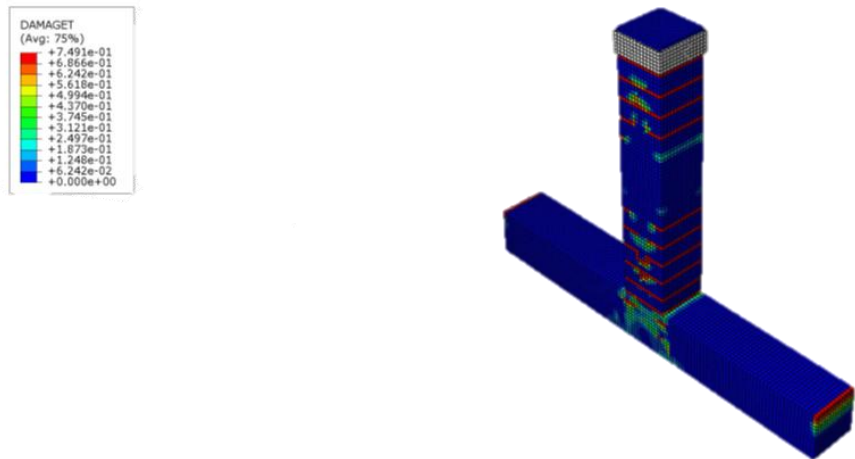
a) RJ beam column joints cracking patterns



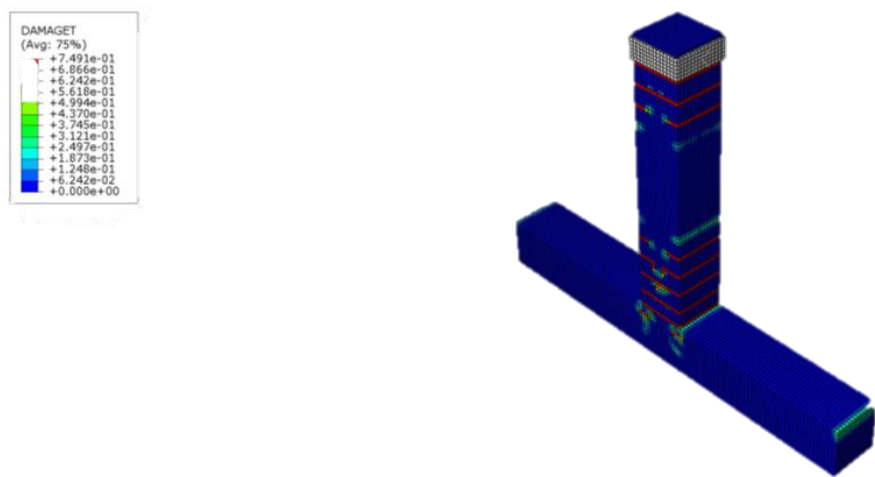
b) GJ-25% Beam column joints cracking patterns



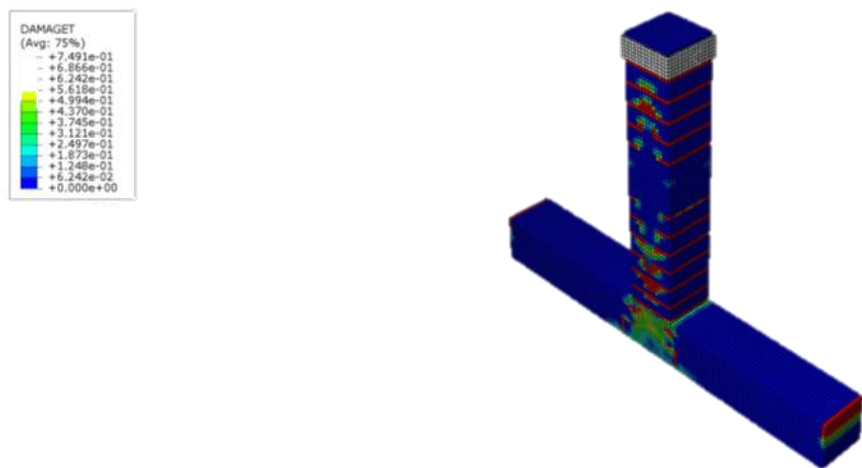
c) GJ-50% Beam column joints cracking patterns



