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Finite Element Analysis of Beam – Column Joints Reinforced with GFRP Reinforcements

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Abstract

Glass Fibre Reinforcement Polymer (GFRP) reinforcements are currently used as internal reinforcements for all flexural members due to their resistance to corrosion, high strength to weight ratios, the ability to handle easily and better fatigue performance under repeated loading conditions. Further, these GFRP reinforcements prove to be the better alternative to conventional reinforcements. The design methodology for flexural components has already come in the form of codal specifications. But the design code has not been specified for beam-column joints reinforced internally with GFRP reinforcements. The present study is aimed to assess the behaviour of exterior beam-column joint reinforced internally with GFRP reinforcements numerically using the ABAQUS software for different properties of materials, loading and support conditions. The mechanical properties of these reinforcements are well documented and are utilized for modelling analysis. Although plenty of literature is available for predicting the joint shear strength of beam-column joints reinforced with conventional reinforcements numerically, but no such study is carried for GFRP reinforced beam-columns joints. As an attempt, modelling of beam-column joint with steel and with GFRP rebars is carried out using ABAQUS software. The behaviour of joints under monotonically increasing static and cyclic load conditions. Interpretation of all analytical findings with results obtained from experiments. The analysis and design of beam-column joints reinforced with GFRP reinforcements are carried out by strut and tie model. Strut and Tie models are based on the models for the steel reinforced beam-column joints. The resulting strut and tie model developed for the GFRP reinforced beam-column joints predicts joint shear strength. Joint shear strength values obtained from the experiments are compared with the analytical results for both the beam-column joints reinforced with steel and GFRP reinforcements. The joint shear strength predicted by the analytical tool ABAQUS is also validated with experimental results.

Keywords: Reinforced Concrete; Beam-column Joint; GFRP Reinforcements; Failure Mechanism; ABAQUS; Strut and Tie Model.

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1. Introduction

Recent developments in *concrete composites* have resulted in several new products which aim to improve the strength, stability and Serviceability of the concrete structures. In general, the structural system comprises of *structural elements* (load-carrying, such as beams and columns) and non-structural elements (such as partitions, false ceilings, doors). The function of the structural elements is to resist efficiently the action of gravity and environmental loads, and the serviceability of the structure without significantly disturbing the geometry and integrity. In the viewpoint of simplified analysis as one-dimensional skeletal elements such as beams, columns, arches, truss elements or two-

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dimensional elements such as slabs, plates and shells are considered. A few structural elements such as beam-column junctions, perforated shear walls may require more rigorous analysis.

In many such instances, where the behaviour of system cannot be predicted, a useful procedure is to idealise the member or region as a series of reinforcing steel tensile ties and concrete compressive struts, interconnected at nodes to form a truss capable of transmitting the loads to the supports, and detailing the reinforcement accordingly. This *strut-and-tie* concept is depicted. It is a very basic concept in structural design that, for transferring a system of loads to the supports, any stable skeletal framework such as a truss, grid, arch or catenary, compatible with the actual deformation pattern, may be delineated, and the members and their joints designed for the resulting forces thereon. The skeleton (or truss/arch/catenary) may be either explicit and externally visible, as in a real truss, or implicit and embedded within a member, as in the case of the truss analogy for shear design of concrete beams and the truss analogy for plate girder design. Technology advancement forces Fibre Reinforcement Polymer (FRP) composites as vital building material especially under aggressive environmental conditions. FRP material is currently used as reinforced for concrete structures in which corrosion protection is a primary concern. FRP material is corrosion resistant and exhibit several properties that make them suitable as structural reinforcement.

Fibre Reinforced Polymer (FRP) materials are well recognized as a vital constituent of the modern concrete structures. The superiority of the FRP materials, in comparison with other conventional building materials like steel, cast iron and reinforced concrete, lies in its improved structural performance, in terms of stability, stiffness, strength (including improved resistance to fatigue loading) and durability [1-3]. Commercially, these FRP materials take the form of cables, sheets, plates etc. FRP materials are now being used in large numbers in many countries, including India, where, after a nascent beginning in 1950, the manufacture of FRP materials has become a major industry. In this context, the need for economical and reliable designs of FRP reinforced concrete structure gains importance. Most of the research efforts, particularly in the early years, have been directed towards the strengthening of masonry and concrete structures with FRP strips, sheets and fabrics [4, 5]. Significant research work (experimental as well as theoretical) has also been achieved in strengthening and retrofitting of diseased concrete structures [6, 7]. However, the use of Hybrid FRP reinforcements in concrete structures, especially the joint behaviour and formulation of design specifications are not well explored and remains still as research area.

From the literature review, it is understandable that enough work has been done in the area of GFRP wrappings of beam-column joints for retrofitting and rehabilitation purposes but the study on the use of non-metallic bars for beam-column joint applications is very scarce. Recently, non-metallic reinforcements are finding greater importance in structural applications in abroad. Despite their successful introduction into the construction industry, widespread acceptance of non-metallic reinforcements by the engineering industry depends on timely development of design guidelines and specifications.

This introduction chapter covers the classification of joints, failure mechanism, Strut and tie model, Glass fibres, manufacturing process and their structural application.

1.2. Classification of Joints

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.

1.2.1. Interior Joint

When four beams frame in to the vertical faces of a column, the joint is called as an interior joint. The effect of loads on the joints, the forces on an interior joint subjected to gravity loading can be depicted as shown in Figure 1a. The tension and compression from the beam ends and axial loads from the columns can be transmitted directly through the joint. In the case of lateral (or seismic) loading, the equilibrating forces from beams and columns as shown in Figure 1b develop diagonal tensile and compressive stresses with in the joint. Cracks develop perpendicular to the tension diagonal A-B Figure 1b in the joint. The compression struts and tension ties are shown by dashed lines and solid lines.

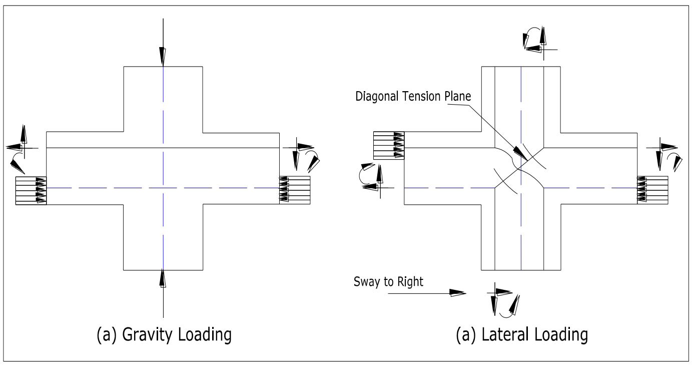


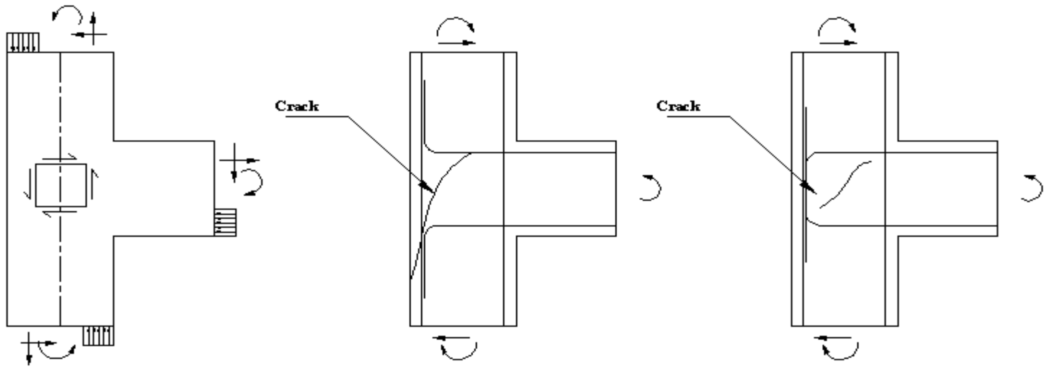
Figure 1. Interior joint

1.2.2. Corner Joint

In a beam when each frames in to two adjacent vertical faces of a column, then the joint is called as a corner joint. Wall type corners from another category of joints where in the applied moments tend to either close or open the corners. Such joints may also be referred as knee joints or L-joints. The stresses and cracks developed in such a joints are shown in Figures 2(a, b, c).

