

**ANALYSIS ON RETROFITTING OF REINFORCED
BEAM-COLUMN JOINTS USING HYBRID FRP**

THESIS REPORT

Submitted by

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of

Master of Technology

in

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DEPARTMENT OF CIVIL ENGINEERING



TKM College of Engineering, Kollam

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DECLARATION

I undersigned hereby declare that the project report, “**Analysis on Retrofitting of Reinforced Beam Column Joint using Hybrid FRP**”, submitted for partial fulfilment of the requirements for the award of the degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of **Prof. Rekha Ambi**, Assistant Professor, Department of Civil Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included; I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

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ABSTRACT

Beam-column junctions are key zones in reinforced concrete structures that are particularly vulnerable to earthquake stresses. As a result, strengthening the beam-column joint is critical in order to save the structure and its people in the event of seismic pressures. Throughout the world, several retrofitting projects utilising fibre reinforced polymer (FRP) composites are being carried out. The purpose of this study is to look at the efficiency of retrofitting beam-column junctions with a hybrid combination of Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP). To assess the performance of the original and improved joint models, nonlinear finite element analysis was used. The performance has been investigated in terms of load carrying capacity, deflection, failure pattern and displacement ductility. On the hybrid FRP system, parameters such as different combinations and length variations are investigated. According to the findings, hybrid FRP is far more effective than monolithic CFRP and GFRP. And length variations have a significant impact on retrofitting capacity; as the area of retrofitting increases, so does the capacity. While retrofitting ability does not change with changes in layer placements, it is mostly determined by the composition ratio of hybrid materials utilised.

Keywords: Beam Column Joint, Retrofitting, CFRP, GFRP, Hybrid FRP.

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Chapter 1

Introduction

1.1 General

Deterioration of concrete structures is currently a major issue on a global scale. The causes of this are numerous, including the occurrence of natural disasters like earthquakes, lack of knowledge on codal provisions in construction, poor quality of supervision etc (Figure 1.1). These factors lead to strength deficient structures. Sometimes overloading of structures results in extreme deformations and corrosion, which require significant attention nowadays. Repair, retrofitting, or strengthening are routinely required actions in the modern construction industry to counteract all these effects on reinforced concrete structures. Damage caused by any of these methods will necessitate a number of repair approaches, the most efficient of which will be chosen in each specific circumstance. In some circumstances, even recently constructed structures require repair and reinforcement to eliminate faults caused by design or construction errors. Beam-column junctions are important regions to consider while analysing and designing moment-resisting reinforced concrete frames. Normal design practice does not include a design check for beam column joints. As a result, design of joint isn't done correctly. Beam-column connections are subjected to high shear stresses in the joint region as a result of seismic pressures. These shear stresses are caused by opposite-sign moments and shear forces on the member ends on either side of the joint core. Typically, high bond stresses are also imposed on reinforcement bars entering into the joint. These stresses lead to diagonal cracking or crushing of concrete in the joint core. These issues have recently been highlighted by the destruction caused by disastrous earthquakes in many nations.

Many existing bridges, industrial structures, urban transportation structures, marine structures, and earth-retaining structures require maintenance or improvement at some point during their service life for a variety of reasons. In this instance, there are two options: replacement or retrofitting. The replacement of entire structures has drawbacks such as high labour and material costs. So, rather than rebuilding the entire structure, it is preferable to repair or upgrade it by retrofitting if practicable and feasible. At the member level (i.e., for beams and columns), various retrofitting techniques are available such as concrete jacketing, steel jacketing, wrapping with fibre reinforced polymer

(FRP) sheets, external prestressing etc. These strategies have shown to be fairly effective throughout the years, with each having its own set of benefits, drawbacks, and restrictions. Retrofitting of beam column joints, on the other hand, remains a major source of worry. Many researchers have examined alternative approaches for retrofitting reinforced concrete beam-column joints, with variable degrees of success.



Figure 1.1 Typical beam-column joint failures (1999 Turkey Earthquake)

(Source: A. Sharma et. al, 2010)

Among these strategies, fiber-reinforced polymer (FRP) composites as retrofit materials have seen significant success in recent years. The superior properties of (FRP) polymer composite materials like high corrosion resistance, high strength, high stiffness, excellent fatigue performance and good resistance to chemical attack etc., has motivated the researchers and engineers to use the polymer composites in the field of rehabilitation of structures

1.2 Beam Column Joint

The area of the column that frames the column and is within the deepest beam's depth is referred to as the beam column joint. The joints must be sturdy and rigid enough to bear the forces generated internally by the framework components. Allowing adjoining members to reach and maintain their maximum capacity is a functional requirement of a joint, which is the zone where beams and columns cross. The main objective of including a beam column junction in a reinforced concrete structure is to effectively transfer the load from connecting components under seismic and gravity loads.

Particularly when the structure is vulnerable to seismic loading, it should be well designed and detailed. Brittle bond and shear failure mechanisms control the failure of reinforced concrete beam column joints during earthquakes.

Beam column joints are classified according to geometry as three types of joints as interior joint, exterior joint and corner joint as shown in fig 1.2. An interior junction is created when four beams frame the vertical faces of a column. When two other beams frame the connection from perpendicular angles and one beam frames into the vertical face of the column, the junction is referred to as an external joint. The joint is known as a corner joint when a beam frames into two neighbouring vertical faces of a column. Beams are anticipated to acquire plastic hinges at their ends and generate flexural overstrength beyond the design strength. Joints should follow a strong column-weak beam design

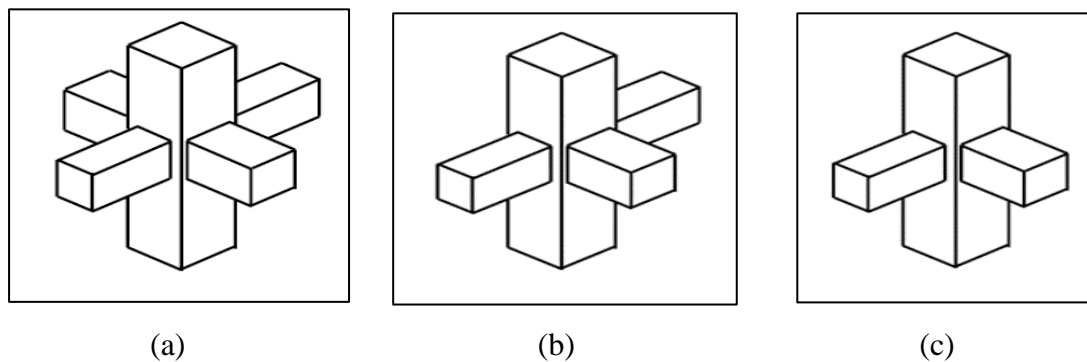


Figure 1.2 Types of joints in a frame: (a) Interior joint, (b) Exterior joint and (c) Corner joint (Source: Uma and Prasad, 2015)

1.3 Fiber Reinforced Polymer Jacketing

Fibre-reinforced polymer (FRP) jacketing is a relatively new technique of jacketing in which strengthening is carried out by using composite jackets made up of FRPs. A matrix, which is often formed of resin like epoxy, and fibres make up the composite material. The fibres are crucial since they will provide the material its mechanical qualities. There can be a mix of different types of fibres used such as Glass, Carbon or Aramid and the matrix which is basically a resin made of polyester, epoxy.

One of fibres' key advantages is that they are very resistant to chloride assault. Fibers also have the benefits of being strong and lightweight. All of these materials exhibit some degree of creep, although tests have shown that the amount of creep in reinforced

concrete is minimal and that the force losses in prestressed concrete are comparable to those in buildings with steel tendons. Fibres are capable of forming round tubes, rectangular tubes, plates, rods or any other linear sections. Figure 1.3 shows the FRP sheet laid over the beams



Figure 1.3 FRP jacketing (Source: www.wikipedia.org)

1.3.1 Carbon Fibre Reinforced Polymer

Carbon fibre reinforced polymer (CFRP) is made up of very thin carbon fibres that range in diameter from 5 to 10 micrometres and are embedded in polyester resin. In CFRP, the reinforcement is made of carbon fibre, which offers strength and rigidity, and epoxy, a popular polymer glue, which bonds the reinforcement in an organised manner. The main benefits of fibres are their low density, low conductivity, strong fatigue strength, high elastic modulus (200-800 GPA), good creep level resistance to chemical effects, and the fact that they do not absorb water. Carbon Fibre Reinforced Polymers are most typically employed in industrial masonry structures for retrofitting of existing structures that have been damaged owing to earthquakes, chemical reactions, environmental effects, and so on. Carbon fibre Reinforced Polymers (CFRPs) are much more substantial than other traditional materials in various domains of application since they are one of the stiffest and lightest composite materials. The use of (CFRP) composite Reinforcement offers a promising solution, such as column wrapping with CFRP composites, which is a popular alternative for improving column seismic resistance. CFRP is now employed for structural rehabilitation of damaged structures caused by ageing and harsh conditions. Because of these benefits, carbon fibre is widely

used in a variety of industries, including aerospace, automotive, military, and recreational uses.

1.3.2 Glass Fibre Reinforced Polymer

Glass Fibre Reinforced Polymer (GFRP) is a polymer consisting of glass fibres that is reinforced by a plastic matrix. Glass fibres are created by combining silica sand, limestone, folic acid, and a few other minor elements. Glass produced fibres are considered the primary reinforcement for polymer matrix composites due to their high electrical insulating properties even at low thickness, low susceptibility to moisture, and high mechanical properties as their specific resistance is greater than steel. Fibre glass is a lightweight, robust, and resistant material that is employed in a variety of sectors due to its superior qualities. Figure 1.4 shows the typical GFRP sheet. Although its strength and stiffness are lower than those of carbon fibre, the material is often significantly less brittle and raw resources are far less expensive. Glass Fibre reinforced polymer is widely used in electronics, home and furniture, boat and marine, medical and automobile industries.



Figure 1.4 GFRP sheet (Source: www.wikipedia.org)

Chapter 2

Literature Review

2.1 General

2.1.1 FRP Strengthening

Beam column connections are the most critical structural components during seismic excitations. Several studies have been conducted to evaluate the cyclic and seismic performance of reinforced concrete joints. These tests revealed that the performance beam column connection needed to be improved using external and internal strategies in order to increase seismic performance. (**Rajaram, P. et.al., 2010, Geethanjali, C. et.aal 2014**). These techniques include the use of concrete jackets, bolted steel plates and jacketing using FRP, supporting with shear wall, bracings etc (**Migliacci A. et al. 1983, Ghobarah A et.al, 1997**)

Among these approaches, fibre-reinforced polymers (FRP) have found widespread use in retrofitting concrete structures. Several studies evaluating various retrofitting procedures were conducted, and FRP was determined to be superior to all of these retrofitting techniques. (**K. Bsisu et al (2015)**), FRP has several advantages, such as quick application, short building time, lightweight, and corrosion resistant qualities, which increase the material's capabilities over other materials. **C. Mohanan et. al., (2016)** has conducted an analytical examination of three retrofitting strategies using finite element analysis to improve the behaviour of reinforced concrete beam column joints in order to improve structure performance and load carrying capacity. Concrete jacketing, steel plate jacketing, and fibre reinforced polymer (GFRP) sheets wrapping are the three techniques. When improving load carrying capacity is the goal, the results demonstrate that using FRP wrapping sheets is the best retrofitting option when compared to the other two techniques. When reducing maximum deflection is the goal, using steel plate jacketing with the right thickness is the best option.

FRP materials contains different types of FRP materials like BFRP, AFRP, GFRP and CFRP. Numerous studies are done to determine the best material for each retrofitting categories. **S.Y. Laseima et al., (2021)** has conducted an experimental study on beam column joints without joint transverse reinforcement. The external beam-column joints of the experimental specimens were strengthened with basalt fibre reinforced polymer (BFRP) and carbon fibre reinforced polymer (CFRP), respectively, to improve their

seismic performance. The beam and column's cross-sections were altered from square to square segments to maximise the confinement impact of the CFRP and BFRP in the core. The experimental results demonstrated that the moment capacity and deflection of CFRP and BFRP strengthened specimens were increased, respectively, and that the square cross-section assisted in preventing CFRP and BFRP debonding in the core. And **Jafar Ali M and Gayathri S (2017)** studied the behaviour of RC beam column joints retrofitted with sheets of CFRP and GFRP. A G+3 story building's beam column joint is taken into consideration and Different thicknesses of CFRP and GFRP sheets are taken into account. According to the results, employing CFRP for retrofitting will result in 50% higher strength (Von-Mises stress) than using GFRP.

2.1.2 Placings of FRP

To augment the existing internal reinforcing, FRP materials can be bonded to the exterior of concrete structures using high strength adhesives. Aside from external bonding, FRP reinforcements can be put inside grooves carved into structural elements in a process known as typically near surface mounting (NSM) (Figure 2.1). This was accomplished by placing steel reinforcement bars into concrete surface grooves and filling them with cement mortar (**Asplund SO et al. (1947)**). When compared to the externally bonding technique (EBR), the near surface mounting technique has several advantages: A wider bond surface induces better anchorage capability, it gives greater resistance to peeling-off, allowing a greater percentage of the tensile strength to be mobilised, no preparation work is necessary other than grooving, resulting in a shorter installation time (**Nanni A (2003), Cruz JMS et al., (2002)**).

Raafat EI-Hacha and Sami H.Rizkalla (2004) conducted study on Near Surface Mounted (NSM) FRP reinforcements for flexural strengthening of concrete structures. Figure 2.1 shows different placings by which FRP are laid over specimen. The stiffness and flexural strength of RC beams are shown to be significantly improved by NSM FRP reinforcing bars and strips. It has one key benefit over externally bonded FRP materials, namely that strengthening using NSM approach results in a larger strength capacity than externally bonded one and significantly increases beam ductility. **Akhlaghi and Mostofinejad (2020)** investigated the effect of using carbon-fiber reinforced polymer (CFRP) composites to improve the lateral strength capacity of exterior reinforced concrete (RC) beam-column connections. Four different anchorage

systems have been evaluated to provide continuity for composites across the joint. The experimental results demonstrated that the 180-degree anchor fan outperformed all other tested anchorage systems, resulting in a complete plastic hinge relocation along the beam from the column face. The EBROG technique eliminated both surface debonding and compressive buckling failure of composite sheets bonded on the top and bottom sides of the beam.

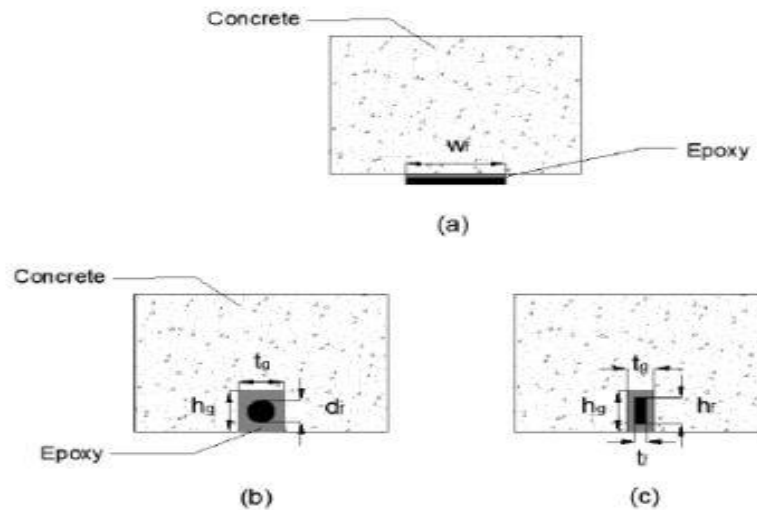


Figure 2.1 FRP placing methods (a) EBR FRP plate (b) NSM FRP rod (c) NSM FRP laminate (Source: Raafat EI-Hacha , 2004)

2.1.3 Factors affecting FRP

The Retrofitting ability of FRP materials depends on different factors like thickness, length of overlap, Resin used, orientation, no of plies used etc. (Mehmat et al. 2014, S. Sheela et al 2012). FRP sheet width affects failure modes in the sense that wider sheets provide better strengthening outcomes by reducing bond stress between the concrete surface and the FRP sheets, resulting in higher flexural beam strength. (Thomsen et al. (2004), McSweeny and Lopez (2005)) . V. Savant et. al., (2021) investigated the bond strength between concrete and carbon fiber reinforced polymer (CFRP) sheet with different thickness like 1.4 mm laminate, 200 GSM, 300 GSM, 400 GSM, and 600 GSM, The carbon fibre reinforced polymer sheet with a thickness of 300 GSM was found to have the strongest bond. According to values for bond strength, bonding behaviour between elements and carbon fibre reinforced polymer should be taken into account when choosing the thickness of carbon fibre reinforced polymer sheets for any strengthening. The thickness of the fibre has an impact on bond strength

in addition to the resin. Whereas when **Jafar Ali M et.al (2017)** examined RC beam column joints with different thickness sheets of CFRP and GFRP, the analysis result concludes that the strength of FRP sheets doesn't significantly increase as they get thicker. As a result, the FRP sheet thickness at the junction of the beam and column should be at its maximum.