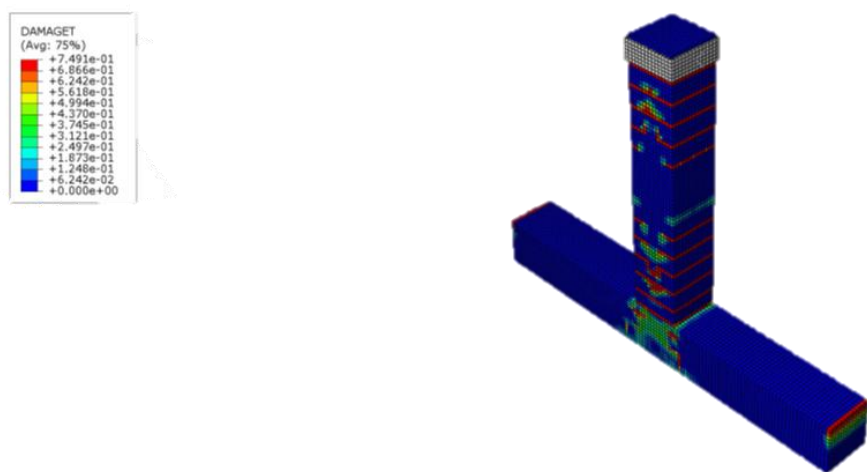
d) GJ-75% Beam column joints cracking patterns



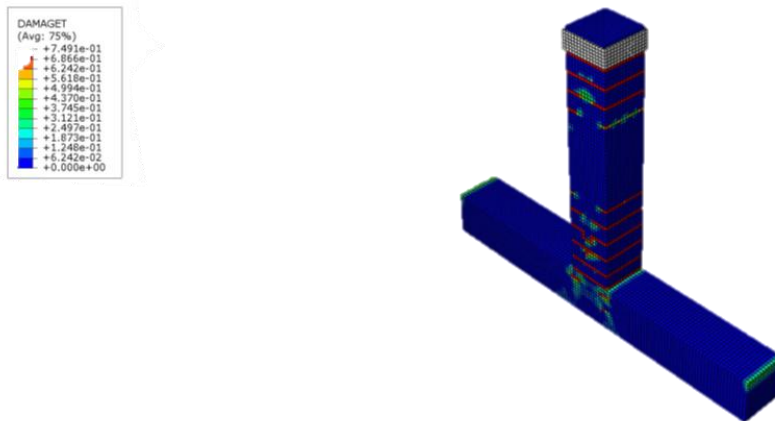
e) GJ-100% Beam column joints cracking patterns



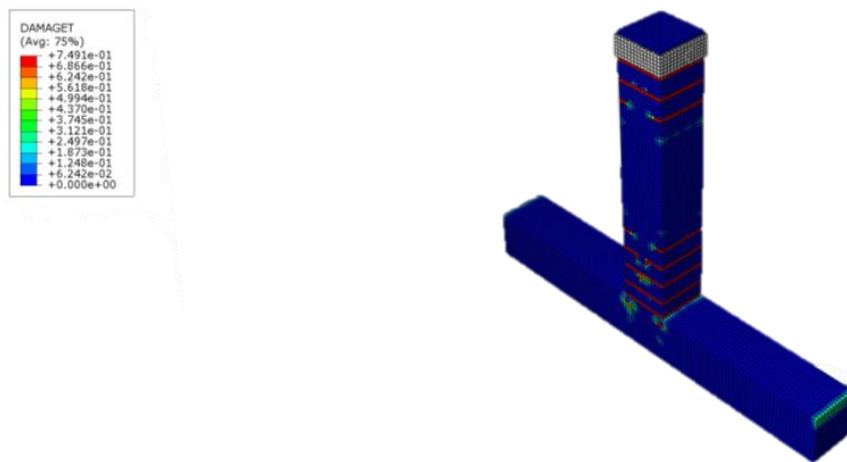
f) AJ-25% Beam column joints cracking patterns