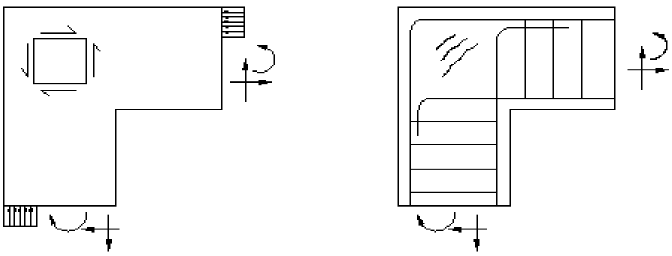
A typical knee joint, subjected to an "opening" bending moment and corner responding actions shown in Figure 3 a, b. It may be noted that the joint is usually subjected to axial forces and shearing forces, in addition to the bending moment. Opening corner joints tend to develop nascent cracks at the re-entrant corner and failure made by the formation of a diagonal tensile crack.

A typical knee joint, subjected to a "closing" bending moment and corner responding actions shown in Figure 4 a, b. The forces developed in a closing joint are exactly opposite to those in an opening corner joint. The major crack is oriented along the corner diagonal. These joints show better efficiency than the opening joints.



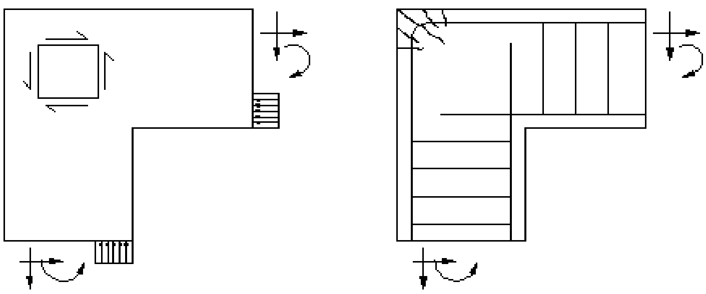
(a) Forces (b) Bars bent away from joint (c) Bars anchored in the joint

Figure 2. Exterior joint



(a) Forces (b) Cracks in an opening joint

Figure 3. Knee joint subjected to 'Opening' moment



(a) Forces (b) Cracks in an closing joint

Figure 4. Knee joint subjected to 'Closing' moment

ACI–ASCE committee recommendations classify the beam-column joint in two categories based on loading conditions and anticipated deformation.

Type 1 joints: These are designed on the basis of strength without considering special ductility requirements.

Type 2 joints: These are designed to have sustained strength under deformation reversals in to inelastic range.

Any joint in structural frame designed to resist gravity and normal wind loads falls in to type-1 category. Joint in framed structures designed to resist lateral loads due to earthquake, blast and cyclonic winds falls in to type 2 categories.

1.3. FRP Materials

FRP materials are generally classified according to resin type, fibre type and fibre architecture. The various types of FRP reinforcements available in the market are shown in Figure 5.

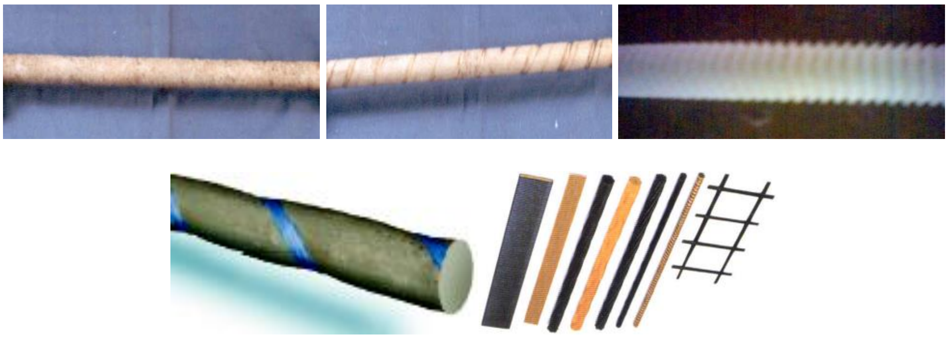


Figure 5. Various types of FRP reinforcements

A report for the use of FRP composites as an internal reinforcements for flexural members. Based on this report, the following points have been arrived at (i) The mechanical properties of FRP bars are typically quite different from those of steel bars, (ii) FRP bars have lesser weight, lower young's modulus but higher strength than steel, (iii) The density of FRP bars is found to be one sixth to one fourth lesser than that of steel [8]. The bond mechanism of FRP reinforcements with concrete under cyclic loading conditions. FRP reinforcements in five different forms are surrounded in concrete blocks and are subjected to a stress level at service nearly 4, 50,000 cycles. Pull out tests have been conducted at the end of the cyclic loading [9]. A simplified reinforced constitutive model based on smeared cracks concept. The model is combined by a compression, a tension and a shear constitutive model for concrete and a constitutive model for steel bar. The simplified constitutive model has fewer parameters and simpler hysteresis loops [10].

The seismic performance of joint in lightly reinforced concrete frames were studied. Mainly focussed on effect of joint rotation, column axial load, cross-reinforcement in the joint and percentage of longitudinal reinforcement in the beam [11]. The beam-column joint model under reversed-cyclic loading which provides a simple representation of the primary inelastic mechanisms. The mode of failure mainly due to anchorage failure of beam [12]. A new analytical model for beam column joint to represent the shear behaviour within the joint panel zone by establishing shear stress - shear deformation history envelope with salient response points, which forms the backbone for the primary curve of the strength - deformation model for joints in non - linear dynamic analysis computational tool [13]. In RC Beam-column joints were cast with adequate and deficient bond of reinforcements. FRP sheets and strips were applied on the joints in different configurations and the columns are subjected to an axial force while the beams are subjected to a cyclic load with well-ordered displacement [14]. The behaviour of exterior beam-column joints turned out to be different from that of interior connections [15]. Various types of joints under seismic action on the critical parameters that affect joint performance mainly bond strength and transfer of shear [16]. Design procedures for the RC beam-column joints under seismic loading condition with a distinct prominence on three international codes of practice viz. ACI 318M-02, NZS 3101: 1995 and EN 1998-1: 2003 [17]. The mode of failure mainly due to concrete crushing or fiber-reinforced polymer (FRP) fracture or deboning [18]. Two types of repeated loading schemes such as constant amplitude fatigue loading (scheme I) and accelerated fatigue loading with variable amplitude (scheme II) are taken for investigation [19]. The use of the non-corrodible fiber-reinforced polymer (FRP) reinforcing bars in parking garages and road overpasses in extreme weather conditions is beneficial to overcome the steel-corrosion problems [20].