Number of layers of FRP also plays a significant role along with the thickness of FRP used. From the study conducted by **K. Bsisu et al., (2015)**, Multiple layers of FRP wide sheets can contribute to additional strength of the beam, but will reduce the ductility of beams. **S. Sheela and B. Anu Geetha (2012)** performed strengthening of concrete specimen using ferrocement, glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CFRP) and studied their behaviour under static as well as cyclic loading. It was found that the rotation at ultimate moment of all the strengthened beam– column joints were greater than that of the control specimens. The specimens strengthened with a greater number of layers of strengthening material showed better moment– rotation characteristics. Other factor on which retrofitting FRP layer depend is the epoxy resin used for the adhesiveness of FRP to the concrete surface. **Mehmat (2014)** studied concrete surfaces with various thicknesses of epoxy resin and concluded that utilising thicker epoxy resin in both CFRP and GFRP beams was extremely efficient in preventing FRP material breakage. **McIsaac and Mak (2019)** studied the bond strength of concrete and fiber-reinforced polymer (FRP) wet lay-up systems employing resins with varying proportions of bio-based content as a partial replacement for epoxy. Bond strength was affected not just by resin but also by fibre type. Glass FRP bond strengths were frequently lower than carbon FRP bond strengths by 12%-29% for the same resin type.

FRP sheet installation was examined by **Campbell, F.C. (2010)**. FRPs are manufactured into laminates by layering single sheets of fibres in various orientations to achieve the appropriate strength and stiffness qualities. The laminate's strength and stiffness qualities are determined by the direction and system in which the plies are laid. **Y.T. Obaidat (2019)** studied on the orientation of FRP on beam column joint and diagonal orientation is concluded as the best orientation as it mode of failure from diagonal cracks to debonding of FRP plates from the joint.

2.1.4 Hybrid Retrofit Method

Different retrofitting techniques involving local retrofit and global retrofit are available to strengthen the damaged specimens. One method will be having advantages over one another. If two or more methods are combined drawbacks can be overcome and more strengthening methods can be invented. **N.S. Hadi and T.M. Tran (2014)** has proposed a new technique that uses concrete jacketing along with CFRP to retrofit reinforced concrete (RC) external beam column T joints. The connections were tested, and the results showed that both the strengthened connections performed much better. In order to resist shear load, the glued concrete covers combined well with the pre-existing concrete. Additionally, the wrap on the modified circular sections increased the confinement impact on the concrete and decreased the likelihood of CFRP debonding at the joints, all of which served to increase the effectiveness of CFRP. **Esmaceli et al. (2015)** has investigated a combination of strain hardening cementitious composite (SHCC) along with laminates of carbon fiber reinforced polymers (CFRP laminates, the retrofitting strategies used was able to restore and improve the performance of beam-column joints, as well as significantly improve the seismic performance of these specimens.

Likewise one or more FRP materials can also be combined to improve the FRP action over joints. **Jianchun Li et al., (2002)** done an experimental work to investigate the behaviour of reinforced concrete frame specimens designed to represent the column-beam connections in plane frames. For this beam column, a specially designed hybrid FRP sheet is used as wrapping. To create FRP, a hybrid blend of carbon and E-glass is used together with roving cloth, carbon cloth, chapped strand mat, and glass fibre tape. Concrete beam-column connections with and without FRP reinforcement underwent a thorough static test and detailed strain analysis. Due to the reinforcement that designed hybrid FRP composites give, the stiffness and load carrying capacity of the specimens are increased, effectively reinforcing concrete structures. Similarly, **Arul Gananaprasngam et al., (2016)** has studied the performance of beam column joints when a hybrid FRP wrapping is provided. BFRP monolithic wrapping, and combined BFRP and GFRP hybrid wrapping are compared as shown in fig 2.2. Based on the test findings, it was determined that the hybrid Basalt and Glass FRPs were superior for treating beam-column junctions. By allowing the beam section of the strong column weak beam design to fail, the entire structure was saved from a catastrophic collapse.



Figure 2.2 Failure of Joint after retrofitted with (a) BFRP monolithically and (b) Hybrid FRP (Source: A. Gananprangam et. al 2016)

2.2 Summary of Literature Review

Retrofitting a structure with FRP results in a noticeable boost in strength since less deflection and stress occur, increasing the structure's overall serviceability. In order for a joint to function properly, it should adhere to the strong column, weak beam principle. If a structure does not meet these requirements, adding FRP will aid in removing the plastic hinge from the beam. The length of the overlay, the thickness orientations, and other variables have an impact on the FRP strengthening. FRP that is oriented diagonally performs better; When considering thickness, the strength rises only up to a certain thickness. Increased thickness will result in a loss of strength if it is more than the ideal value. FRP material can be attached to a surface in two ways: externally or using a form of surface mount. Among this placing method near surface shows effective increase in strength than normal externally bonded systems. When one or more retrofitting techniques are hybridized a much improvement in strength is observed.

2.3 Gap Identified

The research gaps identified from the literature survey are as follows: -

1. There have been few studies on hybrid FRP combinations.
2. The identical composition of Hybrid FRP are not explored
3. Effect of retrofitting FRP length variation on the specimen is not particularly concentrated.
4. There are few studies on the impact of the hybrid system's layer count.

2.4 Objectives of the Study

The objectives of the study are as shown below:

1. To compare the effectiveness of hybrid combination of Carbon and glass FRP
2. To determine the best pattern of placing different FRP material in hybrid system
3. To determine the effectiveness of retrofitting when number of layers are changed within a constant thickness
4. To determine the variation of FRP length over each layer
5. To analyse the joint in terms of ductility, energy dissipation and stiffness

2.5 Scope of the Study

The study is restricted to the following domains:

- Exterior beam-column joint
- Non-linear static analysis
- Analytical study using Ansys
- Design codes ACI 318M-02 and ACI 352R-02 for beam-column joint design
- Use of carbon fiber reinforced polymer and glass fiber reinforced polymer

Chapter 3

Methodology

3.1 General

For analysis, an exterior beam column joint structural model is used. Because of the low cost, quick findings, and capacity to analyse multiple factors in depth, numerical investigation of structures is an appealing research technique. Therefore, a three-dimensional non-linear finite element joint model is built using commercial software Ansys. For conducting the analysis, the first step is the validation of Ansys software based on data from experimental analysis conducted by Mahmoud et al. (2014). For the fulfillment of the defined objectives, the steps followed are design of joint using ACI 352R-02 and ACI 318-2011, structural modelling, nonlinear static analysis, parametric study, development of force-displacement curve and comparative study. The parametric analysis improves understanding of the effect of length and FRP layer location on the beam column junction in Hybrid FRP sheet. A comparison study based on ductility, energy dissipation, and stiffness degradation of retrofitted joints and normal joints also provides an in-depth review of joint performance. The force-displacement curve created from the data can be utilised as a useful tool to compare the performance of both the normal beam column joint and the retrofitted joint. The methodology of the project is outlined as flow chart in the Figure 3.1 shown below.

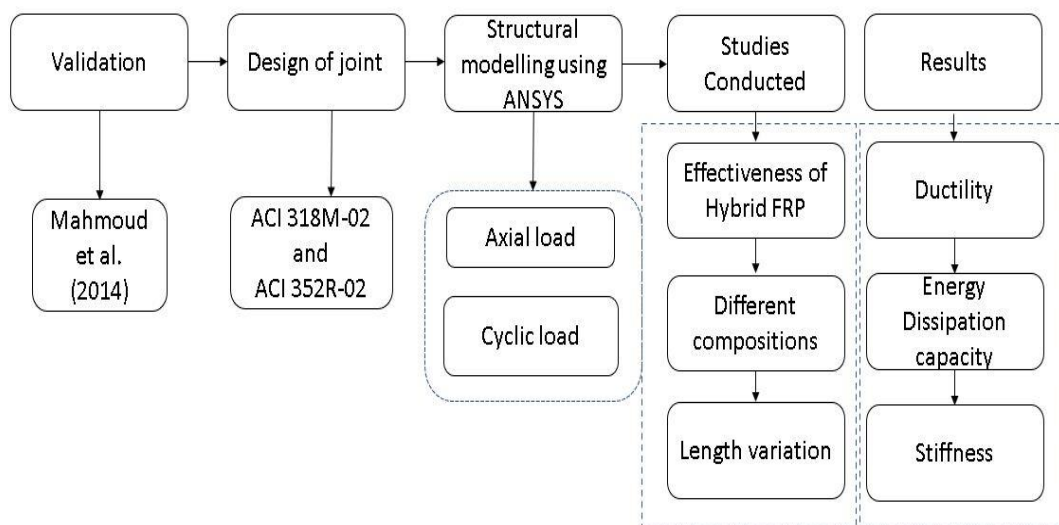


Figure 3.1 Flowchart of project methodology

3.2 Non- Linear Static Analysis

Nonlinear static analysis is performed on the exterior beam-column joint. A nonlinear analysis is one in which a nonlinear relationship exists between the applied forces and displacements. Geometrical nonlinearity, material, and touch can all cause nonlinear effects. As a result of these factors, the stiffness matrix is not constant during the load application. The design procedure for non-linear static analysis is as follows: -

Step 1: Defining material properties

First of all, we will be inputting all the properties of all the materials to be used in the model. We will be defining the compressive strength of the concrete to be used, the stress-strain behavior of concrete, steel and FRP materials used, density of these materials, Elastic modulus and Poisson ratio, etc.

Step 2: Modelling

In our study first column is constructed and then after beam. Both beam and column are bonded together using Boolean function so, it act as a single material. Reinforcement is made and inserted into the specimen.

FRP sheet with required length and thickness are constructed on the surface of joint and bonded together to avoid slipping.

Step 3: Analysis

After the modelling of structure, a constant axial load to be applied on top of the column which corresponds to the gravity load induced by the upper floors. And a cyclic load is to be applied at tip of beam to directly correlate the measured displacements of the joint to the inter-story drift of an entire frame. The load application is quasi-static with displacement control. It is intended to ensure that the applied reversed cyclic load was increased gradually in steps, neither too large nor too small. This is followed by an incremental load applied as displacement control.

Step 4: Comparison

Total deformation, strain energy and force reaction in the direction of deformation are to be obtained. From the results, force displacement graph is plotted to give a clear idea on the performance of both the joints. It also helps to carry out a comparative study

between the performance of normal beam column joint and retrofitted beam column joint.

3.3 Parametric Study

Parametric study is conducted to investigate the behavior of exterior beam column joint. when strengthened with hybrid FRP. Hybrid combination of GFRP and CFRP sheets are made to study the performance of retrofitted joint. Parameters of Hybrid system including length of FRP overlay, change in compositions are compared to find the effective retrofitting technique. Two layers Hybrid FRP is used with one layer containing GFRP and another one layer of CFRP. Both of constant thickness of 1mm.

3.4 Comparative Study

The visualization module displays the analysis results. The output data required in the step module is obtained by this module. The deformation of the joint in the direction of the applied load verses time was obtained as the X-Y plot. Load was defined as a linear function of time in the obtained plot. Thus, the load verses displacement graph can be created by combining the data of load versus time and displacement versus time from the X-Y data. Load deformation graphs for retrofitted joint models were developed. The load displacement graph can be used to calculate the ductility, energy dissipation capacity, and stiffness degradation of joints. The results of the retrofitted joints' analyses were compared to those of the normal joints in order to comprehend the improvement in structural performance of the hybrid FRP retrofitted beam column joint.

3.5 Design of Exterior Beam Column Joint

Exterior beam-column joint is designed using ACI 352R-02 and ACI 318M-02. ACI 352R-02 and ACI 318M-02 are used to design the outside beam-column joint. Only structures made of normal weight concrete with a compressive strength of less than 100 MPa are covered by these codal recommendations. The Type 2 connection is selected for joint design in this investigation. The following are the steps of developing a beam column joint:

Step 1: Determine the material properties and the beam-column joint dimension

The material properties of the beam-column joint that is designed based on the analysis are as follows:

Table 3.1 Material properties of the beam-column joint

PARAMETER	STEEL	CONCRETE
Density (kg/m ³)	7800	2400
Young 'modulus (MPa)	200000	25000
Poisson's ratio	0.30	0.15

Dimensions of exterior beam column joint are as follows:

Column - cross section of 200 mm x 200 mm and height of 1500 mm

Beam - 200 mm x 150 mm cross section and length of 600 mm

Step 2: Calculate the amount of reinforcement

Section 10.9.1 of ACI 318-2011 specifies that the area of longitudinal reinforcement for non-composite compression members should not be less than 0.01 times the gross section of the column and should not be greater than 0.08 times the gross section of the column. In addition, according to section 10.9.2 of the same, the minimum number of longitudinal bars for rectangular or circular sections should be four. Section 10.5.1 of ACI 318-2011 requires beam reinforcement as shown in equation Eq. 3.1. In Eq. 3.2, A_{smin} represents the minimum area of reinforcement, f_c' represents the compressive strength of concrete, b_w represents the web width of the beam, d represents the depth of the beam, f_y represents the yield strength of steel, and A_s represents the area of steel reinforcement. Section 7.10.5.1 of ACI 318-2011 requires at least 8mm diameter ties for longitudinal bars of 30mm or less.

$$\begin{aligned} \text{Minimum reinforcement, } A_{smin} &= (3\sqrt{f_c'} b_w d) / f_y && \text{Eq. 3.1} \\ &= (3 \cdot \sqrt{30} \cdot 200 \cdot 200) / 415 \\ &= 1188 \text{ mm}^2 \end{aligned}$$

$$\begin{aligned} \text{Area of steel reinforcement, } A_{st} &\leq (200 b_w d) / f_y && \text{Eq. 3.2} \\ &\leq (200 \cdot 200 \cdot 150) / 415 \\ &\leq 14458 \text{ mm}^2 \end{aligned}$$

Step 3: Calculate the design shear force of beam-column joint

The magnitude of the shear force of the joint (V_u) is calculated by finding the difference in the amount of tension and compression to the horizontal shear force that works on the column as given by equation Eq. 3.3. where C_s and T_s are the beam compression and tension forces given by equations Eq. 3.4 and Eq.3.5, V_c is the horizontal shear force on the column, is the stress multiplier for longitudinal reinforcement and is equal to 1.25, f_y is the yield strength of steel, The equation Eq. 3.8 gives the column shear force. where M_{prb} is the beam moment, h is the column height, A_s is the sum of top and bottom beam longitudinal reinforcement (Eq. 3.7), d is the beam depth, f_c' is the concrete compressive strength, and b is the beam breadth. The shear force of the joint is to be calculated using all of the above equations and appropriate values.

$$\text{Design shear force of the joint, } V_u = (T_s + C_s) - V_c \quad \text{Eq. 3.3}$$

Sum of top and bottom beam longitudinal reinforcement,

$$\begin{aligned} A_s &= A_{s1} + A_{s2} \\ &= 4 * 0.78 * 122 + 1 * 0.78 * 102 \\ &= 527.28 \text{ mm}^2 \end{aligned}$$

$$\text{Beam compression force, } C_s = \alpha f_y A_s \quad \text{Eq. 3.4}$$

$$\begin{aligned} &= 1.25 * 415 * 302.64 \\ &= 156.99 \text{ KN} \end{aligned}$$

$$\text{Beam tension, } T_s = \alpha f_y A_s \quad \text{Eq.3.5}$$

$$\begin{aligned} &= 1.25 * 415 * 224.64 \\ &= 116.53 \text{ KN} \end{aligned}$$

$$a = (A_s \alpha f_y) / (0.85 f_c' b) \quad \text{Eq.3.6}$$

$$\begin{aligned} &= (527.28 * 1.25 * 415) / (0.85 * 30 * 200) \\ &= 53.63 \end{aligned}$$

$$\text{Beam moment, } M_{prb} = 2 A_s \alpha f_y (d - a/2) \quad \text{Eq. 3.7}$$

$$\begin{aligned} &= 2 * 527.28 * 1.25 * 415 * (150 - 53.63/2) \\ &= 52.72 \text{ KNm} \end{aligned}$$

$$\text{Horizontal shear on column, } V_c = M_{prb} / h \quad \text{Eq. 3.8}$$

$$\begin{aligned} &= (52.72 / 1.5) \\ &= 35.15 \text{ KN} \end{aligned}$$

$$\begin{aligned} \text{Design shear force of the joint, } V_u &= (T_s + C_s) - V_c \\ &= 238.37 \text{ KN} \end{aligned}$$

Step 4: Calculate the concrete shear capacity of joint

Current building codes in high seismic zones require the design of reinforced beam-column joints to take joint shear failure into account. This is due to the observation that joint shear failure occurs prior to beam or column flexural yielding. Eq. 3.9 is used to calculate the concrete shear capacity (V_c).

$$\begin{aligned} \text{Concrete shear capacity, } V_{cs} &= 0.2905\sqrt{f_c'}\sqrt{(1+0.2903 N_u/A_g)} \quad \text{Eq. 3.9} \\ &= 0.2905\sqrt{30}\sqrt{(1+0.2903 *100000/(200*200))} \\ &= 135.55 \text{ KN} \end{aligned}$$

where N_u denotes the axial force acting on the column and A_g denotes the gross column area. The concrete shear capacity of the joint must be determined. If the axial compressive stress in the column N_u/A_g is less than $0.12 f_c'$, the contribution of concrete shear resistance should be ignored.