g) AJ-50% Beam column joints cracking patterns



h) AJ-50% Beam column joints cracking patterns



i) AJ-50% Beam column joints cracking patterns

Figure 4.6 Crack Pattern for Different Beam-column Specimens

4.3.3 Effect of FRP Type and Replacement Ratio on Absorbed energy in Beam–Column Joints

Absorbed energy, also referred to as dissipated energy, is a key indicator of the seismic performance of reinforced concrete beam–column joints subjected to cyclic loading. It is represented by the area enclosed within the load–displacement hysteresis loops. During each loading cycle, the enclosed loop area corresponds to the amount of seismic energy dissipated through material deformation, cracking, and other inelastic mechanisms. Consequently, specimens exhibiting wider and fuller hysteresis loops possess greater energy dissipation capacity, whereas

narrow loops indicate lower energy absorption and reduced seismic resistance. The cumulative absorbed energy is obtained by summing the enclosed areas of all hysteresis loops throughout the loading history.

The hysteresis results presented in Figure 4.5 show a direct relationship between the loop area and the energy dissipation capacity of the beam–column joints. Specimens with wider and more stable hysteresis loops developed higher cumulative absorbed energy, indicating better cyclic performance and improved resistance to earthquake-induced loading. In contrast, specimens with narrow loops and pronounced pinching behavior exhibited lower absorbed energy due to stiffness degradation and reduced inelastic deformation capacity.

The results indicate that the 25% hybrid FRP replacement specimens exhibited the largest hysteresis loop areas and consequently the highest absorbed energy among the hybrid specimens. The presence of sufficient steel reinforcement allowed significant plastic deformation while the FRP reinforcement contributed additional strength and durability. The cumulative absorbed energy of these specimens was higher than that of the specimens with larger FRP replacement ratios, demonstrating their superior seismic performance.

For the 50% hybrid reinforcement specimens, the hysteresis loops remained relatively stable and the cumulative absorbed energy was comparable to that of the control specimen. This balanced behavior suggests that a moderate FRP replacement ratio can maintain adequate stiffness, load-carrying capacity, and energy dissipation while improving durability. Therefore, the 50% replacement ratio provides an effective compromise between structural performance and corrosion resistance.

As the FRP replacement ratio increased to 75% and 100%, the hysteresis loop area gradually decreased, resulting in lower cumulative absorbed energy. The reduction in loop area reflects the limited plastic deformation capability of FRP reinforcement due to its linear-elastic behavior and absence of yielding. Consequently, the reduction in steel content decreased the ability of the joints to dissipate seismic energy through inelastic deformation, leading to reduced seismic resistance and increased stiffness degradation.

A comparison between the two FRP types indicates that the AFRP–steel hybrid specimens generally developed larger hysteresis loop areas and higher cumulative absorbed energy than the corresponding GFRP–steel specimens at the same replacement ratios. The AFRP specimens maintained stable cyclic behavior over successive loading cycles and exhibited less pinching, which contributed to improved energy dissipation capacity. In contrast, the GFRP specimens showed relatively narrower hysteresis loops and lower cumulative absorbed energy, particularly at higher replacement ratios, reflecting their lower deformation capacity under cyclic loading.

Quantitatively, the cumulative absorbed energy obtained from the numerical analysis confirms that specimens with larger hysteresis loop areas consistently dissipated more seismic energy than those with narrower loops. The observed relationship between hysteresis loop area and absorbed energy demonstrates that hybrid AFRP–steel reinforcement provides superior cyclic performance compared with hybrid GFRP–steel reinforcement, while excessive replacement of steel by FRP tends to reduce the energy dissipation capacity of beam–column joints subjected to seismic loading.