The joint without transverse reinforcement exhibits brittle behaviour during an earthquake [21]. In the Bhuj earthquake in Gujarat, the main reason for the failure of most of the structures was the failure of the beam column joints [22]. The experimental studies are confirmed with the analytical studies carried out by finite element models using ANSYS. The ferrocement playing important role for strengthened beam-column joints, it gives better structural performance compared to un-strengthened specimens [23]. Based on the experimental evidences, it can significantly affect nonlinear behaviours, i.e. bond mechanism and shear failure of joints [24]. The reduced effect of axial loading level and longitudinal steel ratio in the ultimate load level when the specimens were strengthened with ferrocement [25]. The combine the demand of the conservative use of materials and the safety requirements. The structure are needed to be designed having sufficient durability and safety as well as consuming minimum amount material. These requirements of a structural design are contradictory to each other and should be optimized [26]. The RC structures with composite materials has been widely increased in the present scenario, because of its light weight, high impact value and flexibility [27]. The shear behaviour of beam -column joints with special captivity in the joint region along with different reinforcement detailing for anchorage of beam bars, confinement in joint and additional reinforcement in beam and column, further Glass Fiber Reinforced Polymer (GFRP) is used as an external confinement [28]. The experimental behavior of full-scale beam-column space (three-dimensional) joints under displacement-controlled cyclic loading. Beam column joint subjected to seismic force will experience large shear forces, diagonal tension and high bond stresses in the reinforcement bars [29]. Hence distinctive attention need to be given for design and construction of beam column joint subjected to seismic loading. Based on the location of joint, beam-column joint are classified as interior, exterior and corner joint [30].

1.4. Objectives and Scope

Objectives of this present study are given below:

- To create a data set to form the mechanical properties of concrete, steel, GFRP reinforcements and bond properties between concrete and steel/GFRP.
- Validate the data set with already available data from literature.
- To simulate the model using ABAQUS software with the help of the following elements; Continuum Solids and rebar elements.
- To conduct the experiments to find the behaviour of beam-column joints reinforced with conventional steel and GFRP reinforcements.
- To study the joint behaviour of Joints under monotonically increasing static and cyclic load conditions.
- Interpretation of analytical findings with results obtained from experiments.

Scope of this present study is restricted to:

- Analysis of Exterior Beam-Column joint reinforced with GFRP reinforcements.
- Analysis of Beam-Column joint under static and cyclic load conditions.
- Analysis is restricted to material non-linearity.

2. Experimental Investigations

2.1. Test Program

2.1.1. Specimens

The experimental investigation consists of twelve reinforced concrete beam-column joint with various parametric conditions. The test program consists of three series of test (Series A, B and C). The specimens and their properties, loading conditions and the test parameters are listed below.

2.1.2. Test Series A

Test Series A consists of four beam-column joint specimens with identical dimensions, geometry and reinforcing arrangement. The reinforcements used in the experiment are varied vide, Threaded GFRP, sand coated GFRP, grooved GFRP, and the conventional steel. The specimen consists of beam of size 150 mm × 200 mm and column of size 200 mm × 150 mm. The height of the column is 2000 mm and the length of the beam is 1000mm. Figure 6 shows the typical beam column joint with all reinforcement details.

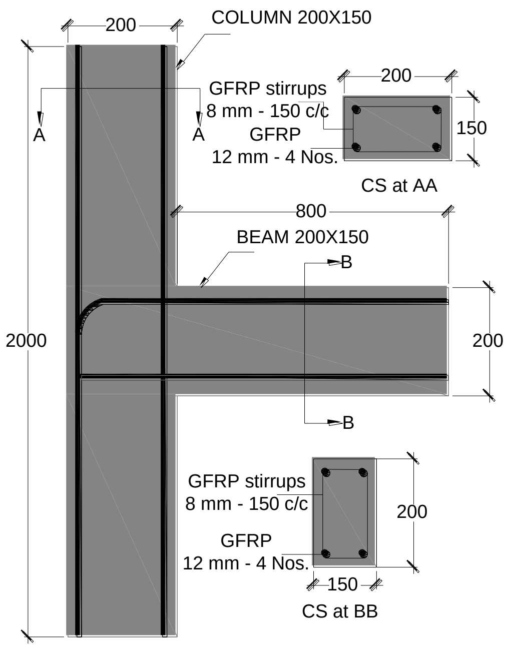


Figure 6. Typical beam-column joint with reinforcement details

2.1.3. Test Series B

Test Series B consists of four beam-column joint specimens with identical dimensions, geometry and reinforcing arrangement with two different concrete grades. The first specimen is of grade M20 and the next specimen is of grade M30. The beam and the column are reinforced with conventional steel as well as GFRP reinforcements used in this study.

2.1.4. Test Series C

Test Series C consists of four beam-column joint specimens with identical dimensions, geometry based on the provision of the shear reinforcements to the joint region. The specimens are reinforced in such a way that the joints are having with and without stirrups. The reinforcement details for both type of reinforcements are shown in Figures 7 and 8.

(a) GFRP (b) Steel

Figure 7. Beam - column joint with stirrups

(a) GFRP (b) Steel

Figure 8. Beam - Column Joint without stirrups

2.1.5. Specimen Details

- BCJSFT – Beam column joint with Threaded GFRP bars;
- BCJSFG – Beam column joint with Grooved GFRP bars;
- BCJSFS – Beam column joint with Sand coated GFRP bars;
- BCJS – Beam column joint with steel reinforcement;
- BCJS20 – Beam column joint with steel reinforcement with M20 grade concrete;
- BCJSFT20 – Beam column joint with Threaded GFRP bars with M20 grade concrete;
- BCJS30 – Beam column joint with steel reinforcement M30 grade concrete;
- BCJSFT30 – Beam column joint with Threaded GFRP bars with M30 grade concrete;

- BCJS1 – Beam-Column Joint with Steel reinforcement without joint stirrups;
- BCJFT1 – Beam-Column Joint with GFRP reinforcement without joint stirrups;
- BCJS3 – Beam-Column Joint with Steel reinforcement with joint stirrups;
- BCJFT3 – Beam-Column Joint with GFRP reinforcement with joint stirrups.

2.2. Construction

All the form works were made with steel panel. They are positioned in horizontal direction. The cages of reinforcements are installed in the formwork and mixed concrete was placed in the formwork. Figure 9 shows a typical beam column joint specimen casted in the mould with strain gauges installed in it.

Figure 9. Typical beam – column Joint specimen ready for testing

2.3. Reinforcements

Main reinforcements of column and beam were made from high yield strength deformed steel bars of 12 mm diameter for control specimens and GFRP bars of same diameter used for GFRP specimens. The control specimen is reinforced with 4 nos. of 12 mm dia. and 8mm dia. stirrups for beam and 4 nos. 12mm dia. and 8 mm dia. ties for column.

2.4. Mechanical Properties of Materials

2.4.1. Concrete

Concrete mix M20, M25 and M30 were designed as per IS recommendations. PPC was used for concrete. Locally available sand having fineness modulus of 2.75 and specific gravity of 2.57 was used as fine aggregate. Crushed stone with maximum size 20 mm having fineness modulus of 7.15 and specific gravity of 2.73 was used as coarse aggregate. Average compressive strength of 150 mm size cubes after 28 days of moist curing was found to be 38 N/mm^2, 44.22 N/mm^2 and 52 N/mm^2 respectively.

2.4.2. Steel and GFRP

The various properties of reinforcements that are related to the present study are investigated through laboratory experiments and the results are presented in table 1. The stress strain curve for HYSD bar and GFRP bars are shown in Figures 10 and 11.