Step 5: Calculate the joint shear strength

The horizontal shear in the joint must be checked independently in each direction in connections with beams framing in from two perpendicular directions. The design shear force V_u is computed on a horizontal plane at the joint's mid-height by taking into account the shear forces on the joint's boundaries as well as the normal tension and compression forces in the members framing the joint. Eq. 3.11 is used to calculate the joint shear strength (V_n). Eq. 3.10 should also be met.

$$\phi V_n \geq V_u \quad \text{Eq. 3.10}$$

$$V_n = 0.083\sqrt{f_c'}b_jh_c \quad \text{Eq. 3.11}$$

$$b_j = (b_b + b_c)/2 \quad \text{Eq. 3.12}$$

Effective width of joint transverse to the direction of shear,

$$\begin{aligned} b_j &= (b_c + b_b)/2 \\ &= (200+200)/2 \\ &= 200 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{Joint shear strength, } V_n &= 0.083\sqrt{f_c'}b_jh_c \\ &= 0.083*20*\sqrt{30}*200*1500 \\ &= 4980 \text{ KN} \end{aligned}$$

$$\phi V_n \geq V_u$$

$$0.85 * 4980 \geq 238.37 \text{ KN}$$

where ϕ is the strength reduction factor and equals 0.85, V_n is the shear strength factor reflecting joint confinement by lateral members and equals 20, b_j is the effective width of joint transverse to shear (Eq. 3.12), h_c is the full depth of column, b_b is the web-width of beam, b_c is the core dimension of tied column, and m is the slope to define the effective width of joint transverse to shear. The joint shear strength must be determined. The design philosophy embodied in Eq. 3.12 is that the joint can resist the specified shear forces if the concrete within the joint is adequately confined during anticipated earthquake-induced loading and displacement demands.

Step 6: Design shear force of joint stirrup

The amount of design shear force that must be resisted by stirrups V_s is given by the equation Eq. 3.13 and is to be obtained.

$$\begin{aligned} \text{Design shear force, } V_s &= V_u - V_c && \text{Eq. 3.13} \\ &= 203.22 \text{ KN} \end{aligned}$$

Chapter 4

Validation

The Ansys software was validated using the results published by Mohamed H. M. et al. (2014). Experimental research for the structural performance of reinforced concrete (RC) external beam-column joints rehabilitated with carbon fiber reinforced polymer (CFRP) is presented in this work. In addition to an appropriately detailed control specimen, the programme includes testing 10 half-scale specimens separated into three groups that cover three possible flaws. The flaws under consideration include the lack of transverse reinforcement within the joint core, insufficient bond length for the beam main reinforcement, and an insufficiently spliced implanted column on the joint. To repair the defective beam-column joints, three distinct strengthening schemes were adopted, including externally bonded CFRP strips and sheets as well as near surface mounted (NSM) CFRP strips. Failure criteria such as ultimate capacity, mode of failure, initial stiffness, ductility, and developed ultimate strain in reinforcing steel and CFRP were studied and compared for each group of control and CFRP-enhanced specimens.

Ansys software was used to simulate the experimentally tested model. The model was built in the same manner as the experimental setup and is composed of M20 grade concrete. The reinforcement details of the beam-column joint used in the study are shown in Figure 4.1. The segment comprises a 900 mm long extruded beam and cross-sectional dimensions of 200 x 300 mm. At its mid-height, this beam was attached to a column. The column's cross-section measured 200 x 300 mm. The columns' entire length was 2.3 m, divided into two equal portions, bottom and upper. High tensile steel was used for the beam's upper and lower reinforcement, as well as the column's primary longitudinal steel reinforcement. The main steel reinforcement of the beam was three bars of 16 mm diameter, while the secondary steel reinforcement was two bars of 12 mm diameter. On the other hand, the column was reinforced with four bars of 16 mm diameter at each corner of the column cross-section. The stirrups for both beam and column were mild steel bars of 8 mm diameter and spaced every 100 mm and 150 mm for the beam and the column, respectively. In addition, three stirrups were added at the beam-column joint. The longitudinal reinforcement

for the beam and columns was deformed bars with a yield strength of 400 MPa, while the stirrups were conventional mild steel with a yield value of 240 MPa..

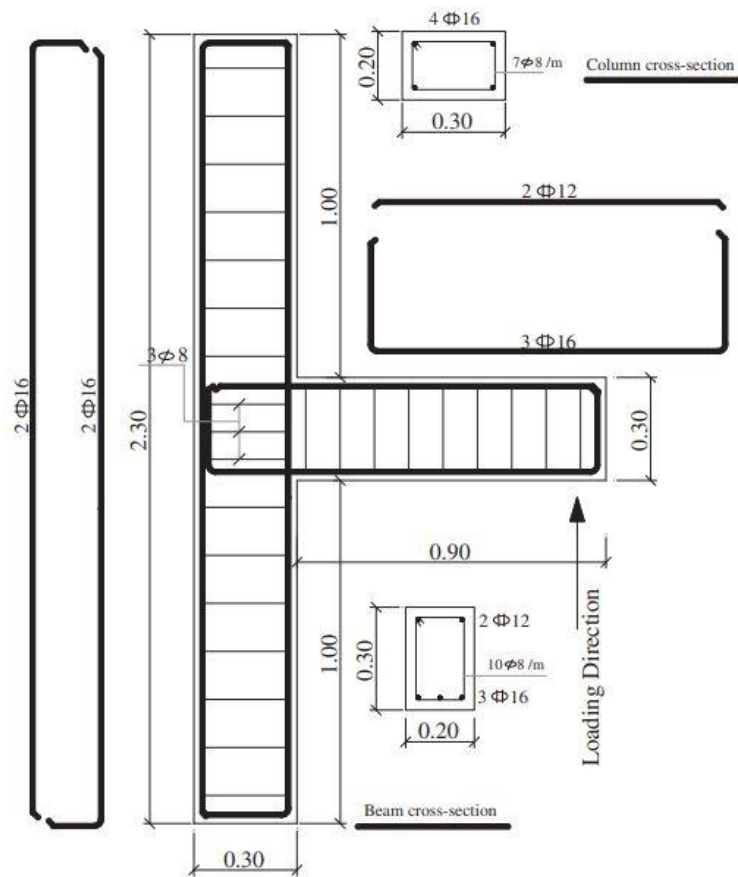


Figure 4.1 Reinforcement details for beam column joint

(Source: Mahmoud et al., 2014)

Both column ends of the specimens were considered hinged. Before loading the beam, a compression load of 200 kN was given to the column to simulate the load in a genuine structure. During the loading phase, the column load was kept constant. As a result, the beam was loaded to failure in stages.

The joint model developed in Ansys is shown in figure 4.2. Meshed model with mesh size of 40 is shown in figure 4.3. Loading stage of beam column joint is shown in figure 4.4. and the deformed model of joint after loading stage is shown in figure 4.5

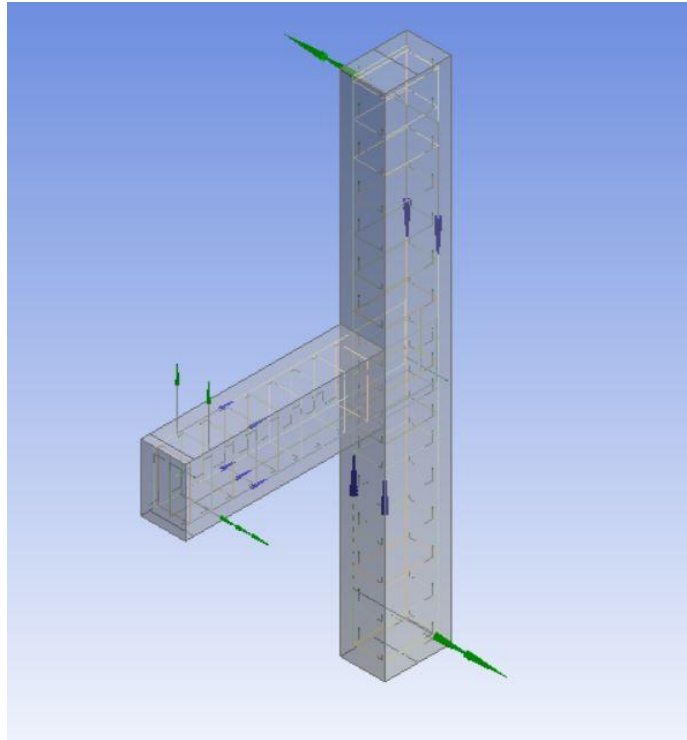


Figure 4.2 Beam column joint model in Ansys
(Source: Mahmoud et al., 2014)

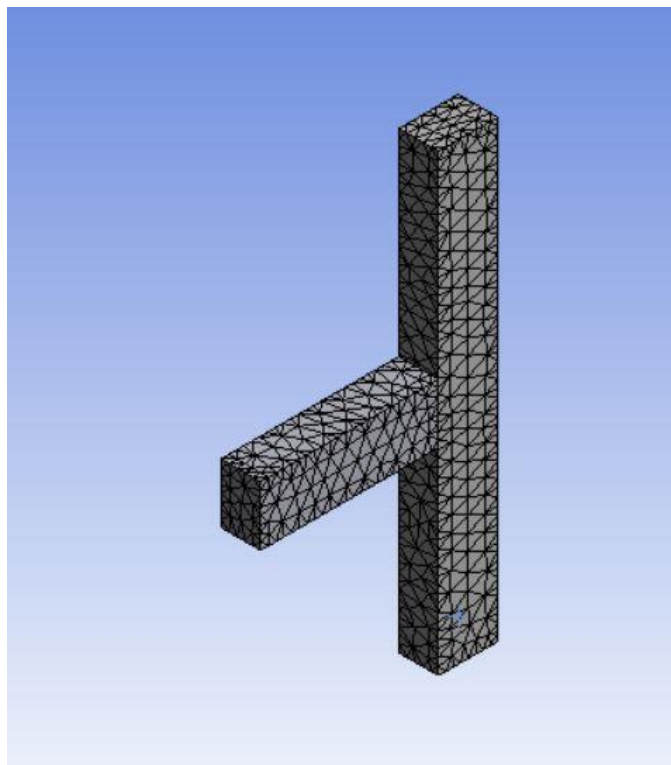


Figure 4.3 Meshed model in Ansys
(Source: Mahmoud et al., 2014)

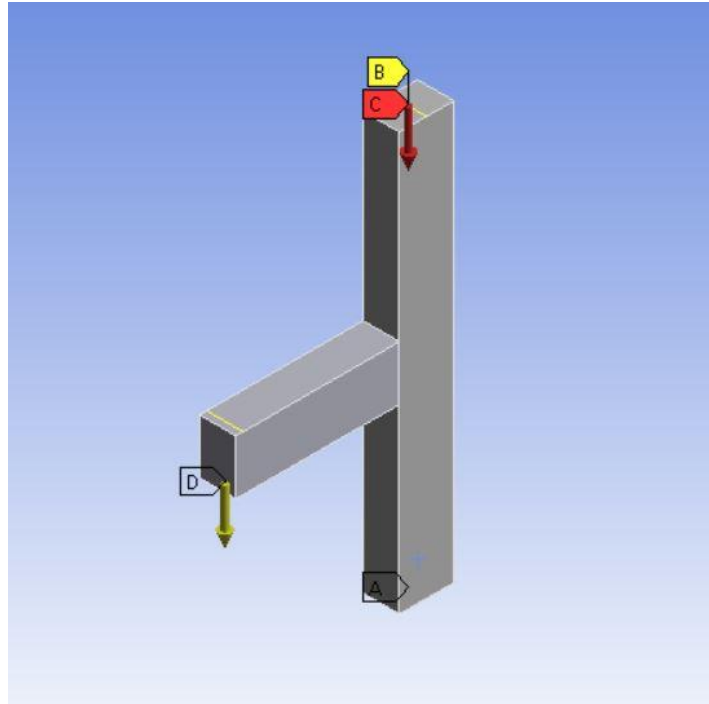


Figure 4.4 Loading Model in Ansys
(Source: Mahmoud et al., 2014)

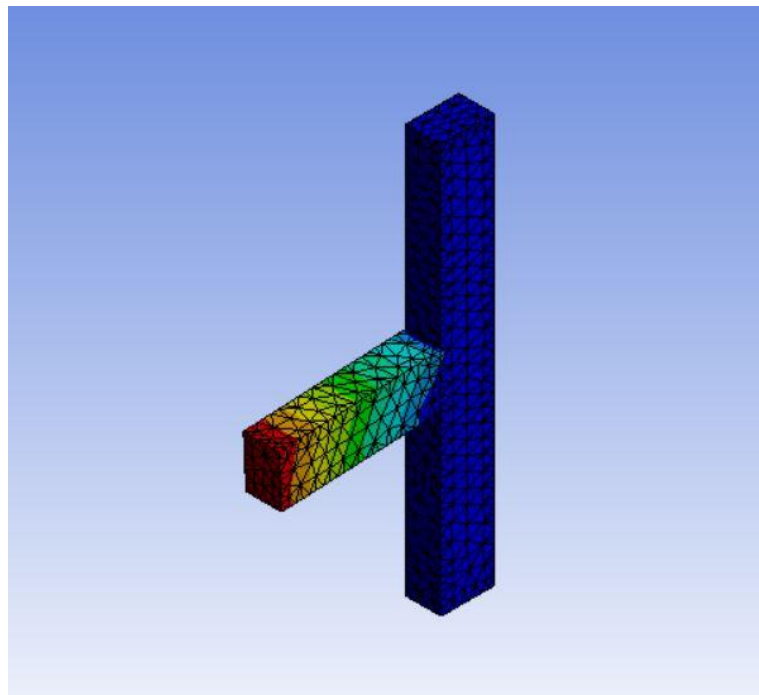


Figure 4.5 Deformed Model
(Source: Mahmoud et al., 2014)

Figure 4.6 shows the graph comparing the reported experimental results and finite element results obtained. The finite element analysis results of the exterior connection specimen with 40 mm mesh sizes are studied in this work to analyse the mesh size

sensitivity of the numerical model. The graphs show that the finite element findings are very close to the experimental data.

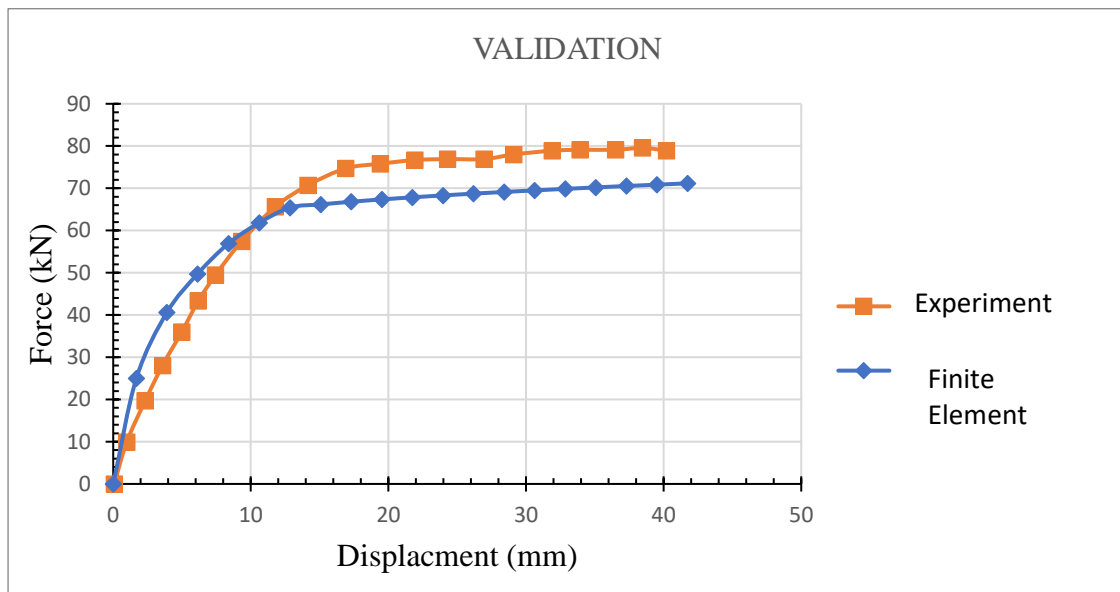


Figure 4.6 Comparison of Experimental and finite element analysis

Parity Curve is plotted for the ultimate load and displacement within a 10% variation as shown in Fig 4.7 and 4.8