Using the control specimen (RJ = **1037.422046 kN·mm**) as the reference, the percentage change is calculated as:

$$\% \text{ Change} = \frac{\text{Specimen Energy} - \text{RJ Energy}}{\text{RJ Energy}} \times 100$$

Table 4.5 Calculated values of Absorbed Energy and Change from Control

Specimen	Cumulative Absorbed Energy (kN·mm)	Change from Control (RJ) (%)
RJ	1037.422046	–
G/S-25%	1067.092192	+2.86%
G/S-50%	1005.809108	–3.05%
G/S-75%	934.665610	–9.91%
G/S-100%	581.525934	–43.95%
A/S-25%	1096.142280	+5.66%
A/S-50%	1022.864504	–1.40%
A/S-75%	1004.103575	–3.21%
A/S-100%	697.831121	–32.73%

As shown on table

- A/S-25% showed the highest improvement in energy absorption, increasing by 5.66% over the control.

- G/S-25% also improved the energy absorption by 2.86%.
- Moderate replacement levels (50–75%) generally caused slight reductions in absorbed energy.
- Full replacement (100%) significantly reduced the energy absorption capacity:
 - ✓ G/S-100%: 43.95% reduction.
 - ✓ A/S-100%: 32.73% reduction.
- Compared with GFRP, AFRP specimens retained a higher energy absorption capacity at equivalent replacement ratios, particularly at high replacement levels.

4.3.4 Effect of FRP Type and Replacement Ratio on Displacement Ductility in Beam–Column Joints

Displacement ductility ratio is defined as the ratio of ultimate displacement to yield displacement $\mu = \Delta u / \Delta y$. It represents the ability of a structural member to undergo large inelastic deformation without significant loss of strength. Ductility is an important parameter in evaluating the seismic performance of reinforced concrete beam–column joints subjected to cyclic loading.

The results show that the hybrid FRP-steel reinforcement significantly affected the ductility behavior of the joints. Specimens reinforced with 25% and 50% FRP replacement exhibited the highest ductility ratios and more stable cyclic performance. At these ratios, the steel reinforcement effectively contributed to plastic deformation, while the FRP bars enhanced the tensile resistance and delayed stiffness degradation.

When the FRP ratio increased to 75% and 100%, the ductility ratios decreased noticeably. The reduction in steel content limited the yielding behavior and decreased the inelastic deformation capacity of the joints. Consequently, the specimens showed lower displacement capacity and relatively brittle behavior under cyclic loading.

A comparison between AFRP and GFRP specimens indicates that AFRP-steel hybrid joints generally exhibited higher ductility than GFRP-steel hybrid joints at the same reinforcement ratios. This is mainly due to the higher toughness and better deformation capacity of aramid fibers. AFRP specimens maintained wider hysteresis loops and sustained larger displacements before failure.

In contrast, GFRP-reinforced joints showed comparatively lower ductility because of the relatively brittle behavior of glass fibers. Although GFRP bars provided adequate strength, the joints experienced faster stiffness degradation and reduced deformation capacity, especially at higher replacement levels.

Table 4.6 Calculated values of Displacement Ductility and Change from Control

Specimen	Ultimate Displacement, Δu (mm)	Yield Displacement, Δy (mm)	Ductility Factor, μ	% Change from RJ
RJ	77.77	35.0	2.222	0.00
GJ-25	78.00	31.0	2.516	+13.24%
GJ-50	78.00	27.0	2.889	+30.01%
GJ-75	76.00	36.0	2.111	-5.00%
GJ-100	70.00	41.0	1.707	-23.16%
AJ-25	78.00	30.0	2.600	+17.01%
AJ-50	78.00	26.1	2.989	+34.51%
AJ-75	77.00	35.6	2.163	-2.66%
AJ-100	71.00	40.0	1.775	-20.12%

Compared with the reference specimen (RJ), the GFRP and AFRP reinforced joints exhibited varying ductility responses depending on the replacement ratio. Moderate replacement levels improved ductility, with GJ-50 and AJ-50 showing increases of approximately 30.0% and 34.5%, respectively. However, higher replacement ratios resulted in reduced ductility, with GJ-100 and AJ-100 exhibiting decreases of 23.2% and 20.1%, respectively. Among all strengthened specimens, AJ-50 demonstrated the highest ductility enhancement relative to the reference specimen.