Table 1. Tensile properties of reinforcements

Properties	GFRP rod (Threaded)	GFRP rod (Sand coated)	GFRP rod (Grooved)	Steel Fe 415 rod (S)
Longitudinal Tensile strength (MPa)	600	690	525	448.2
Longitudinal modulus (GPa)	42.86	57.5	35	207.5
Strain	0.014	0.012	0.015	0.002
Poisson's ratio	0.22	0.22	0.2	0.3

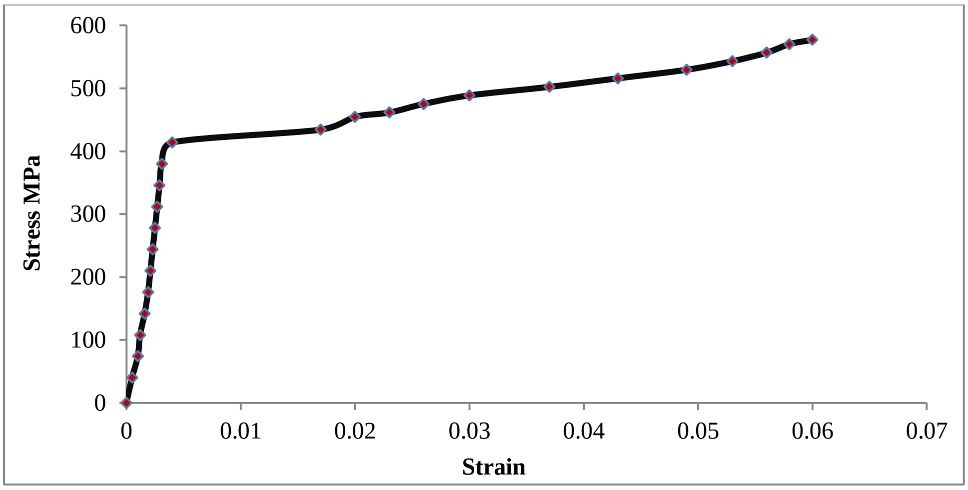


Figure 10. Stress-Strain curve for HYSD bar

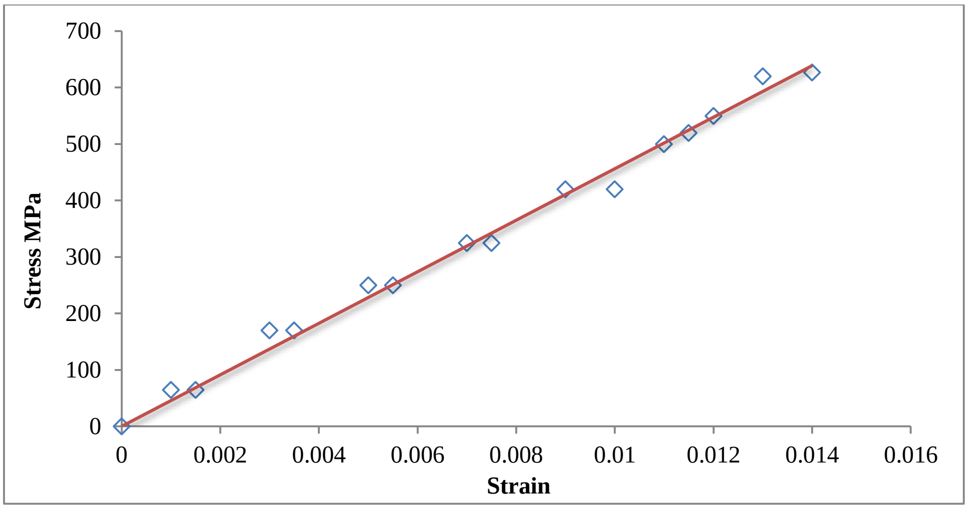


Figure 11. Stress-Strain Curve for GFRP rods

2.5. Experimental Setup and Instrumentation

The experimental setup and the instrumentation for a typical beam column joint are shown in Figures 12 and 13. Displacements on beam are measured by LVDT at the loading point and at the mid span. Another LVDT is used to measure the deflection at the mid height of the column. A hydraulic jack (capacity 10 tonnes) was used for applying a vertically downward force on top face of the beam at distance 90 mm from beam-column interface producing moment and shear force on the joint. The load increments applied on the beam was 1kN. The readings of the LVDT are recorded at regular intervals from the displacement indicator during the loading. Demec readings are also measured using Demec Gauge at five points across the joint interface. After widening of cracks, when deflections started increasing very fast, dial gauges are removed and load on the beam is increased till failure. The specimen is considered as failed when load applied on beam started decreasing. Observations are also made regarding crack formation as well as the mechanism of failure of the joint. The crack pattern for steel and GFRP specimens are shown in Figure 14 and 15.

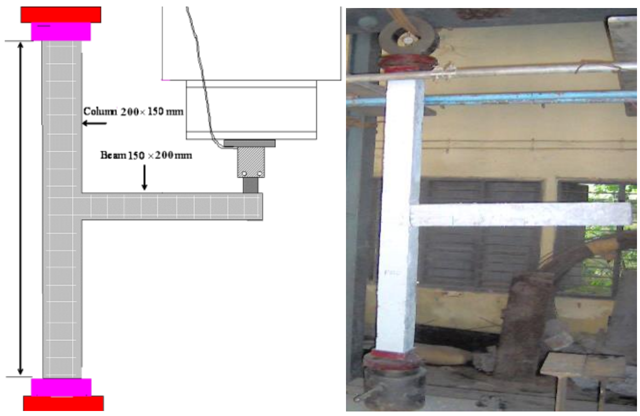


Figure 12. Experimental setup (Line diagram & Test set up)

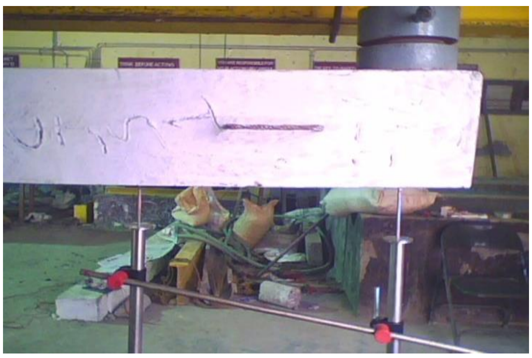


Figure 13. Instrumentation setup

Figure 14. Failure specimen (rebar)

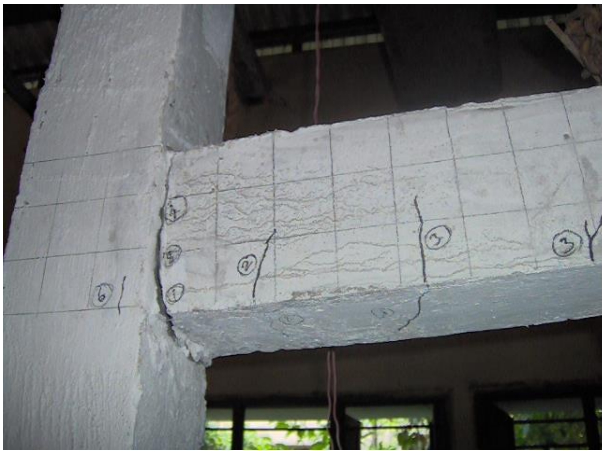


Figure 15. Failure specimen (GFRP)

2.6. Load-deflection Relationship

Based on the experiment results load-deflection relationship curve have been plotted and the following Figures 16 and 17 shows the load-deflection relationship for control specimen and GFRP specimen.