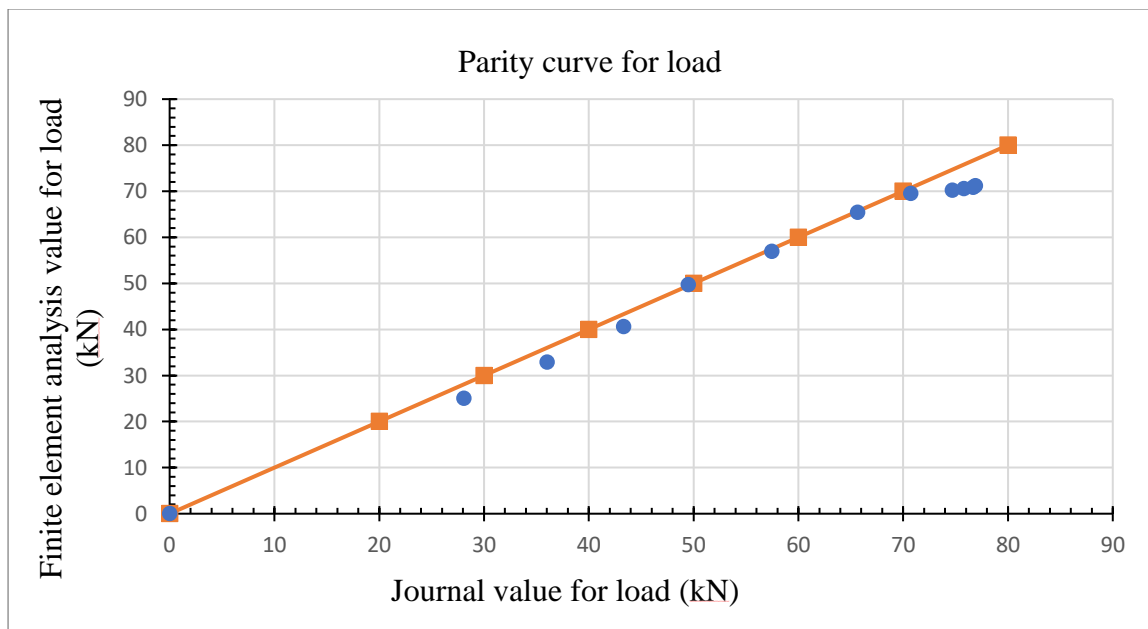


Figure 4.7 Parity Curve for load

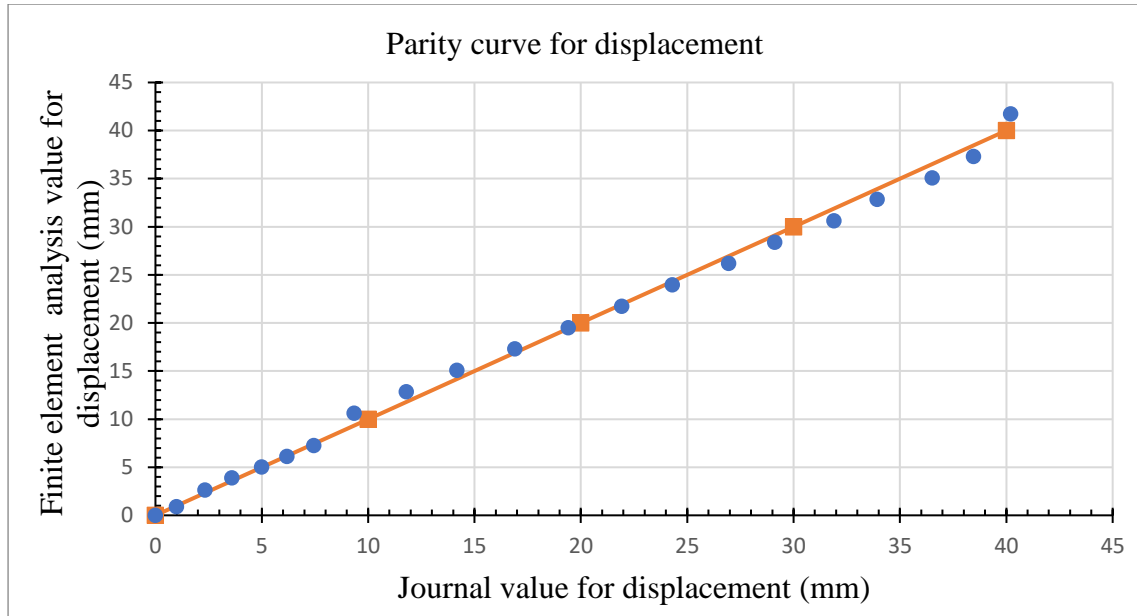


Figure 4.7 Parity Curve for displacement

The ultimate load value and displacement value from the numerical analysis and from the experimental analysis are tabulated below in Table 4.1. A variation of 8.53% and 3.68% are observed in ultimate load and displacement values respectively for mesh size 40. Since the difference is less than 10% the software and model can be used for analysis.

Table 4.1 Comparison of ultimate load and displacement of joint

Parameters	From experimental analysis	Mesh size= 40mm	Error %
Ultimate load (KN)	78.90	72.168	8.53%
Displacement	40.20	41.74	3.68%

Although the impacts of mesh size and strain localization in the numerical model are within the margins of error expected for most numerical simulations based on plasticity models, there are minor changes in peak lateral loads and displacements. The minor variances could be attributed to variations in the unknown assumptions used in establishing material attributes and the interaction between reinforcement and concrete.

Chapter 5

Numerical Analysis of Beam Column Joint

5.1 Modelling in Ansys

The exterior beam column joint is developed in Ansys and is shown in figure 7.1. The structural dimensions are summarized in having a vertical column with a cross section of 200 mm x 200 mm intersecting a horizontal beam with a 200 mm x 150 mm cross section. The height of the specimen is 1500 mm and the beams extend by 600 mm before and after the connection. The longitudinal reinforcement of the column is 4 number of 16 mm diameter rebars and the shear reinforcement is 8 mm diameter stirrups with a spacing of 80mm given in figure 5.1. The beam steel reinforcement is 4 number of 12 mm diameter rebars, and 1 bar of 10 mm diameter with shear reinforcement of 8 mm diameter stirrups with a spacing of 80 mm. Clear cover of 40mm is provided for beams and column. The details of reinforcement of joint developed in Ansys is shown in figure 7.1.

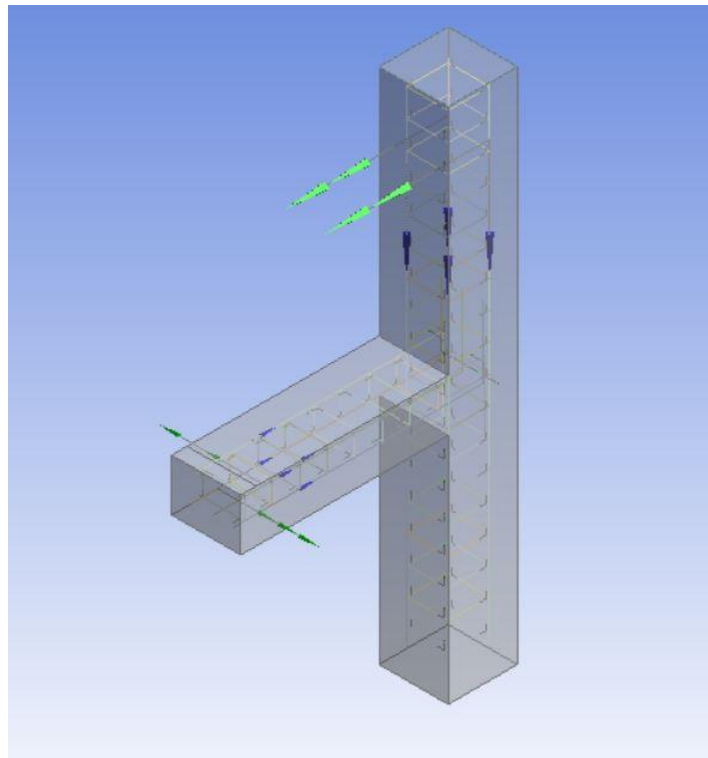


Figure 5.1 Reinforcement details of model developed in Ansys

Total of 9 different models are made for the comparison. That include different variation in FRP provided. Nine models comprise of MODEL 1 of Normal beam column joint, then two models with single layer of unidirectional CFRP and GFRP wrapped around the joint, fourth model comprises of Hybrid FRP combining two layers of CFRP and GFRP. Then different parametric changes of hybrid models are modeled with 3 models comprising of changing CFRP and GFRP layer position in hybrid system. Again 3 models are modelled with changing length of different FRP layer.

5.2 Elements Used in Ansys

Concrete had been modelled using SOLID65 element. Reinforcing bar has been modelled using LINK180 element. Contact surface has been modelled as bonded condition.

5.2.1 SOLID65

SOLID65 is a 3-D modelling element used in Ansys software for solids with or without reinforcing bars (rebar). The solid has the ability to crack in tension and crush in compression. In concrete applications, for example, the element's solid capacity can be used to represent the concrete, while the rebar capability can be utilised to model reinforcing behaviour. The element is defined by eight nodes, each of which has three degrees of freedom: translations in the nodal x, y, and z directions. It is possible to declare up to three different rebar requirements. The consideration of nonlinear material properties is the most essential component of this part. Concrete has the ability to crack (in three orthogonal directions), crush, distort, and creep.

5.2.2 LINK180

LINK180 is a three-dimensional spar that may be used in a range of engineering applications. The element can be used to simulate trusses, sagging cables, linkages, springs, and other structures. The element is a uniaxial tension-compression element with three degrees of freedom at each node: nodal x, y, and z translations. There are tension-only (cable) and compression-only (gap) alternatives available. No bending of the element is considered, as in a pin-jointed structure. Plasticity, creep, rotation, significant deflection, and large strain are all supported. LINK180 includes stress-stiffness terms by default in any study that contains large-deflection effects. The following properties are supported: elasticity, isotropic hardening plasticity, kinematic

hardening plasticity, Hill anisotropic plasticity, Nonlinear hardening plasticity, and creep.

5.3 Material Properties

5.3.1 Concrete

Properties of concrete were taken similar to that defined in nonlinear general materials. The concrete defined in the software is of compressive strength 30MPa. The material property of concrete used in software is listed in Table 5.1

Table 5.1 Material properties for concrete

Yield Stress	Inelastic strain
2.925	0.0001
5.7	0.0002
8.325	0.0003
10.8	0.0004
13.125	0.0005
15.3	0.0006
17.325	0.0007
19.2	0.0008
20.925	0.0009
22.5	0.001
25.2	0.0012
28.125	0.0015
28.8	0.0016
29.7	0.0018
29.925	0.0019
30	0.002
30	0.0024
30	0.0026
30	0.0028
30	0.0031
30	0.0033
30	0.0035

5.3.2 Reinforcing steel

Properties of reinforcement steel were taken similar to that defined in nonlinear general materials. The steel defined in the software is of yield strength 250MPa. Steel reinforcement of tensile strength 415Mpa is also used for providing reinforcement and 250 MPa bars are used for stirrups, listed in Table 5.2 . The reinforcement was modelled using isotropic behaviour. As plastic straining occurs, the yield surface changes size uniformly in all directions, causing the yield stress to increase (or decrease) in all stress directions.

Table 5.2 Properties of reinforcement for the joint

Bar Diameter (mm)	Cross sectional area (mm ²)	Yield strength (MPa)
16	200.96	415
12	113.04	415
10	78.5	415
8	50.24	250

5.3.3 Modelling of FRP

The beam-column joint model is strengthened using unidirectional CFRP and GFRP sheets. The fiber behaviour is linear elastic up to failure with rupture failure. Figure 5.2 shows the Model of exterior beam column joint retrofitted with hybrid FRP sheet. The mechanical properties for the CFRP sheet and GFRP sheets are listed as in table 5.3 and 5.4

Table 5.3 Properties of CFRP sheet (Source: AbuTahnat Y.B. et. al., 2018)

Material Property	CFRP
Density (g/cm ³)	600
Elastic modulus (Mpa)	165000
Poisson Ratio	0.2
Tensile strength (MPa)	2800
Thickness (mm)	1

Table 5.4 Properties of GFRP sheet (Source: T. Selvi et. al., 2018)

Material Property	GFRP
Density (Kg/mm ³)	1800
Elastic modulus (Mpa)	26000
Poisson Ratio	0.28
Tensile strength (MPa)	530
Thickness (mm)	1

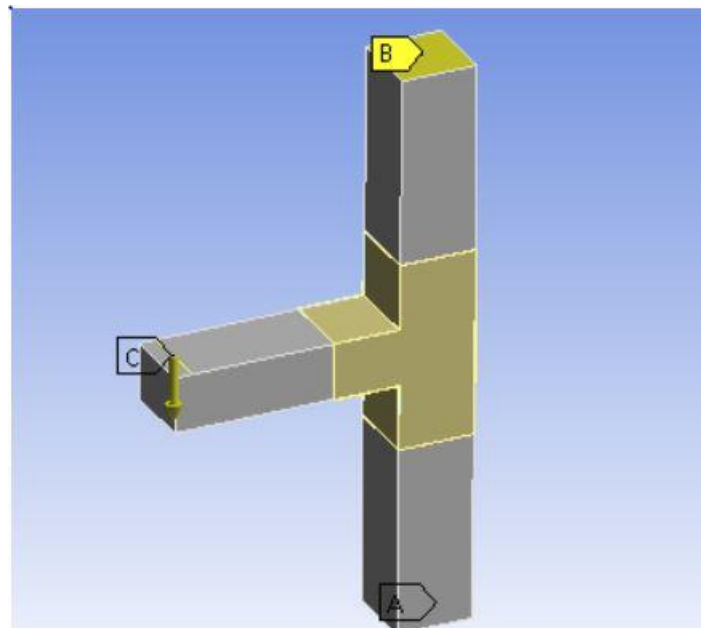


Figure 5.2 Model of exterior beam column joint retrofitted with hybrid FRP sheet

5.4 Loading and Boundary Conditions

A constant axial load is initially applied to the column's top. A cyclic load is then provided at the beam's tip to control displacement. The top end of the column is restrained by a stiff surface, allowing it to behave like a pin, while the bottom end is restrained by a rigid surface, allowing it to behave like a fixed end. The connection at the top prevented the column's lateral displacement, but it was free to rotate and extend. The loading and boundary condition of normal joint and retrofitted joint is shown in figure 5.3 and 5.4 respectively.

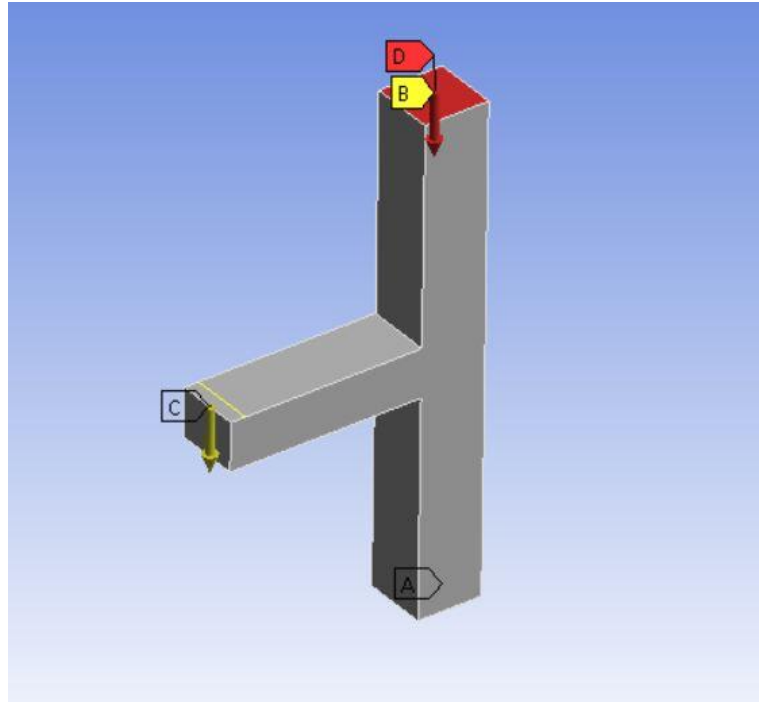


Figure 5.3 Loading and boundary conditions of joint in Ansys

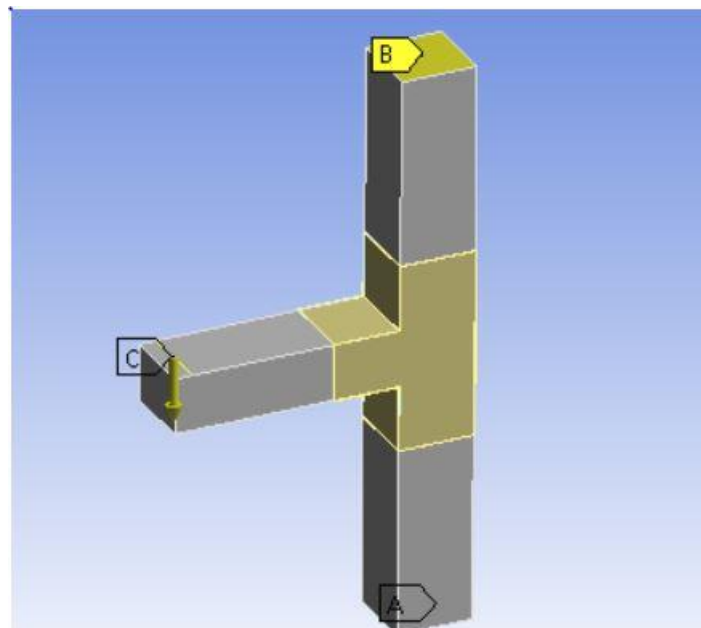


Figure 5.4 Loading and boundary conditions of Hybrid FRP retrofitted joint in Ansys

5.5 Mesh Arrangement

Meshing is important in engineering simulation because it splits complex geometries into simple parts that can be employed as different local approximations of the wider domain. A model's mesh arrangement affects the simulation's accuracy, convergence, and speed. The meshing method takes up a large amount of time while obtaining simulation results. The faster and more exact the answer, the better and more automated

the meshing tools. Figures 5.5 and 5.6 show a meshed model of a normal joint and a retrofitted joint. A mesh size of 40 mm is used in this study.