4.3.5 Effect of FRP Type and Replacement Ratio on Stiffness in Beam–Column Joints

Stiffness is an important parameter for evaluating the ability of reinforced concrete beam–column joints to resist deformation under cyclic loading. In this study, the secant stiffness was determined from the slope connecting the peak loads in the positive and negative loading directions during each loading cycle. Stiffness degradation occurred progressively during repeated loading due to the formation and propagation of flexural and shear cracks, concrete crushing, bond deterioration between reinforcement and concrete, reinforcement slip, and the accumulation of permanent deformations within the joint region. As these damage mechanisms developed, the ability of the joint to resist additional deformation gradually decreased, leading to a reduction in structural stiffness.

The results indicate that the stiffness behavior of the beam–column joints was significantly influenced by both the type and replacement ratio of FRP reinforcement. The control specimen reinforced with conventional steel bars maintained the highest stiffness and exhibited the slowest degradation throughout the loading history. This behavior is mainly attributed to the high elastic modulus of steel (approximately 200 GPa) and its yielding capability, which allows the reinforcement to redistribute stresses and maintain the integrity of the joint under cyclic loading.

The hybrid specimens with 25% and 50% FRP replacement exhibited relatively stable stiffness behavior. At these replacement levels, the presence of steel reinforcement provided adequate rigidity and ductility, while the FRP reinforcement contributed additional tensile strength and corrosion resistance. Consequently, these specimens experienced moderate stiffness degradation and satisfactory cyclic performance.

As the FRP replacement ratio increased to 75% and 100%, the stiffness of the joints decreased more rapidly. The reduction in steel content limited the plastic deformation capacity of the reinforcement, while the linear-elastic behavior of FRP bars reduced the ability of the joint to redistribute stresses after cracking. In addition, the progressive development of concrete cracking, bond slip, and localized damage accelerated the deterioration of stiffness under repeated loading cycles.

A comparison between the AFRP–steel and GFRP–steel hybrid specimens indicates that the AFRP-reinforced joints generally maintained higher stiffness and better cyclic stability than the corresponding GFRP specimens. This difference can be explained by the mechanical properties of the two FRP materials. AFRP possesses a higher tensile strength and generally a higher elastic modulus than GFRP, enabling it to carry larger tensile forces while limiting deformation under cyclic loading. Moreover, AFRP exhibits excellent fatigue and impact resistance, which contributes to improved structural performance during repeated load reversals. In contrast, GFRP has a relatively lower elastic modulus, resulting in greater deformation and faster stiffness degradation as the loading cycles progress.

The bond characteristics between the reinforcement and the surrounding concrete also influence the stiffness behavior of the beam–column joints. Effective bond interaction ensures efficient stress transfer and reduces reinforcement slip during cyclic loading. The AFRP–steel hybrid specimens exhibited better stress distribution and reduced bond deterioration, which contributed to maintaining higher stiffness throughout the loading history. Conversely, the lower stiffness of GFRP reinforcement and its associated bond-slip effects promoted larger crack widths and greater deformation, leading to a more rapid reduction in joint stiffness.

Table 4.7 Calculated values of Stiffness and Change from Control

Specimen	Load (kN)	Displacement (mm)	Stiffness (kN/mm)	Change from RJ (%)
RJ	4.27	77.77	0.05491	–
GJ-25	4.06	78	0.05205	-5.20
GJ-50	3.71	78	0.04756	-13.37
GJ-75	3.22	77	0.04182	-23.84
GJ-100	3.05	68	0.04485	-18.31
AJ-25	4.20	78	0.05385	-1.93
AJ-50	3.94	78	0.05051	-8.00
AJ-75	3.86	77	0.05013	-8.70
AJ-100	3.66	71	0.05382	-1.97