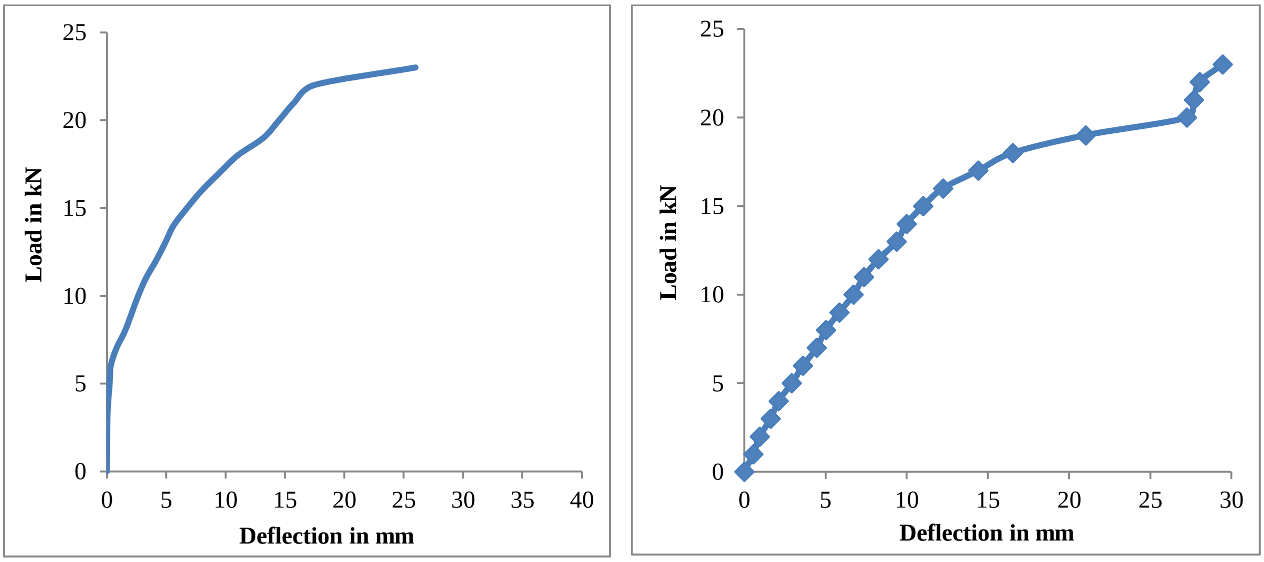


Figure 16. Experimental load-deflection relationship BCJS-1 and BCJS-3

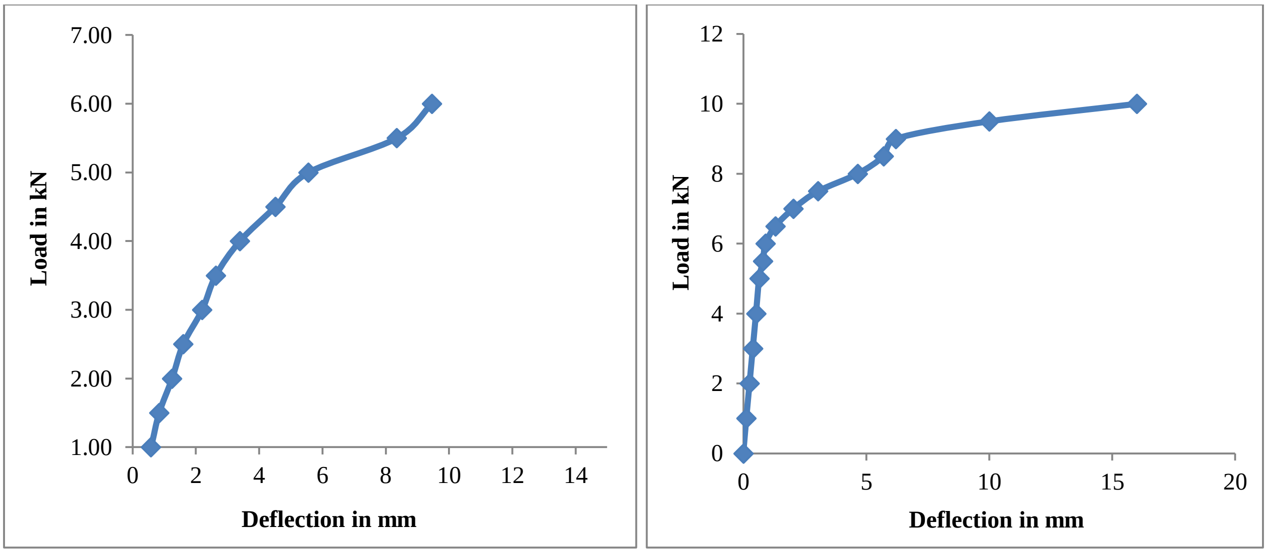


Figure 17. Experimental load-deflection relationship BCJFT-1 and BCJFT-3

3. Finite Element Software (ABAQUS)

ABAQUS is a suite of powerful engineering simulation programs, based on the finite element method, which can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. In a nonlinear analysis ABAQUS automatically chooses appropriate load increments and convergence tolerances.

3.1. Finite Element Modelling of Beam-Column Joint

To study the behaviour of the beam column joint, the specimens were modelled and analyzed using a Finite Element Software ABAQUS using the above said element types and the material properties. The models developed in ABAQUS software with conventional and non-conventional reinforcement detailing. An axial load of 10 kN is applied on the column with fixed base and a roller support at the top. The load on the beam is applied at a distance of 100 mm from the cantilever end. The models were analyzed for both the monotonic and cyclic loadings.

3.1.1. Sectional Properties

The parameters to be considered for Solid element (C3D8R) are material name, material dimensions and orientation angles (in X and Y direction). The parameters to be considered for Rebar element are cross sectional area and initial strain. The values were entered for rebar element as given in the table 2 and ABAQUS model shown in Figure 18.

Table 2. Sectional constants

Element name	Element type	Particulars	Values
Rebar main	Rebar (Main bars of the Beam)	Cross Sectional Area	113.097 mm^2
Rebar column	Rebar (Main bars of the Column)	Cross Sectional Area	113.097mm^2
Rebar beam str	Rebar (Beam Stirrups)	Cross Sectional Area	50.265 mm^2
Rebar col ties	Rebar (Column Lateral Ties)	Cross Sectional Area	50.265 mm^2

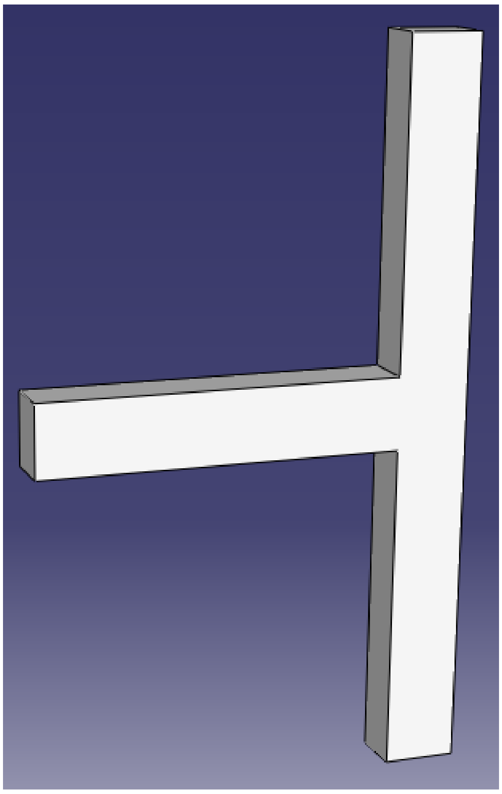


Figure 18. ABAQUS model

3.1.2. Material Properties

The material used in this problem is the concrete material and is assumed to be linearly elastic. Thus a single linear elastic material is created for the model. The properties that are to be defined for the solid continuum model are Mass density, Young's modulus, Poisson's ratio, concrete damaged plasticity, concrete smeared cracking and Mohr coulomb plasticity. For the reinforcing bars, the yield stress f_y = 432 MPa and the tangent modulus is 847 MPa. The concrete cube compressive strength f_{ck} is 44.22 MPa, 80% of which is used as the cylinder strength (Table 3 and 4).