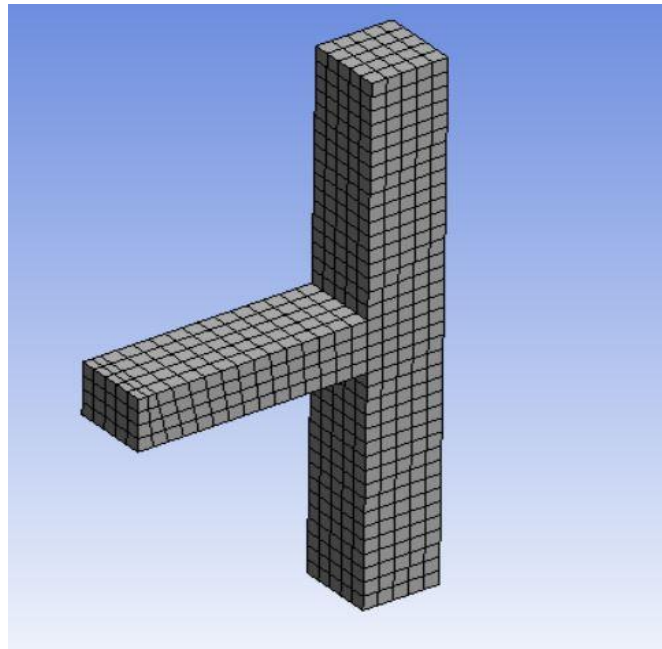


Figure 5.5 Meshed model of joint

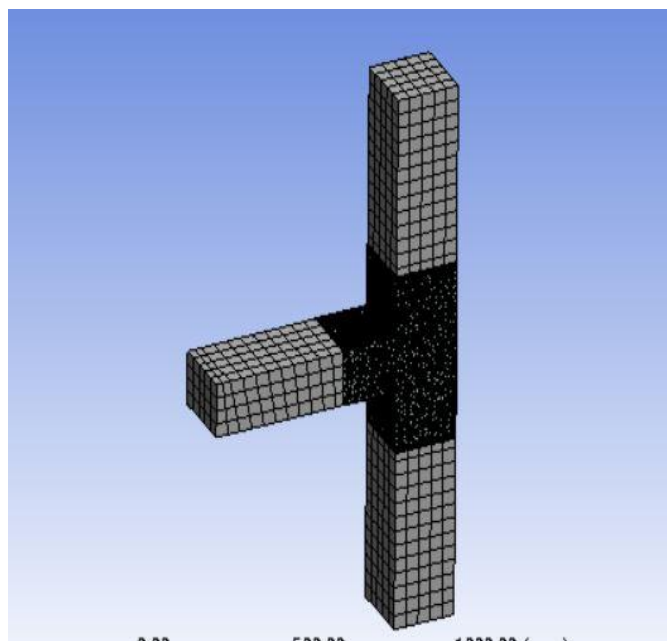


Figure 5.6 Meshed model of FRP retrofitted joint

Chapter 6

Result and Discussions

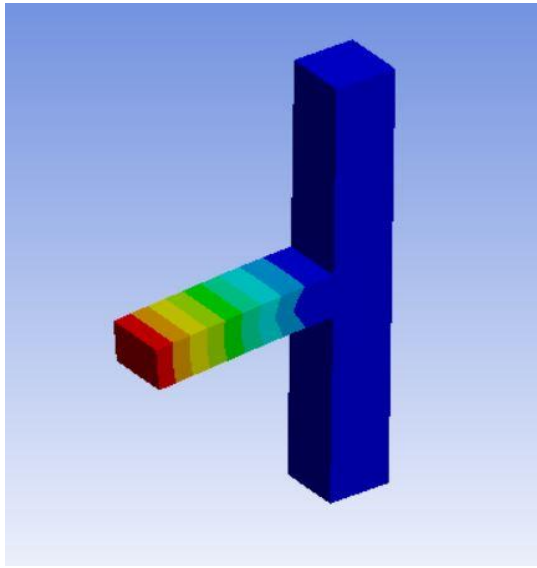
6.1 General

The numerical analysis on retrofitted beam column joint was performed to evaluate the improvement in load carrying capability of retrofitted joint with hybrid FRP and is compared to that of a normal joint. The effect of factors, namely change in hybrid layer composition and length variation of distinct layers in hybrid system, was explored, and the results are discussed in the following sections.

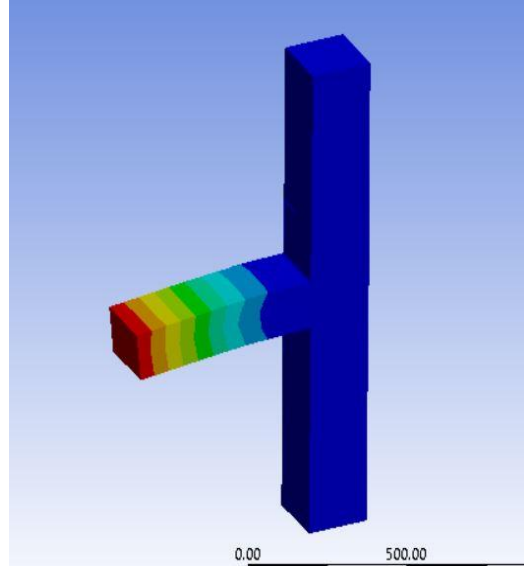
6.2 Effect of Hybrid FRP in Beam Column Joint

6.2.1 Hybrid Glass Carbon FRP

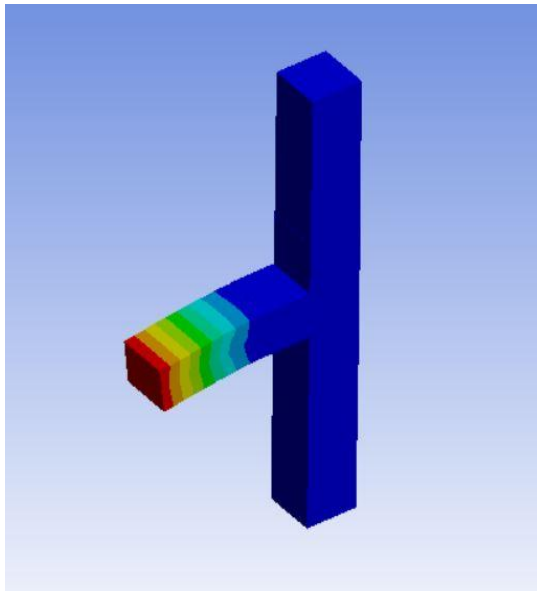
To investigate the effect of Hybrid FRP sheets on the performance of beam column joints, beam column joints retrofitted with a layer of CFRP sheets and a layer of GFRP sheets of the same thickness and a combined two layer of CFRP and GFRP were numerically analysed, and the results were compared to the load carrying capacity of a normal joint. Deformed model of retrofitted joint with different FRP is shown in figure 6.1 and figure 6.2 represents the load displacement curve for beam column joint retrofitted with GFRP, CFRP and hybrid FRP and that of a normal joint. According to the graph, Hybrid FRP sheet increases the load carrying capacity of the joint more than Normal beam column joint. The load carrying capacity of a retrofitted beam column junction with CFRP was greater than that of GFRP, and a hybrid of both materials demonstrates much greater strength than a single material retrofit. The improvement in the load carrying capacity of retrofitted beam column joint with GFRP, CFRP and Hybrid FRP were 5.2%, 7.5% and 8.6 % higher than that of the normal beam column joint. Figure 6.3 shows the efficiency-displacement factor curve for retrofitted joint with different FRP combinations. The variation of efficiency and load factor curve is similar in all three cases and hence the result is verified.



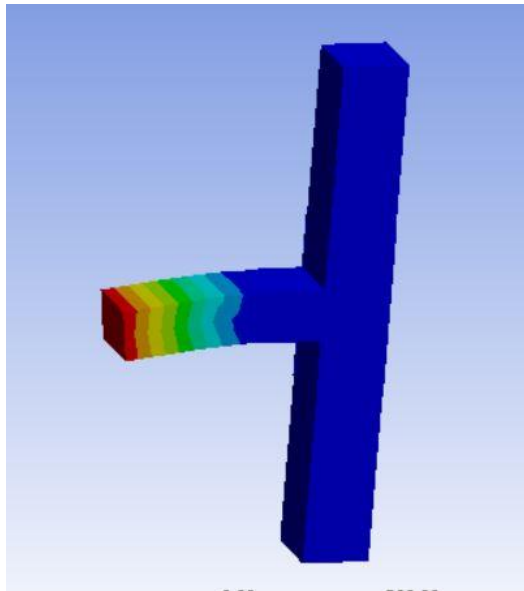
(a) Normal Beam column joint



(b) GFRP retrofitted Joint



(c) CFRP retrofitted joint



(d) Hybrid FRP retrofitted joint

Figure 6.1 Deformed model of different FRP retrofitted joint: (a) Normal Beam Column Joint, (b) GFRP (c) CFRP and (d) Hybrid FRP

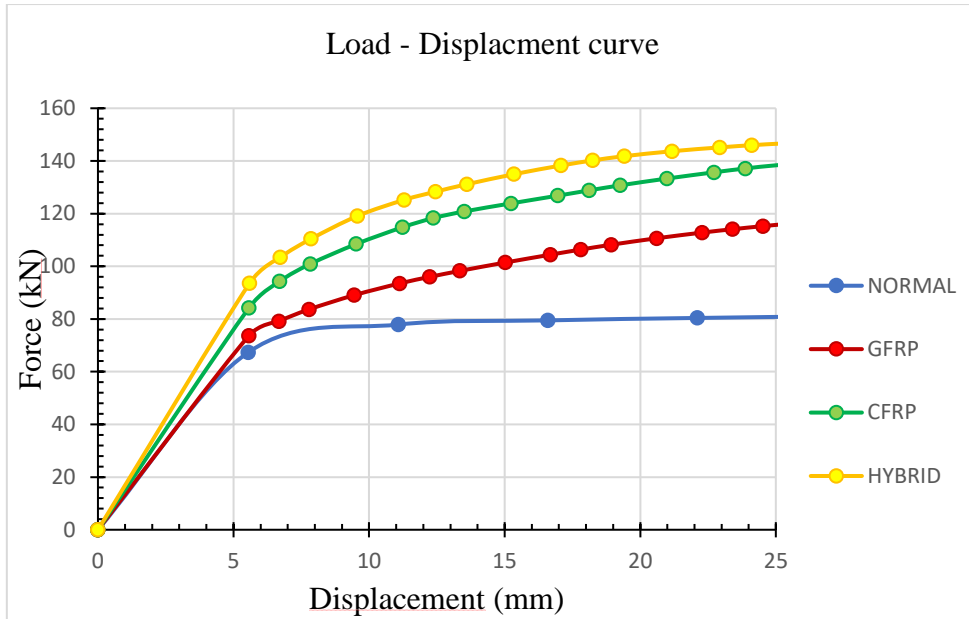


Figure 6.2 Load-displacement curve for retrofitted joint with different FRP materials

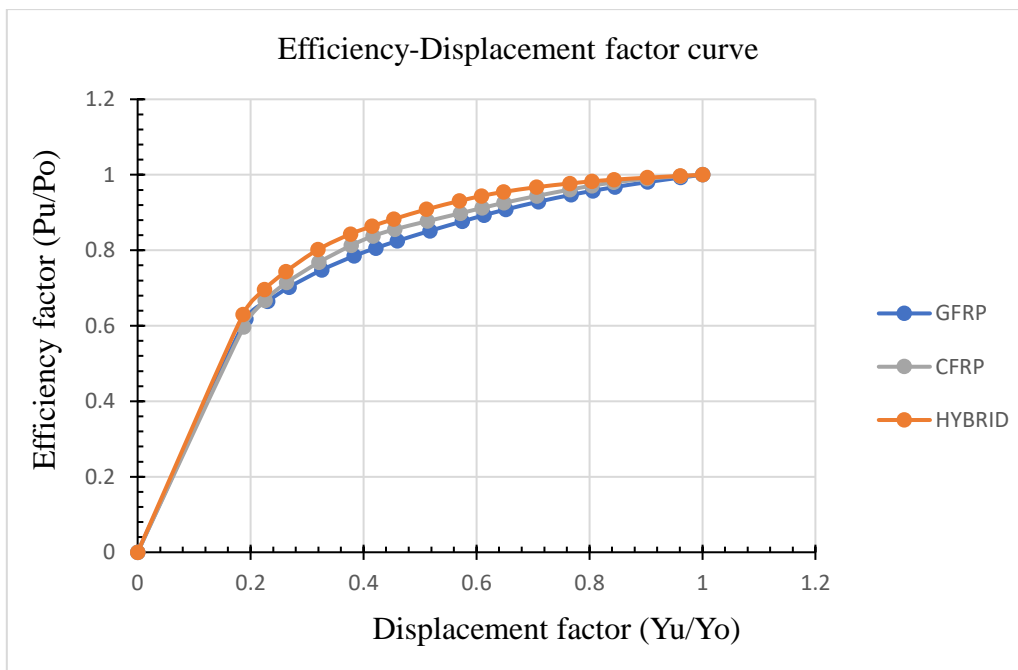
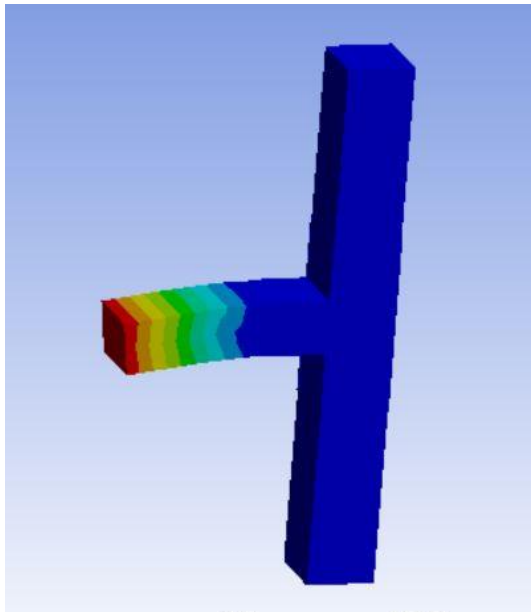


Figure 6.3 Efficiency-displacement factor curve for retrofitted joint with different FRP materials

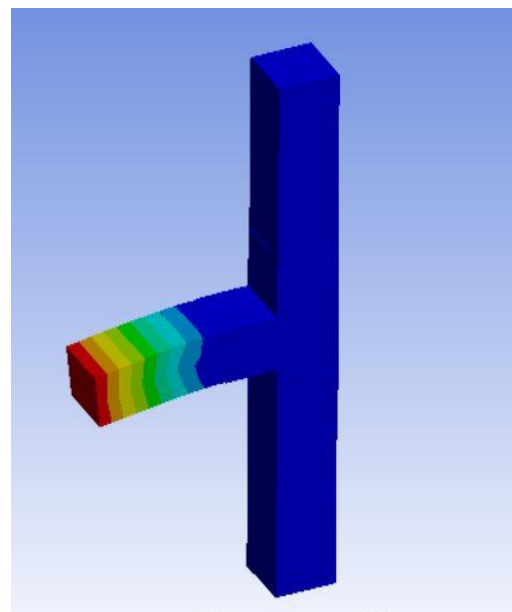
6.2.2 Different Combination of Hybrid FRP

Beam column joints are retrofitted with three styles of hybrid FRP pattern to explore the influence of hybrid FRP layer position on beam column joint performance. As first Hybrid model consisting of CFRP sheet first and second sheet as GFRP, second hybrid model contains GFRP in first layer and CFRP in second layer, and the third model is a sandwich type hybrid frp where two CFRP layer of half thickness cover

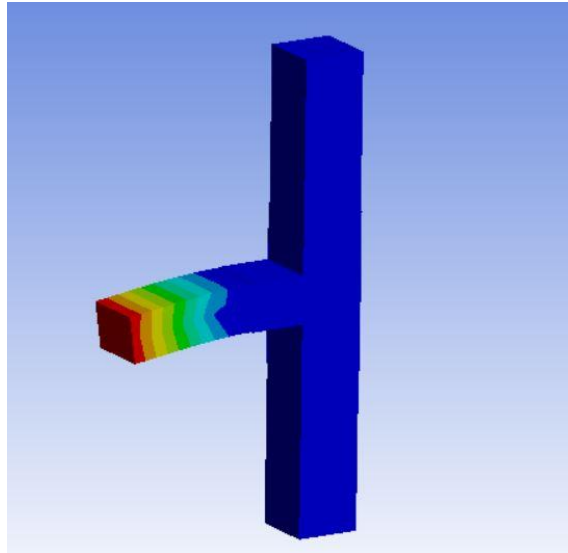
GFRP sheet. The outcomes of these three models were quantitatively examined and compared. Figure 6.4 depicts a deformed model of a retrofitted joints. Figure 6.5 depicts the load displacement curve for a beam column joint retrofitted with different hybrid positioning model. The graph indicates that there is no fluctuation in load carrying capacity when the position of the hybrid system changes. The position of materials has no effect on the hybrid system; instead, the composition of the hybrid pattern is important. Only the layers in all three models change, while the composition ratio of CFRP and GFRP remains constant. In the sandwich FRP pattern, the joint initially grows in capacity, but in the end, all models exhibit comparable behaviour. As shown in figure 6.6, the variation of the efficiency factor and load factor curve for the retrofitted joint is similar in all three cases, indicating that the result is correct.