The stiffness comparison indicates that all FRP-reinforced specimens exhibited lower secant stiffness than the control specimen. Among the GFRP-reinforced joints, stiffness decreased with

increasing replacement ratio, with reductions of 5.20%, 13.37%, 23.84%, and 18.31% for GJ-25, GJ-50, GJ-75, and GJ-100, respectively. The AFRP-reinforced joints showed comparatively smaller reductions, ranging from 1.93% to 8.70%, with AJ-25 and AJ-100 maintaining stiffness values close to that of the control specimen. Overall, the AFRP-reinforced joints demonstrated better stiffness retention than the GFRP-reinforced joints, indicating their superior ability to maintain structural rigidity under loading.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In the present study, the cyclic behavior of reinforced concrete beam–column joints reinforced with hybrid Aramid Fiber Reinforced Polymer (AFRP)-steel and Glass Fiber Reinforced Polymer (GFRP)-steel bars was investigated. Five different reinforcement ratios of FRP-to-steel bars, namely 0%, 25%, 50%, 75%, and 100%, were considered to evaluate the influence of FRP type and replacement ratio on the seismic performance of the joints. The specimens were subjected to constant axial loading on the column and reversed cyclic loading on the beam.

The main observations included crack propagation patterns and load–displacement hysteresis curves. In addition, important seismic performance parameters such as displacement ductility, absorbed energy and stiffness degradation were evaluated and compared for all specimens. Based on the obtained results, the following conclusions can be drawn:

- The incorporation of hybrid FRP reinforcement significantly influenced the cyclic behavior of the beam–column joints. Specimens reinforced with 25% and 50% FRP replacement exhibited stable hysteresis curves, improved deformation capacity, and better overall cyclic performance compared to higher FRP replacement ratios.
- The AFRP-steel hybrid joints generally demonstrated better cyclic performance than the corresponding GFRP-steel hybrid joints. AFRP specimens showed wider hysteresis loops, higher absorbed energy, improved ductility, and slower stiffness degradation due to the higher toughness and deformation capacity of aramid fibers.
- In terms of crack propagation, the hybrid FRP-steel reinforced joints showed reduced crack width and delayed crack development compared to the reference reinforced concrete joint. However, increasing the FRP ratio beyond 50% resulted in more concentrated cracking and reduced crack distribution due to the lower ductility of FRP reinforcement.
- Regarding displacement ductility, the specimens with 25% and 50% FRP replacement exhibited higher ductility ratios and more stable inelastic deformation behavior. In contrast,

specimens with 75% and 100% FRP reinforcement showed significantly lower ductility because of the linear-elastic and relatively brittle behavior of FRP bars.

- The absorbed energy results indicated that the 25% hybrid reinforcement ratio provided the highest energy dissipation capacity, while the 50% replacement ratio exhibited energy absorption behavior close to that of the reference joint. Increasing the FRP content to 75% and 100% reduced the energy dissipation capacity of the joints.
- Stiffness degradation increased with increasing FRP replacement ratio. The reference reinforced concrete joint maintained the highest stiffness, while the specimens with 100% FRP reinforcement exhibited the lowest stiffness and the largest reduction in deformation resistance under cyclic loading.
- Comparing the two FRP types, AFRP reinforcement provided better overall seismic performance than GFRP reinforcement, particularly in terms of ductility, absorbed energy, and cyclic stability.

5.2 Recommendations

Further studies are recommended to achieve a deeper understanding of the behavior of FRP-reinforced beam-column joints under cyclic loading. Future research may include the following aspects:

- Investigation of the stress-strain behavior of AFRP and GFRP bars using strain gauges installed directly on the reinforcement bars during cyclic loading.
- Evaluation of other FRP types such as Carbon Fiber Reinforced Polymer (CFRP) and Basalt Fiber Reinforced Polymer (BFRP) in hybrid reinforcement systems.
- Study of the behavior of beam-column joints reinforced with FRP bars in columns or in both beams and columns simultaneously.
- Investigation of FRP bars used as transverse reinforcement to evaluate their influence on confinement, shear resistance, and crack control.
- Examination of additional seismic performance parameters such as equivalent damping ratio, residual displacement, and plastic hinge formation.
- Numerical and analytical modeling of hybrid FRP-steel reinforced beam-column joints to validate and extend the experimental findings.

- Investigation of the long-term durability and environmental performance of AFRP- and GFRP-reinforced joints under aggressive exposure conditions such as corrosion, temperature variation, and moisture effects.

6 Reference

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