Table 3. Material properties

Element Type	Material Properties	
Rebar for steel	Young's Modulus	2.1×1011 N/m^2
	Poisson's Ratio	0.3
	Yield Stress	448.2 × 106 N/m^2
	Longitudinal Modulus	207 × 106 N/m^2
Rebar for GFRP	Young's Modulus	6.0 ×1010 N/m^2
	Poisson's Ratio	0.2
	Yield Stress	1.3 × 108 N/m^2
	Longitudinal Modulus	42.86 × 106 N/m^2
Solid C3D8R Concrete	Young's Modulus	32517 × 106 N/m^2
	Poisson's Ratio	0.15
	Shear transfer coefficients for an open crack	0.2
	Shear transfer coefficients for a closed crack	0.9
	Uniaxial tensile cracking stress	3.71 × 106 N/m^2
	Uniaxial crushing stress	35.376 × 106 N/m^2

Table 4. Typical short-term mechanical properties of GFRP reinforcements

Property	GFRP
Density (kg/m^3)	2100
Longitudinal modulus (GPa)	39
In–plane shear modulus (GPa)	3.8
Longitudinal tensile strength (MPa)	1080
Transverse tensile strength (MPa)	39
In - plane shear strength (MPa)	89
Ultimate longitudinal tensile strain (%)	2.8
Ultimate transverse tensile strain (%)	0.5
Longitudinal compressive strength (MPa)	620
Transverse compressive strength (MPa)	128

It is required to consider the geometric non-linearity, when the material non-linearity is adopted. Hence, the large deformation effects have to be included in the analysis. Then the convergence difficulties will be eliminated to some extent. The convergence criteria for the displacement may be used instead of the convergence criteria for the force. It is known that, though the force convergence will give accurate results, the displacement convergence will be reliable where very accurate results need not be necessary.

3.1.3. Elements

C3D8R: The ELEMENT option deals with the element-nodal connectivity list. The element type is specified using the TYPE parameter. The choice of element type is as important as any other aspect of a finite element analysis. In this model the element used is C3D8R - 8-node linear brick element. In this the C represents Continuum and D represents Displacement H represents Hybrid (Figure 19).

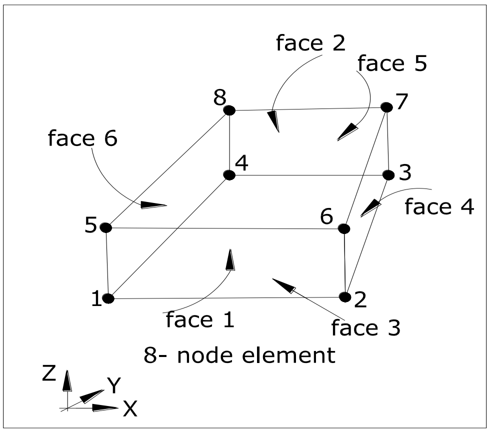


Figure 19. Continuum solid element

Rebar: Rebar is used to define layers of uniaxial reinforcement in solid elements (such layers are treated as a smeared layer with a constant thickness equal to the area of each reinforcing bar divided by the reinforcing bar spacing) (Figure 20).

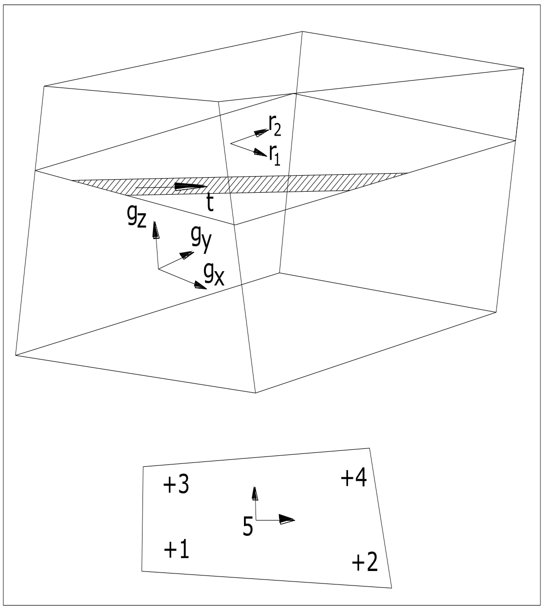


Figure 20. Rebar model in 3D element

3.1.4. Meshing

The finite element mesh is created for the model. ABAQUS uses a number of different meshing techniques. The default meshing technique assigned to the model. The Beam-Column Joint is modelled in different mesh sizes. It is suggested that finer mesh model will give accurate results and the coarser one will take less time for analysis (Figure 21).

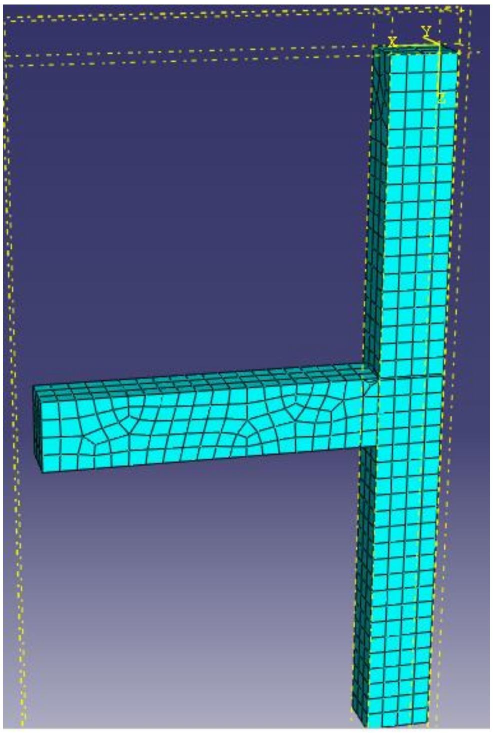


Figure 21. Meshing applied to the model

3.1.5. Post processing

The post processing involves the visualization of the deformed model shape and also plotting the results (Figures 22 and 23).