(a) CFRP at bottom and GFRP at top



(b) CFRP at bottom and GFRP at top



(a) CFRP at top and bottom and GFRP at middle

Figure 6.4 Deformed model of retrofitted joint with different combinations of hybrid FRP :(a) CFRP at bottom and GFRP at top, (b) GFRP at bottom and CFRP at top (c) Sandwich hybrid pattern

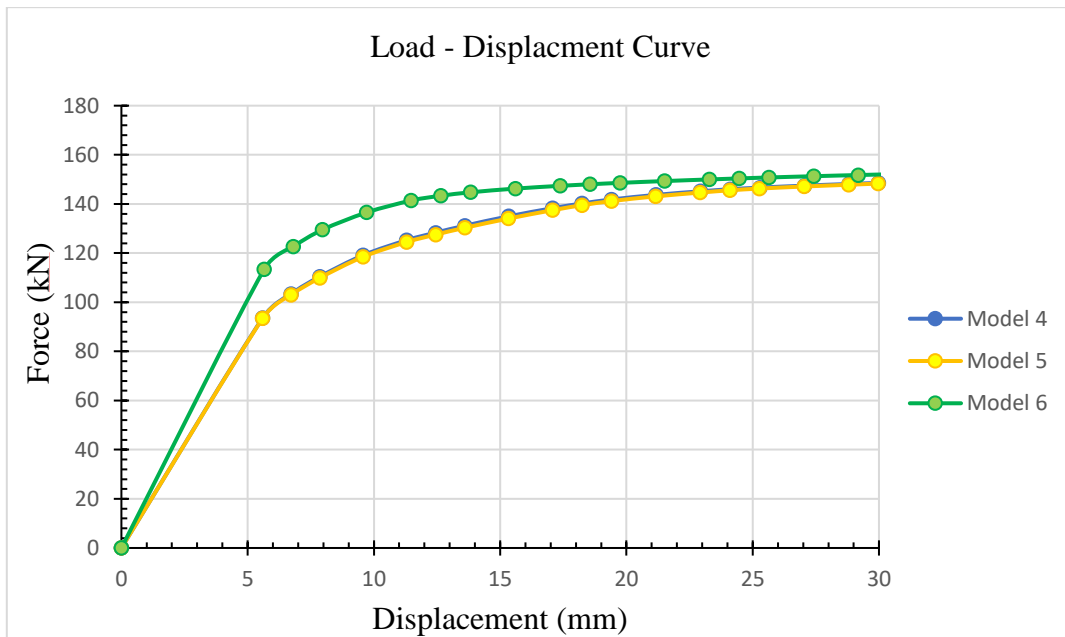


Figure 6.5 Load-displacement curve for retrofitted joint with different combination of hybrid FRP

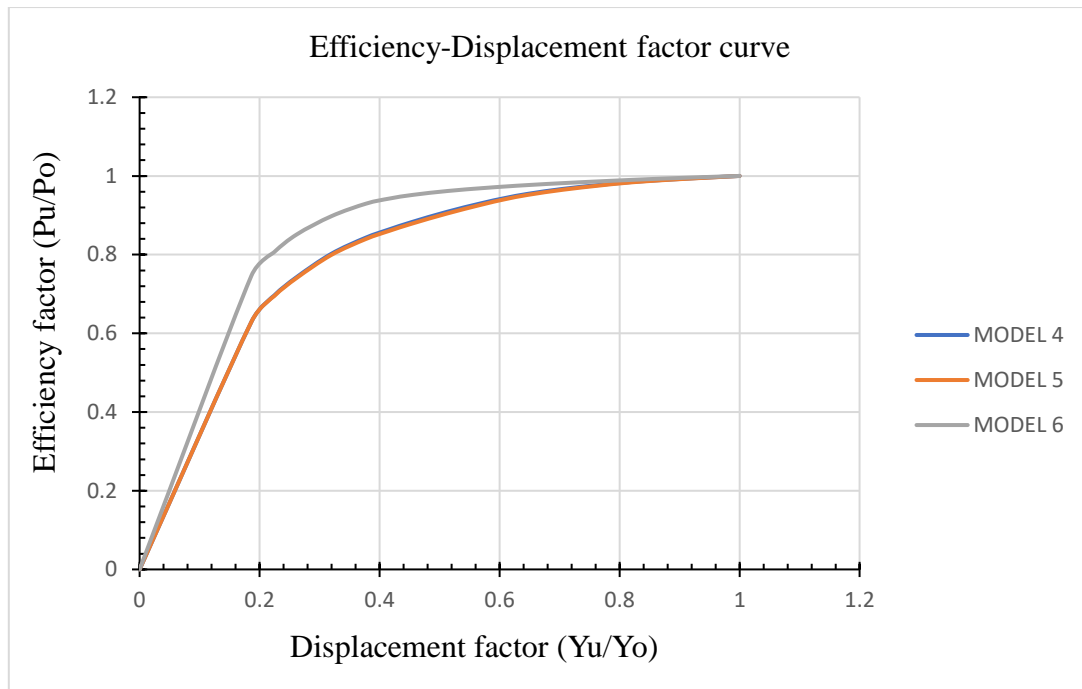
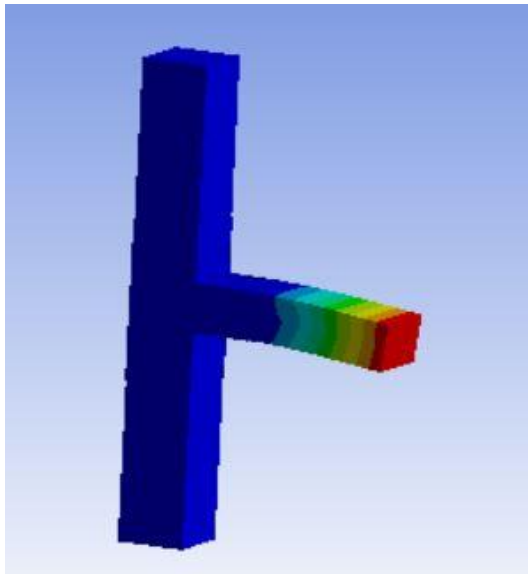


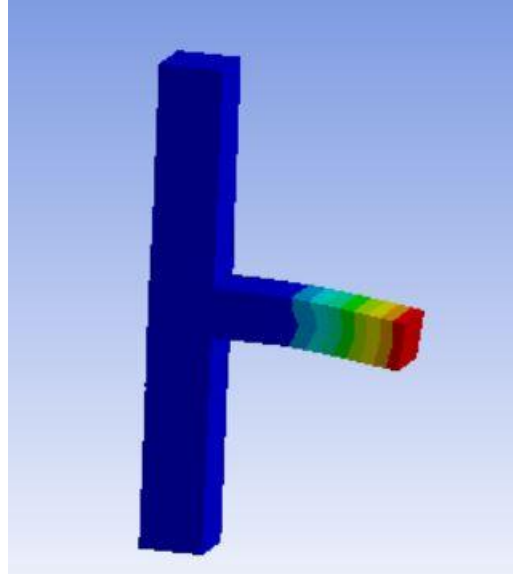
Figure 6.6 Efficiency-displacement factor curve for retrofitted joint with different hybrid FRP combinations

6.2.3 Length variation of hybrid FRP

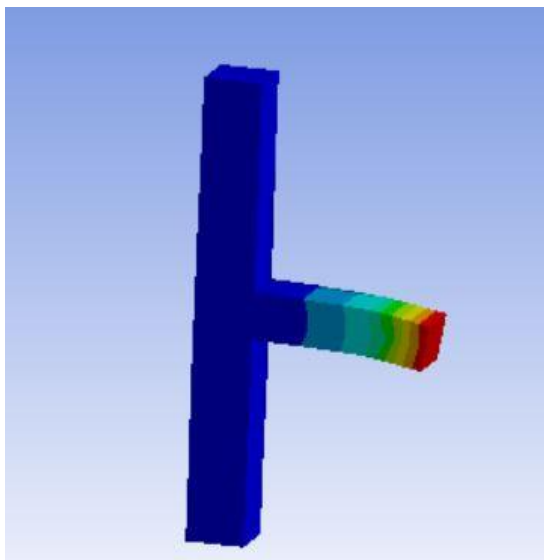
To investigate the effect of layer length variation in hybrid FRP layers on beam column joint performance, hybrid beam column joints with three different lengths are retrofitted. The first model is a hybrid FRP with two layers of the same length, the second model has a top layer of half the length and a bottom layer of the same length, the third model has two layers where the top FRP layer length is not changed and the bottom FRP layer length is doubled, and the fourth model has a top layer of half the length and a bottom layer of double length. These models are analysed and compared. The model with the longer length has a higher retrofitting capacity than the other versions. Top layer length variation has a minimal impact on beam column joint performance, however bottom layer length variation has a significant impact. A 73% improvement in load carrying capacity can be obtained by doubling the length of joints upgraded with hybrid FRP of the same length. Figure 6.7 depicts deformed models of a retrofitted joint with varying length and Figure 6.8 depicts the load displacement curve for a beam column joint retrofitted with varying length



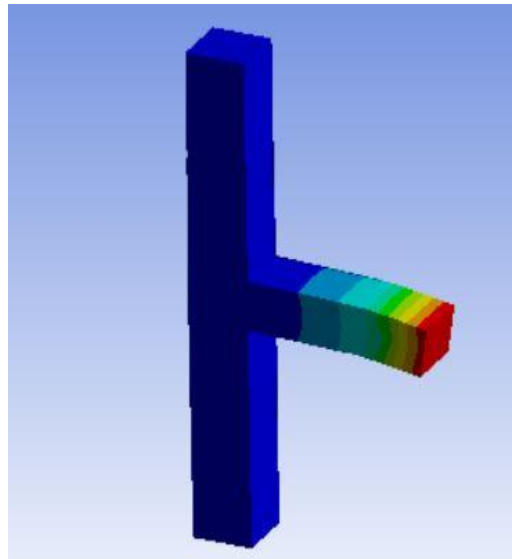
(a) Same length layers



(b) Top layer with half length



(a) Bottom layer length doubled



(b) Bottom layer doubled and top layer half length

Figure 6.7 Deformed model of retrofitted joint with varying length :(a) same length, (b) Top layer halved (c) bottom layer doubled (d) bottom doubled and top halved

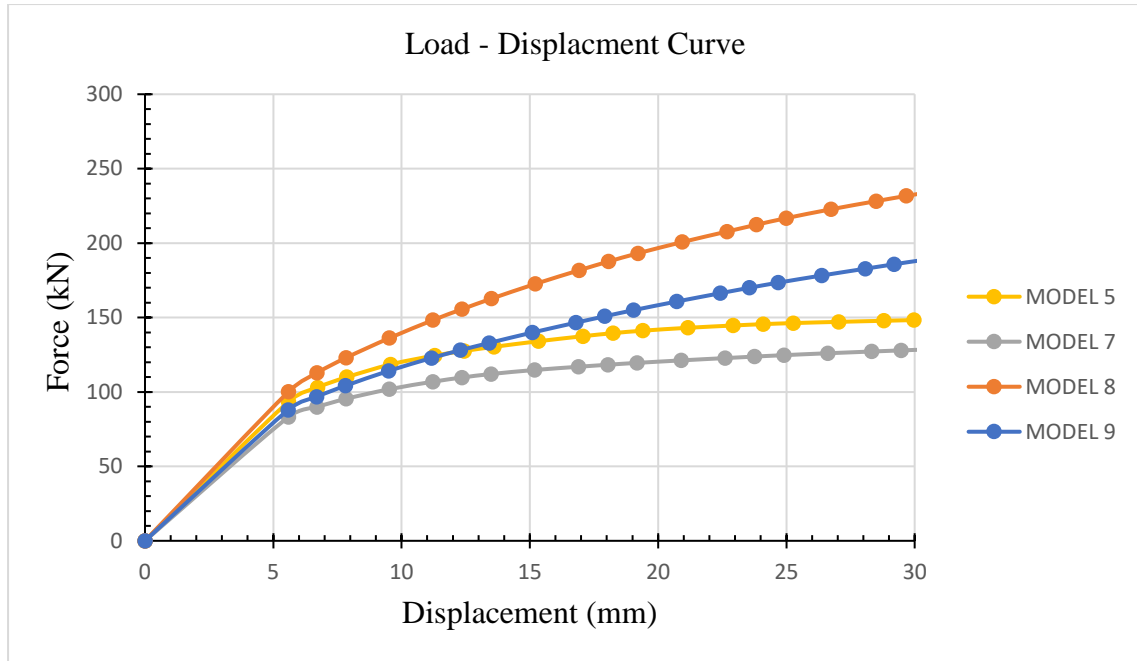


Figure 6.8 Load-displacement curve for retrofitted joint with varying length in hybrid frp models

6.4 FIRST CRACK LOAD

A beam column's first crack load is the load at which the crack begins to form. By comparing the deformed model with the load against time curve, Ansys determines the first fracture load. Figure 6.9 depicts deformed model of a beam column joint. Figure 6.10 depicts the deformed model retrofitted with Hybrid FRP. Table 6.1 compares the first crack load of each model. The first crack load of a normal beam column joint is 67.38 whereas the first crack load has increased to 93.61 for Hybrid FRP. When different combinations of hybrid FRP are compared, Sandwich Hybrid FRP have a greater first crack load than other models. Sandwich FRP pattern shows initial increased capacity but ultimate capacity for all the models remains same. In case of length variation of layers in hybrid pattern, layer with double length shows improvement by 7 kN than with the same length FRPs. The strong link produced between the injected epoxy and the concrete prevented fracture propagation within the concrete as well as crack propagation within the initially undamaged concrete of the enhanced specimen.

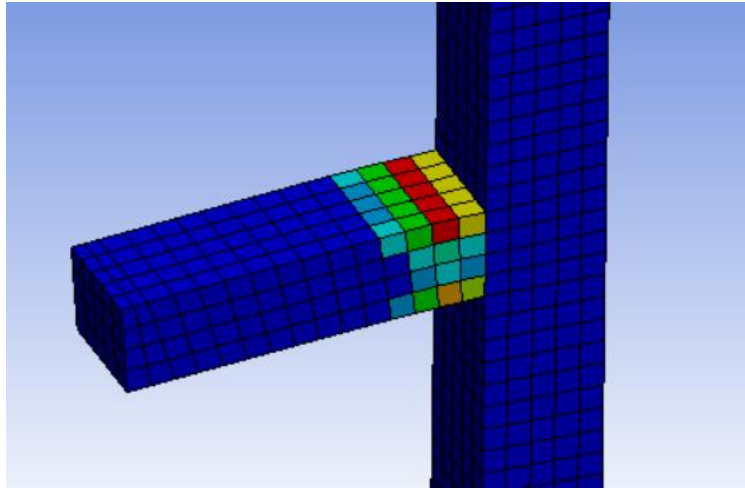


Figure 6.9 Crack formation in beam column joint

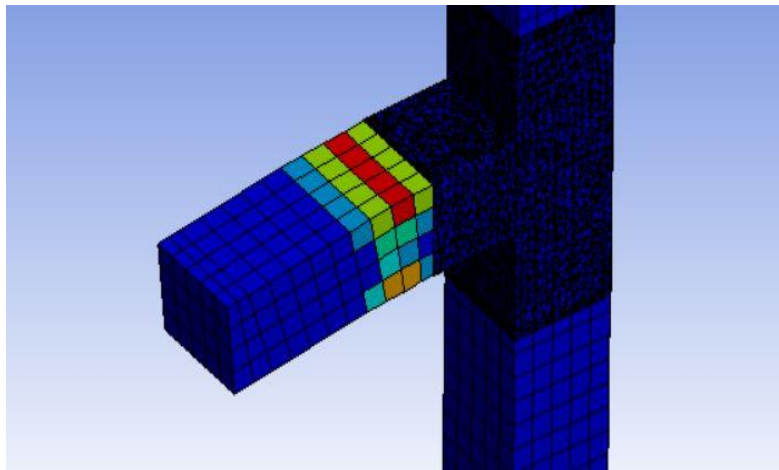


Figure 6.10 Crack formation in retrofitted model

Table 6.1 First crack load of beam column joint models

Specimen	First crack load (kN)
(a) Hybrid FRP	
Model 1	67.38
Model 2	73.60
Model 3	84.27
Model 4	93.61
(b) Different Combination of hybrid FRP	
Model 4	93.61
Model 5	93.48
Model 6	113.41
(c) Variation in Length	
Model 5	93.48
Model 7	83.13
Model 8	100.04
Model 9	87.92

6.5 Comparison of Models in Terms of Ductility, Energy Dissipation Capacity and Stiffness Degradation

6.5.1 Cyclic Loading

The analysis of specimens' load-displacement hysteretic response is crucial for assessing their seismic performance. It allows for the assessment of ductility and energy dissipation, two critical aspects of structural performance under lateral stresses. Which can be used to assess the cyclic performance of beam-column joint. Figure 6.11 depicts the cyclic loading history applied to the models. Push values are shown by positive hysteretic plots, whereas pull values are represented by negative region curves.

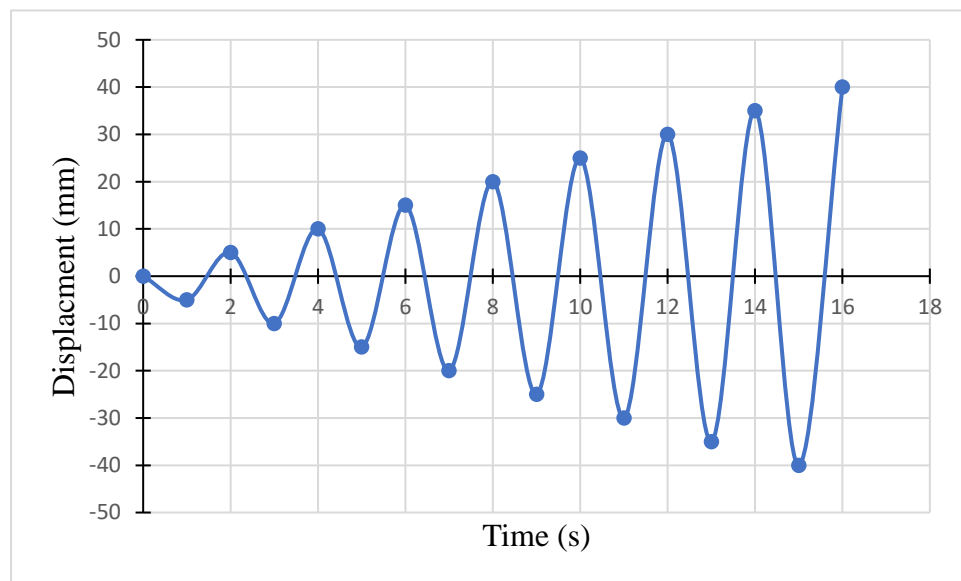


Figure 6.11 Cyclic loading history

The hysteretic behaviour of the external joint was evaluated in terms of ductility, energy dissipation capacity, and stiffness degradation. Figures 6.12–6.14 show that the ultimate loads and deformation capabilities for models retrofitted with hybrid FRP are much higher than those for regular beam column joints and single FRP wrapped joints illustrated in figure 6.12. This is primarily because externally bonded CFRP sheets promote joint confinement. The hysteresis loop in Figures 6.13 is comparable, with the same ultimate load and ultimate displacement. Taking into account the hysteresis loop of retrofitted joints of different length. As demonstrated in the figures 6.14, when the length of the FRP increases, the graph extends more than other length variations. Which indicates that as the length of retrofitting increases, so does the final capacity of joints. When the top layer length is shortened, the loop becomes smaller as the area of retrofitting is reduced. During the elastic stage, the loop's area remained steady under

both push and pull stresses. The cracking stage then started, causing stiffness loss in the specimen as the area of the loop increased with each loading cycle.

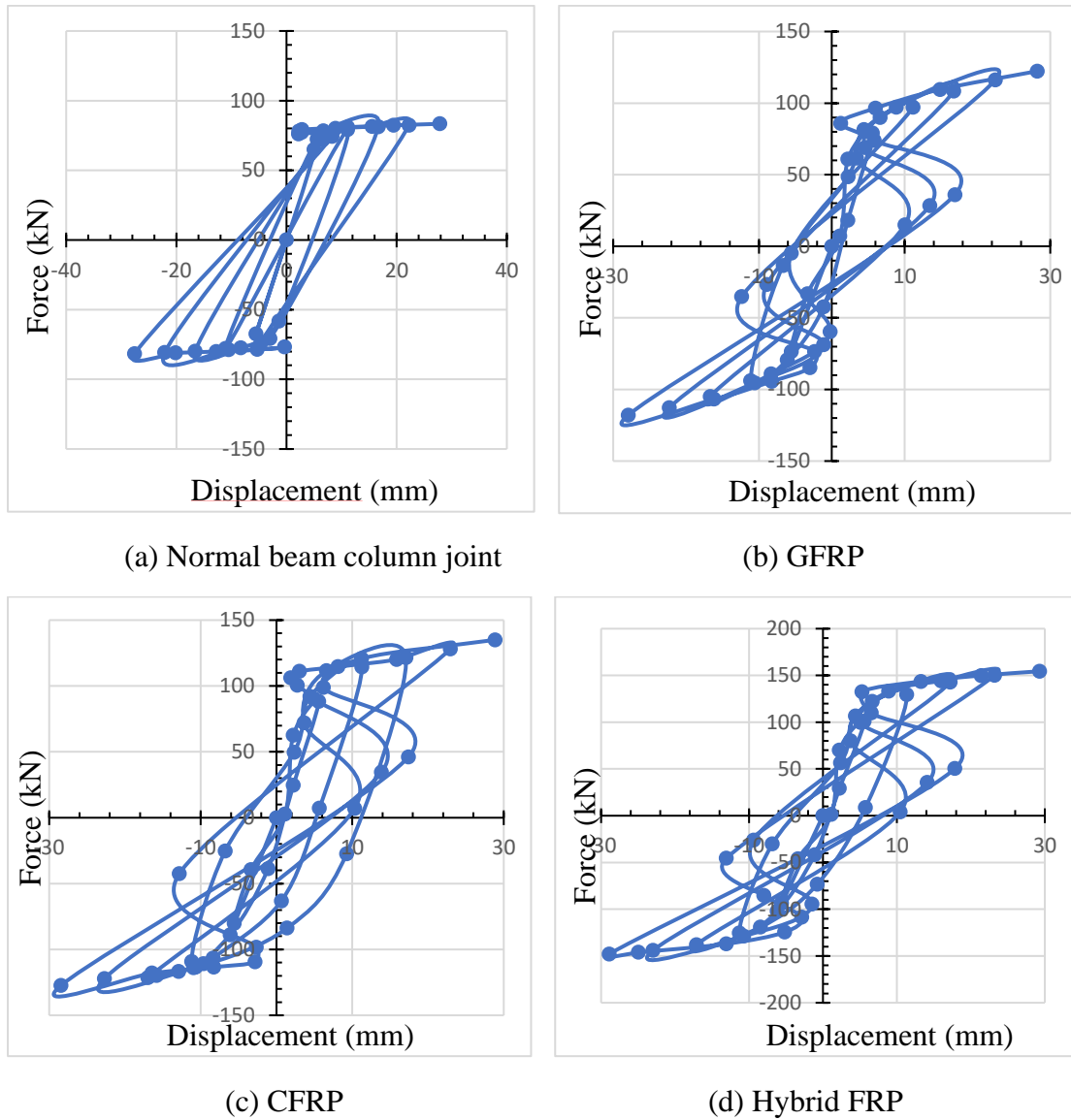
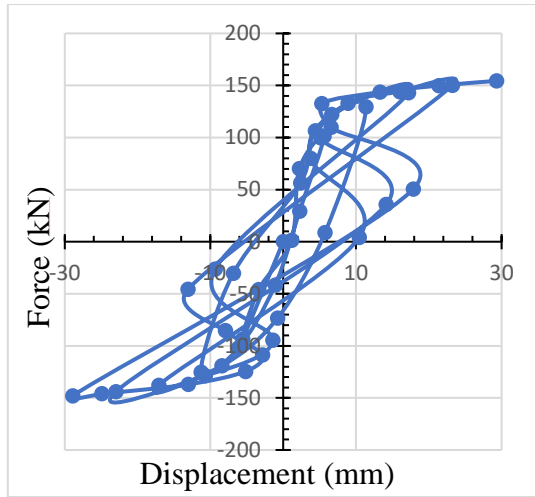
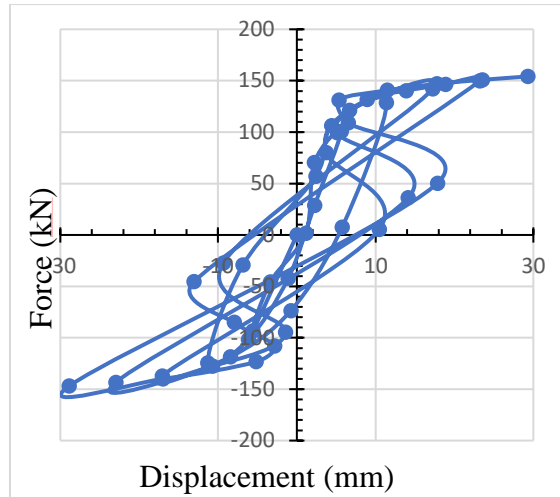


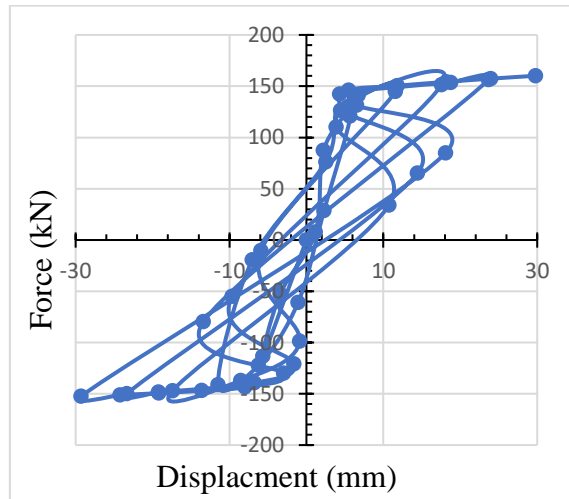
Figure 6.12 Hysteretic response of retrofitted joint with different FRP material: (a) Normal beam column joint, (b) GFRP (c) CFRP and (d) Hybrid FRP



(a) CFRP at bottom and GFRP at top

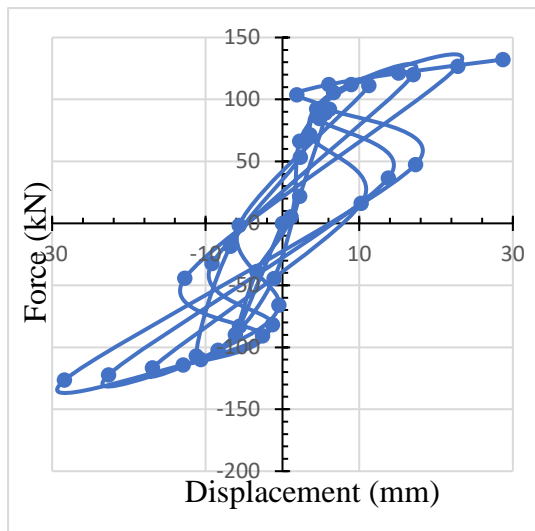


(b) GFRP at bottom and CFRP at top

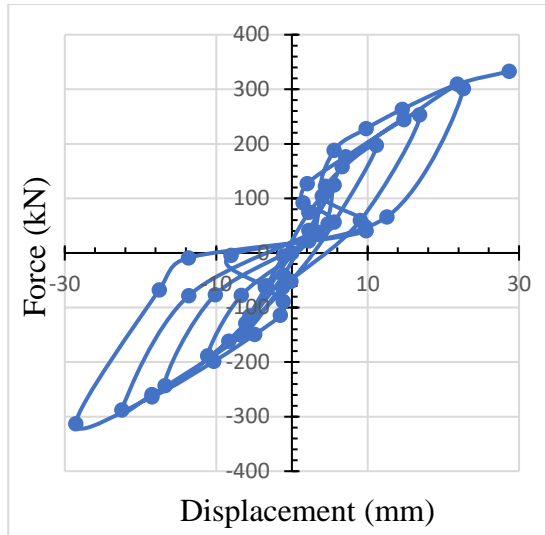


(c) Sandwich GFRP with two layers of CFRP

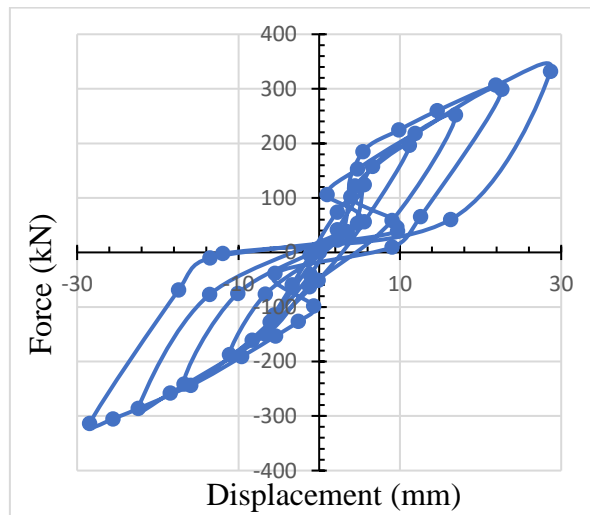
Figure 6.13 Hysteretic response of retrofitted joint different combination of hybrid FRP :(a) CFRP at bottom and GFRP at top, (b) GFRP at bottom and CFRP at top and (c) Sandwich GFRP with two layers of CFRP



(a) Top layer halved



(b) Bottom layer doubled



(c) Bottom layer doubled and top layer halved

Figure 6.14 Hysteretic response of retrofitted joint with varying length:(a) Top layer halved, (b) Bottom layer doubled and (c) Bottom layer doubled with top layer halved

6.5.2 Ductility

The ability of a structure and its elements to tolerate large inelastic deformation without appreciably losing strength is characterised as ductility. Durable structures can waste hysterically significant quantities of energy under inelastic cyclic deformations. Ductility is an important measure for quantifying a structure's or element's seismic behaviour. The method used to determine curvature ductility, commonly known as the ductility factor, is based on that given by Lee and Pan (2003). Hence, the ductility factor (μ_ϕ) can be given by:

$$\mu = d_u / d_y$$

In which: ϕ_u is the ultimate curvature of the analysed cross section; ϕ_y is the yielding curvature at the same cross section.

When the longitudinal reinforcement approaches the steel yielding stress, the yielding curvature is defined, however the ultimate curvature must be carefully chosen. Ductility is defined as the element's capacity to distort without losing considerable resistance. This section compares the ductility performance of the retrofitted models. During inelastic cyclic motions, a ductile structure can release considerable amounts of energy in a hysteretic mode. Table 6.2 shows the maximum and yield displacement values, as well as the ductility of the numerically analysed models. It can be seen that all joints had good seismic performance. The usage of hybrid FRP increases ductility as compared to retrofitting joints with single material FRP. Because CFRP is more ductile than GFRP, combining the two materials boosted the ductile capacity of the junction substantially. When different hybrid combinations are compared, all of them have the same ductility capacity. Whereas length variation has a considerable impact on joint ductility. The length of the retrofitting layer increases ductility, whereas the length of the top layer decreases ductility. Ductility is determined by the length of both layers. Ductility decreases as layer length decreases, and increases as retrofitted length increases. Table 6.2 compares the ductility ratio of each model, Hybrid FRP is very much effective in ductility improvement condition. It increases the ductility by 7.85% when compared to normal beam column joint where CFRP and GFRP can only increase by a value of 4.42 and 7.04%. When in case of Different combination all the models differ in ductility by a negligible percentage and is considered as similar ductility behaviour. In case of varying length increases in length can increase the ductility by 3.17% and when length is reduced value decreases by 1.5%. When both the case is compared that is one layer doubled and other halved ductility increases only by 0.56%.

Table 6.2 Displacement ductility factor for models

Specimen	Displacement at yield (mm)	Displacement at maximum load (mm)	Ductility factor	% Increase
(a) Hybrid FRP				
MODEL 1	5.548	27.60	4.97	-
MODEL 2	5.59	29.04	5.19	4.42
MODEL 3	5.57	29.69	5.32	7.04
MODEL 4	5.595	29.98	5.36	7.85
(b) Different combinations				
MODEL 4	5.595	29.98	5.36	-
MODEL 5	5.596	29.97	5.35	0.18
MODEL 6	5.65	30.36	5.37	0.18
(c) Variation in length				
MODEL 5	5.596	29.97	5.35	-
MODEL 7	5.587	29.47	5.27	-1.51
MODEL 8	5.586	30.84	5.52	3.17
MODEL 9	5.579	30.03	5.38	0.56

6.5.3 Energy dissipation capacity

In concrete constructions, energy dissipation includes energy dissipated by steel reinforcements, energy dissipated during crack growth, and friction between crack surfaces. Certain structural members are capable of withstanding massive deformations. As a result, they diffuse energy and mitigate the impacts of seismic pressures on the structure. When a building is subjected to a violent earthquake, a building with a better energy dissipation capability can absorb more energy, eventually ending in the building collapsing. Inelastic action causes energy dissipation. The energy dissipated in each cycle is defined as the area under the cycle in a specimen's cyclic response. The energy loss due to inelastic action in that cycle is equal to the area contained within a hysteretic loop. The higher the dissipation of energy, the fatter the

cycle. Cumulative energy dissipation is the sum of the energy dissipated in successive loops throughout the test.

Figures 6.15-6.17 depict the cumulative energy dissipation versus drift ratio for normal and retrofitted specimens. Table 6.3 displays the total energy dissipation capacity of all beam column joint models. All of the retrofitted hybrid models outperformed the standard beam column joint in terms of energy dissipation, demonstrating that the rehabilitation strategy is effective. After a 1.3 percent drift ratio, energy dissipation began to rise significantly for all the models when retrofitted with FRP sheets, as shown in figure 6.15. Hybrid FRP has an increased energy dissipation capacity than other models. This demonstrates that Hybrid FRP wrapping is an effective method for preserving and increasing the energy dissipation capacity of heavily damaged concrete elements. When considering the different combinations of hybrid FRP sandwich pattern shows a better energy dissipation performance than other two models from a drift ratio of 1.3. The remaining two models with two layers containing CFRP and GFRP combination shows similar graph denoting no significance change in performance as in figure 6.16. In case of varying length of FRP layers, upto drift ratio of 0.9 all the models show similar performance but after this drift ratio FRP with increased layer shows reduction in its energy dissipation ability. As the layer length reduces it increases energy dissipation by small amount which can be considered negligible due to small change and can be assumed as constant as shown in Figure 6.17. At a drift ratio of 4.8 percent, the improvement in energy dissipation for GFRP, CFRP and hybrid FRPs was 21 percent, 84% and 91% higher than that of normal beam column joint. At a drift ratio of 5.19 percent, Model with 2 layers of hybrid system have same energy dissipation property and in sandwich hybrid pattern it increases by 16.4%. At a drift ratio of 4.9 percent, the energy dissipation capacity of increasing the FRP layer length increases by 34% than providing FRP with same length FRP layers. It was determined that joints rehabilitated using the proposed strengthening system dissipate more energy than the control when subjected to large lateral displacements of other structural members, ensuring the structure's safety

Table 6.3 Total energy dissipation capacity of models

Specimen	Total Energy Dissipation Capacity (kNm)
(a) Hybrid FRP	
MODEL 1	1.86
MODEL 2	2.24
MODEL 3	3.45
MODEL 4	3.56
(b) Different combinations	
MODEL 4	3.56
MODEL 5	3.58
MODEL 6	3.98
(c) Variation in length	
MODEL 5	3.58
MODEL 7	3.52
MODEL 8	4.54
MODEL 9	4.51