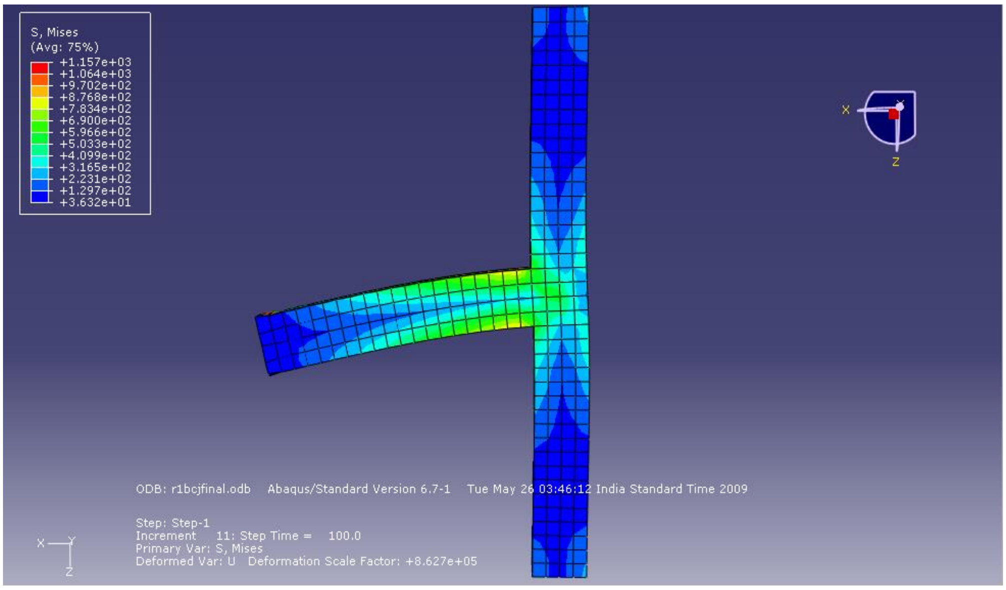


Figure 22. Stress contour variation in the

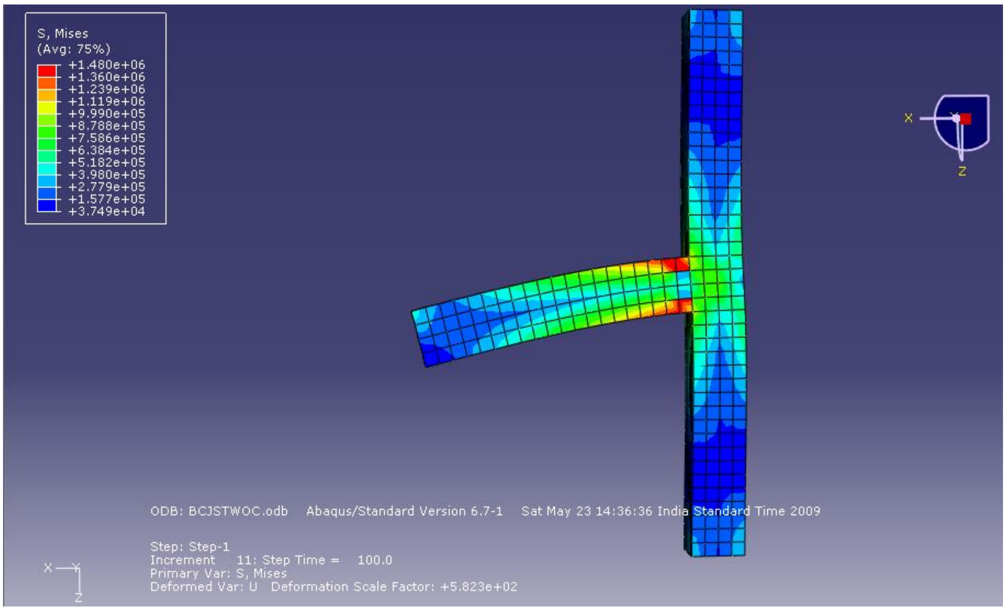


Figure 23. Stress contour in the ABAQUS model due to cyclic loading ABAQUS model due to static loading

The extensive modelling and implementation of finite element analysis for beam column joints. In order to assess the ability of the proposed finite element model to simulate the behaviour of beam column joints tested experimentally under monotonic loading conditions, a full scale beam column joints have been considered. A detailed material data required for modelling and analysis were carried out. The procedure for modelling are described with the different element, material properties. The comparative study between the experimental and the analytical results shows that the model created in the software is more reliable. Finally the results obtained from the FEM analysis are presented.

5. Theoretical Investigation

In the case of joints strut and tie concept is well suitable for the analysis to find the stress distribution at the joints. A new design equation based on strut and tie concept is proposed for predicting the joint shear strength of monotonically loaded exterior GFRP reinforced beam column joints. For this purpose, the influence of several key variables on the behaviour of beam-column joints are inspected using results of parametric studies on an experimental database compiled from a large number of exterior joint tests.

Present design guidelines:

The ACI-ASCE Committee and EC8 recommend the following design equations for the shear strength of monotonically loaded joints (Equations 1 and 2).

$V_{jd} = 1.058\sqrt{f_c b_{eff}} h_c$ (ACI – ACSE Committee 352) (1)

$$V_{jd} = 0.525 f_c^{2/3} b_{eff} h_c \text{ (EC8 Ductility class DCL)} \quad (2)$$

In order to investigate the reliability of the above design equations, the authors carried out several parametric studies on monotonically loaded exterior beam-column joints.

5.1. Parametric studies on joint shear strength

The parametric investigation of exterior beam-column joint behaviour is carried out based on the previous tests available in the literatures, tests carried out in our laboratory and the present tests done in our laboratory. The loading in all the tests were monotonic. The monotonically loaded exterior beam column joints are investigated considering the test conditions. Examining a large number of individual series of tests as a single database has the advantage of observing which variables have a significant influence on joint shear strength in all tests and which variables interact with each other.

Table 5 shows the experimental database used in this study. The database comprises the results obtained in our laboratory and the other researchers like Ortiz [31], Kordina [32], Scott [33], Scott & Hamill [34], Taylor [35], and Parker & Bullman [36]. The specimen forms included in the database are shown in Figure 24 (a, b, c) shows the notations used in this study

Table 5. Experimental Database

Investigator	Specimen	Detail	H mm	L mm	h_b/h_c	b_c/b_b	Beam rein. Ratio	Column rein. Ratio	f_c	Col axial load	$V_{jpredicted}/V_{jactual}$	Failure modes
Ortiz	BCJ 1	L bar	2000	1050	1.33	1	1.1	2.19	34	0	0.68	Joint shear -js
	BCJ 2	L bar	2000	1100	1.33	1	1.1	2.19	38	0	0.77	js
	BCJ 3	L bar	2000	1100	1.33	1	1.1	2.92	33	0	0.64	js
	BCJ 4	L bar	2000	1100	1.33	1	1.1	3.65	34	0	0.78	js
	BCJ 5	L bar	2000	1100	1.33	1	1.1	3.65	38	300	0.72	js
	BCJ 6	L bar	2000	1100	1.33	1	1.1	3.65	35	300	0.68	js
	BCJ 7	L bar	2000	1100	1.33	1	1.1	3.65	35	300	0.68	js
Kordina	RE 2	L bar	3000	1000	2	1	0.9	2.41	25	240	0.66	js
	RE 3	L bar	3000	1000	1.5	1	1.8	2.41	40	400	0.96	js
	RE 4	L bar	3000	1000	1.5	1	1.2	2.41	32	51	0.83	js
	RE 6	L bar	3000	1000	1.5	1	1.2	2.41	32	213	0.91	js
	RE 7	L bar	3000	975	1.4	1	1.3	1.61	26	650	0.87	js
	RE 8	U bar	3000	975	1.4	1	1.3	1.61	28	525	0.9	js
	RE 9	U bar	3000	975	1.4	1	1.3	1.61	28	770	0.86	js
	RE 10	U bar	3000	975	1.56	1	1.2	1.61	24	551	0.94	js
Taylor	P1/41/24	L bar	1290	470	1.43	1.4	2.4	4.1	33	240	0.97	js
	P2/41/24	L bar	1290	470	1.43	1.4	2.4	4.1	29	240	0.94	js
	P2/41/24A	L bar	1290	470	1.43	1.4	2.4	4.1	47	240	0.92	js
	A3/41/24A	L bar	1290	470	1.43	1.4	2.4	4.1	27	240	0.88	js
	D3/41/24	L bar	1290	470	1.43	1.4	2.4	4.1	53	60	0.89	js
	B3/41/24	L bar	1290	470	1.43	1.4	2.4	4.1	22	240	0.92	js
	C3/41/24BY	U bar	1290	470	1.43	1.4	2.4	4.1	32	240	1.04	js
	C3/41/13Y	U bar	1290	470	1.43	1.4	1.4	4.1	28	240	0.95	js
Scott	C1AL	L bar	1700	750	1.4	1.36	1.1	4.29	33	50	0.87	js
	C4	L bar	1700	750	1.4	1.36	2.1	4.29	41	275	0.89	js
	C4A	L bar	1700	750	1.4	1.36	2.1	4.29	44	275	0.86	js
	C4AL	L bar	1700	750	1.4	1.36	2.1	4.29	36	50	0.86	js
	C7	L bar	1700	750	2	1.36	1.4	4.29	35	275	0.9	js
	C3L	U bar	1700	750	1.4	1.36	2.1	4.29	35	50	1.03	js