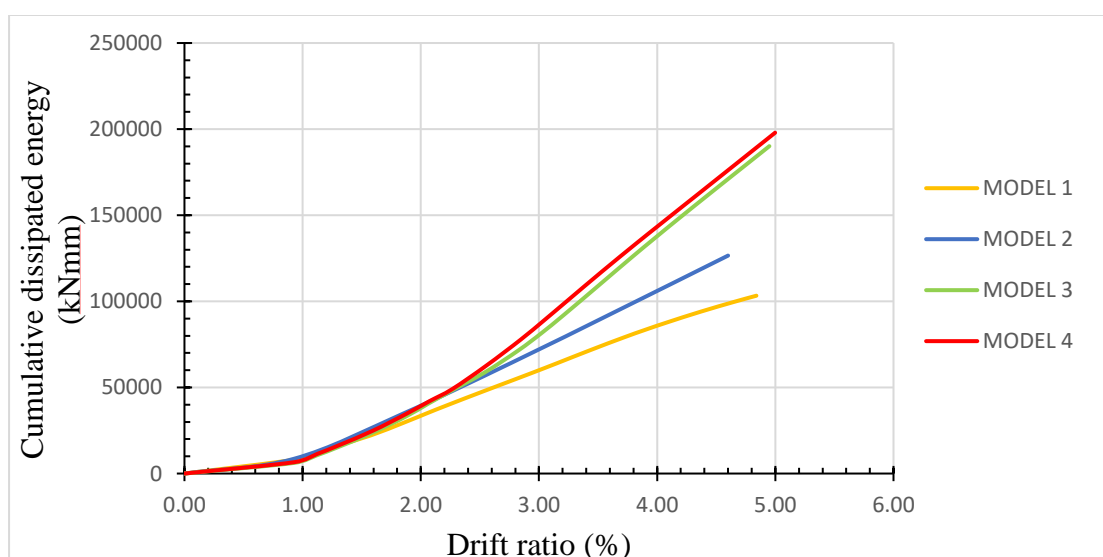


Figure 6.15 Cumulative energy dissipation against drift ratio for retrofitted joint with different FRP materials

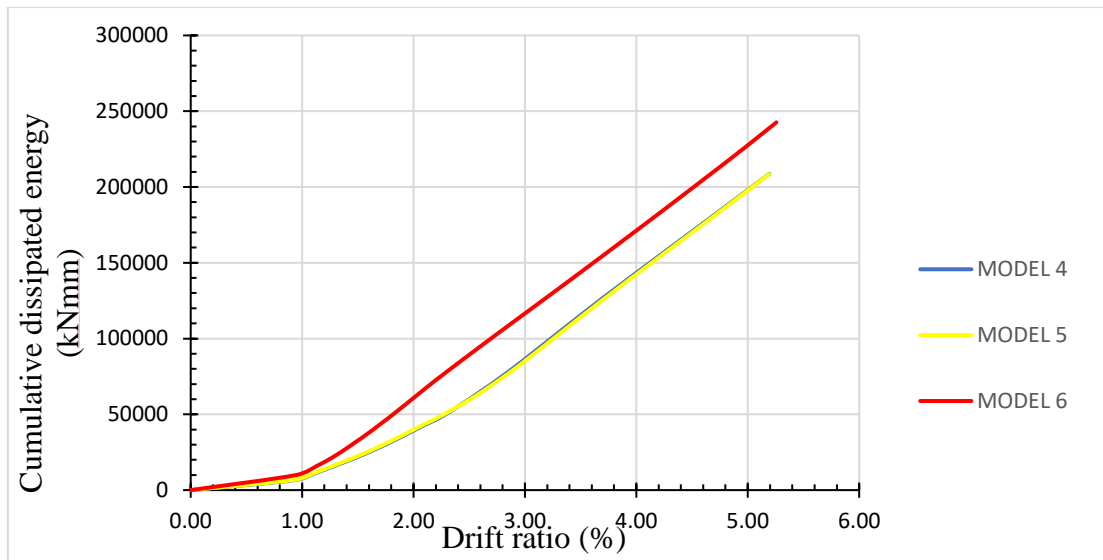


Figure 6.16 Cumulative energy dissipation against drift ratio for retrofitted joint with different combinations of hybrid FRP

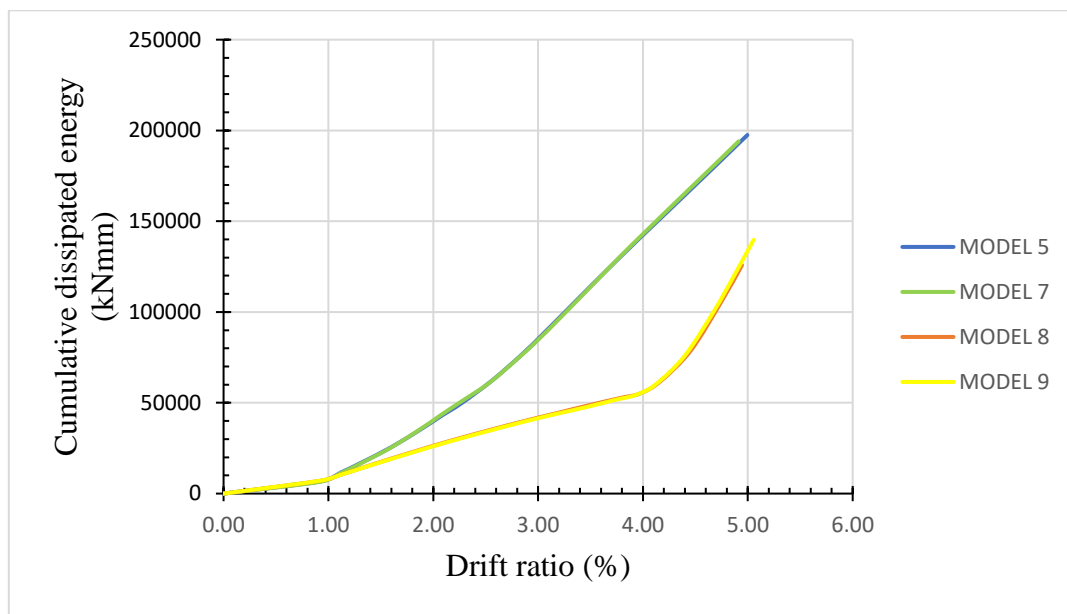


Figure 6.17 Cumulative energy dissipation against drift ratio for retrofitted joint with varying FRP length

6.5.4 Stiffness degradation

Stiffness degradation is the decrease of stiffness when the lateral movement of a structure increases. In other words, when the load on the specimen increases, the required force for a given displacement reduces. Flexural and shear cracks, shear deformation of the connection core, loss of cover, concrete nonlinear behaviour, longitudinal rebar yielding, concrete compression failure, longitudinal rebar slippage, longitudinal steel failure or buckling, and second-order forces all erode a concrete

structure's stiffness. The low rate of strength degradation is crucial for RC constructions in mild earthquakes, when non-structural materials can sustain some damage but structural elements must be strong enough to remain elastic and avoid destruction. The increased initial stiffness and lower rate of stiffness degradation will improve the behaviour of the beam column joint during an earthquake. In general, as the cycle numbers increase, the stiffness of the beam column joint decreases gradually. As a result, at each drift ratio, the joint cyclic stiffness is defined as the slope of the line connecting the maximum points of the first reversal cycle in the lateral load-displacement response, which can be expressed as follows:

$$K_{i=} (P_i^+ - P_i^-) / (d_i^+ - d_i^-)$$

where P_i and d_i are the maximum load and corresponding displacement in either the positive or negative direction. Table 8.4 shows the initial stiffness value for each model. Figures 6.18-6.20 show the stiffness degradation versus drift ratio of different hybrid FRP. In case of hybrid FRP, the initial stiffness is more than the other materials stiffness, but eventually it degrades and reaches value lesser than single material. Which describes that stiffness degradation of Hybrid FRP is more than other models. Which shows the effectiveness of material in reducing the stiffness. This is due to the fact that the retrofitted specimen was created by externally bonding FRP sheets to an undamaged concrete specimen. Almost all retrofitted specimens in the case of different combinations shows similar stiffness characteristic. Sandwich hybrid system shows increase in the stiffness than other two models as in figure 6.19. In case of varying length stiffness of layer with double length has more stiffness. As the length of top layer decreases stiffness shows a decrease than its original form. as shown in figure 6.20.

Table 6.4 Initial stiffness of models

Specimen	Initial stiffness (kN/mm)
(a) Hybrid FRP	
MODEL 1	12.14
MODEL 2	13.22
MODEL 3	15.12
MODEL 4	16.73
(b) Different combinations of hybrid FRP	
MODEL 4	16.73
MODEL 5	16.70
MODEL 6	20.06
(c) Variation in length	
MODEL 5	16.70
MODEL 7	14.88
MODEL 8	17.91
MODEL 9	15.76

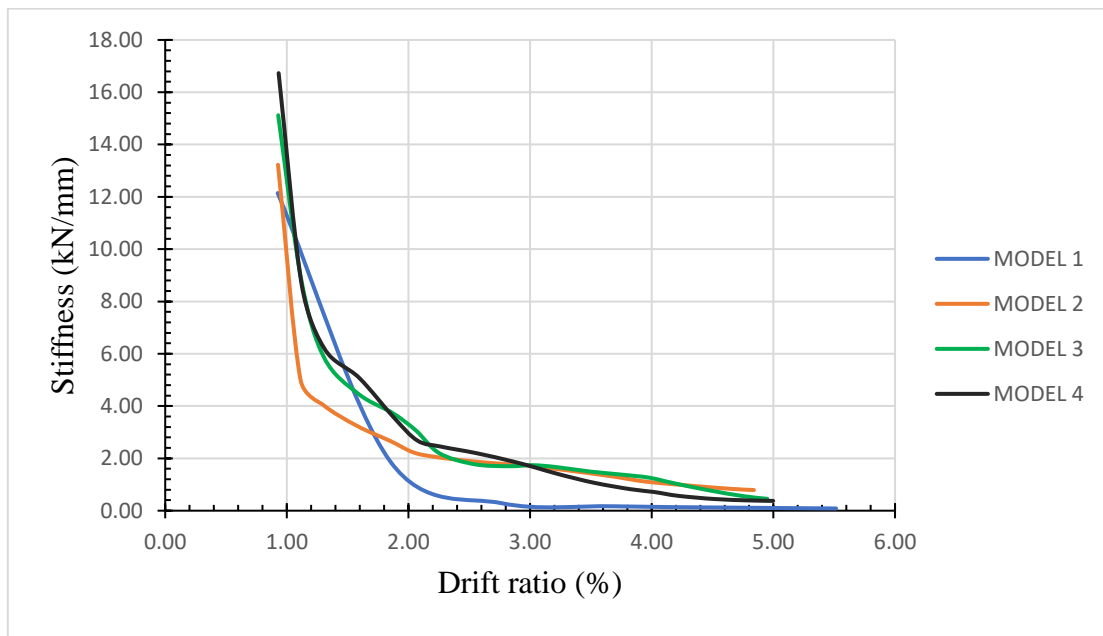


Figure 6.18 Stiffness degradation against drift ratio curve for retrofitted joint with different FRP materials

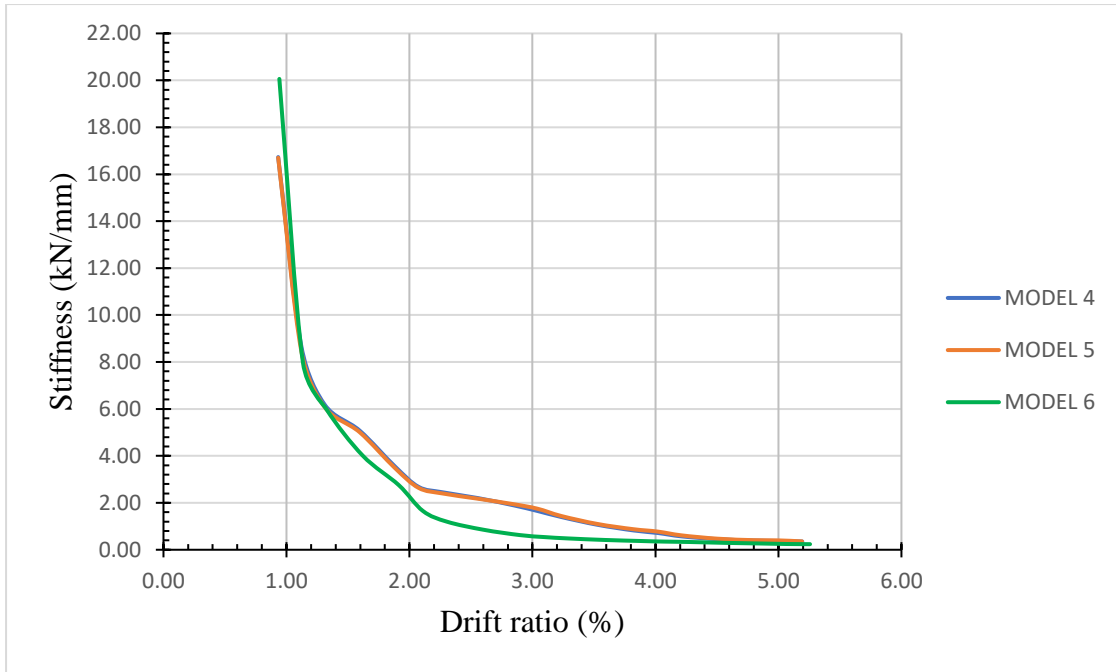


Figure 6.19 Stiffness degradation against drift ratio curve for retrofitted joint with different combinations of Hybrid FRP

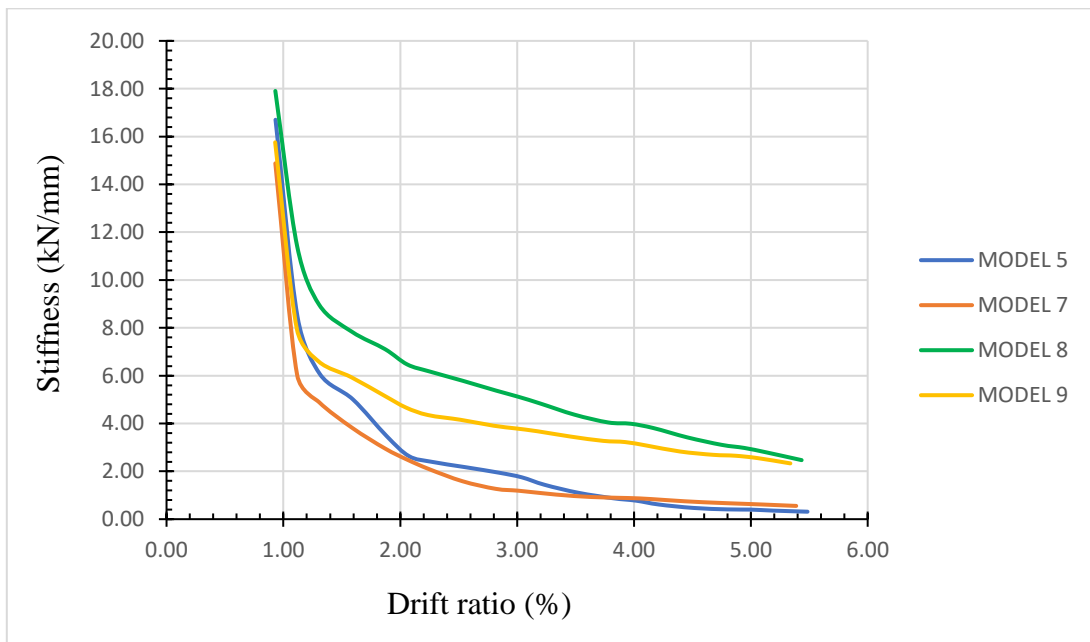


Figure 6.20 Stiffness degradation against drift ratio curve for retrofitted joint with varying length of FRP layers

Chapter 7

Conclusion

FRP wrapping has been shown to be a superior retrofitting approach. As a result, a hybrid combination of GFRP and CFRP is investigated to determine the effectiveness of the hybrid system in comparison to single FRP wrapping. In the first phase of the research, a hybrid FRP is compared to a standard and single material FRP retrofitted beam column joint.

- Hybrid FRP wrapping outperforms traditional retrofitting
- It has high load carrying capacity, ductility, energy absorption and stiffness than normal beam column joint

Next, we determined the optimal hybrid FRP system combination, in which layers of hybrid systems are modified in different patterns.

- The sandwich pattern of hybrid FRP has been shown to be a superior hybrid model.
- In terms of load carrying capability, all patterns exhibit similar behaviour; however, for ductility, energy dissipation, and stiffness, sandwich Hybrid is superior.
- The load carrying capability of a specimen is determined by the hybrid's composition rather than the placement of each element in the hybrid system.

We then investigated the effect of retrofitting hybrid layer length. For which investigations are undertaken on FRP layers with doubled and halved lengths and are compared to FRP layers of the same length.

- Increasing the length of the retrofitting layer improves the performance of the retrofitted specimen, whereas decreasing the length decreases the performance.
- Bottom layer length contributes more towards the behaviour of retrofitting as it is in contact with the concrete surface.
- As length grows, so does ductility, energy dissipation, and load carrying capability, but stiffness decreases.
- Variation in top layer length has little influence on stiffness. The length of the bottom layer has a greater impact on stiffness.

Each retrofitting method has advantages and disadvantages. While retrofitting, methods should be selected in accordance with the strengthening objective. Combining two strategies can be quite effective in achieving one or more goals. As a good material for retrofitting, FRP can be used with other materials to get additional properties. When compared to GFRP, CFRP is significantly more expensive. Therefore, it is more cost-effective to add GFRP to it than to use two layers of CFRP sheets. The study looks at the impact of length and FRP layer combinations on strengthening, which can be used to obtain the required joint capacity that is needed while strengthening.

7.2 Future Scope

The proposed study has its own limitations which should be taken into consideration in future works. Future studies should focus on the following:

- Sandwich Hybrid model studies can be concentrated
- Layer-by-layer overlap in a hybrid system and single layer hybrid compositions can be compared
- Factors such as hybrid system orientation, thickness, and placement effect can be targeted.

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