	C6	U bar	1700	750	1.4	1.36	2.1	4.29	40	275	1.05	js
	C6L	U bar	1700	750	1.4	1.36	2.1	4.29	46	50	0.94	js
	C9	U bar	1700	750	2	1.36	1.4	4.29	36	275	0.93	js
	C4ALN0	L bar	1700	750	1.4	1.36	2.1	4.29	42	50	0.88	Punching-p
	C4ALN1	L bar	1700	750	1.4	1.36	2.1	4.29	46	50	0.85	js
	C4ALN3	L bar	1700	750	1.4	1.36	2.1	4.29	42	50	0.78	js
	C4ALN5	L bar	1700	750	1.4	1.36	2.1	4.29	50	50	0.85	js
	C4ALH0	L bar	1700	750	1.4	1.36	2.1	4.29	104	100	0.86	p
	C6LN0	U bar	1700	750	1.4	1.36	2.1	4.29	51	50	0.92	js
	C6LN1	U bar	1700	750	1.4	1.36	2.1	4.29	51	100	0.96	js
Scott & Hamil	C4ALH1	L bar	1700	750	1.4	1.36	2.1	4.29	95.2	100	0.93	Bending - b
	C4ALH3	L bar	1700	750	1.4	1.36	2.1	4.29	105.6	100	0.97	b
	C4ALH5	L bar	1700	750	1.4	1.36	2.1	4.29	98.4	100	1	b
	C6LN3	U bar	1700	750	1.4	1.36	2.1	4.29	49	50	0.92	js
	C6LN5	U bar	1700	750	1.4	1.36	2.1	4.29	37	50	0.74	js
	C6LH0	U bar	1700	750	1.4	1.3	2.1	4.29	101	100	0.72	js
	C6LH1	U bar	1700	750	1.4	1.36	2.1	4.29	102	100	0.98	js
	C6LH3	U bar	1700	750	1.4	1.36	2.1	4.29	97	100	0.93	js
	4a	L bar	2000	850	1.67	1.2	0.9	1.09	39	0	-	Compression -c
	4b	L bar	2000	850	1.67	1.2	0.9	1.09	39	300	1.05	js
	4c	L bar	2000	850	1.67	1.2	0.9	1.09	37	600	0.83	js
	4d	L bar	2000	850	1.67	1.2	0.9	4.38	39	0	0.97	js
	4e	L bar	2000	850	1.67	1.2	0.9	4.38	40	300	0.92	js
Parker	4f	L bar	2000	850	1.67	1.2	0.9	4.38	38	600	0.78	js
	5a	L bar	2000	850	1.67	1.2	0.9	2.67	42	0	-	c
	5b	L bar	2000	850	1.67	1.2	0.9	2.67	43	300	1.08	js
	5d	L bar	2000	850	1.67	1.2	1.4	2.67	43	0	-	c
	5e	L bar	2000	850	1.67	1.2	1.4	2.67	45	300	-	c
	5f	L bar	2000	850	1.67	1.2	1.4	2.67	43	600	0.86	js
	BCJSFT	L bar	2000	1000	1	1	2.26	2.26	35.37	10	1.33	b
	BCJSFG	L bar	2000	1000	1	1	2.26	2.26	35.37	10	1.36	b
	BCJSFS	L bar	2000	1000	1	1	2.26	2.26	35.37	10	1.28	b
	BCJS	L bar	2000	1000	1	1	2.26	2.26	35.37	10	1.00	js
	BCJS20	L bar	2000	1000	1	1	2.26	2.26	30.4	10	1.02	js
Present study	BCJSFT20	L bar	2000	1000	1	1	2.26	2.26	30.4	10	1.13	b
	BCJS30	L bar	2000	1000	1	1	2.26	2.26	41.6	10	0.93	js
	BCJSFT30	L bar	2000	1000	1	1	2.26	2.26	41.6	10	1.01	b
	BCJS1	L bar	2000	1000	1	1	2.26	2.26	35.37	10	0.96	js
	BCJFT1	L bar	2000	1000	1	1	2.26	2.26	35.37	10	1.01	b
	BCJS3	L bar	2000	1000	1	1	2.26	2.26	35.37	10	0.92	js
	BCJFT3	L bar	2000	1000	1	1	2.26	2.26	35.37	10	0.90	b

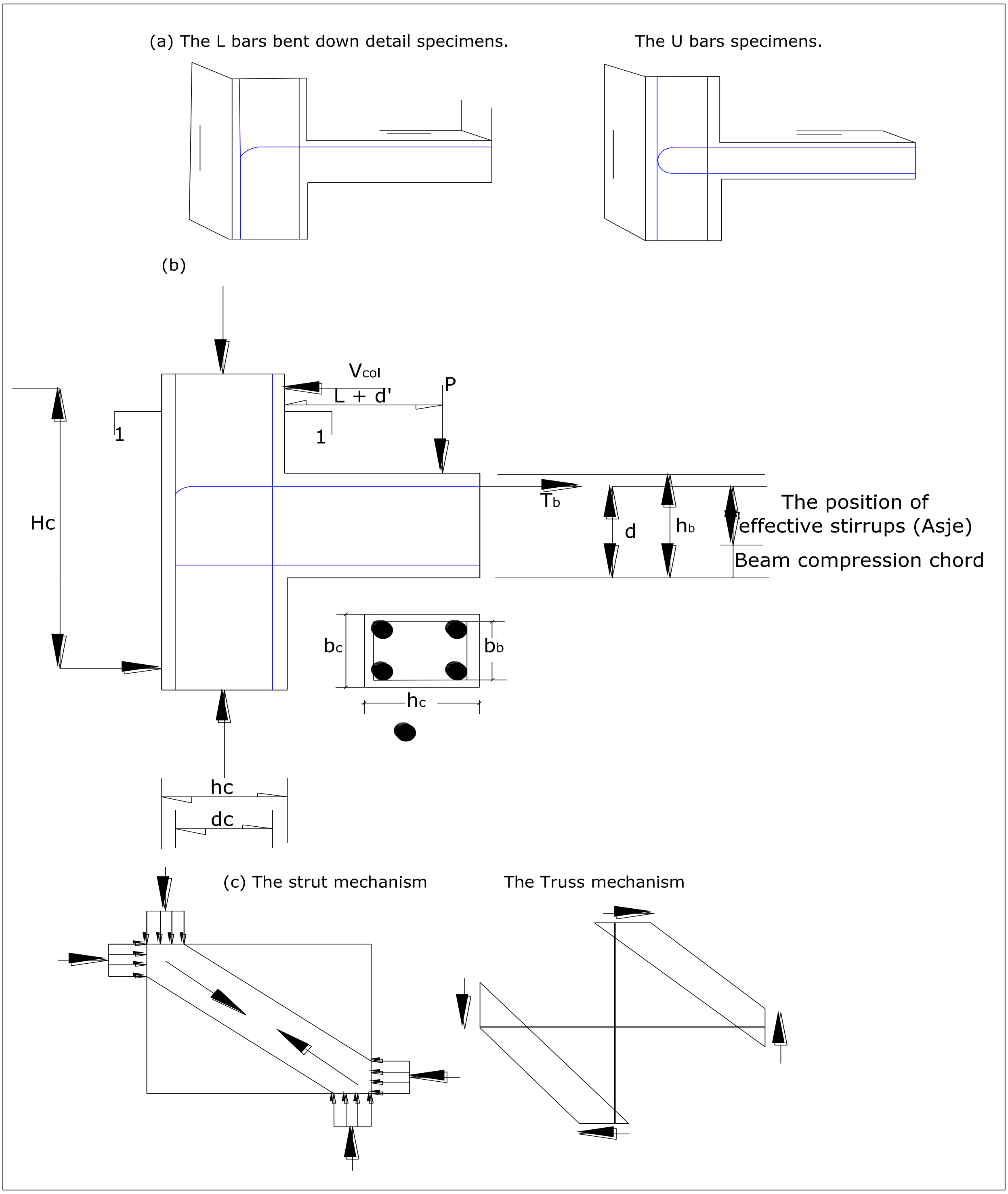


Figure 24. (a) Typical specimen shape in the experimental database; (b) Typical elevation and notations used for exterior beam column joints; (c) The strut and truss mechanisms

The theoretical expressions for the exterior beam-column joint reinforced with GFRP reinforcements. Firstly, the equation proposed considers the influence of beam longitudinal reinforcement ratio, which was not taken into account in previously suggested design equations. Secondly, as the influence of this parameter is taken into account, a more realistic estimate of the influence of joint aspect ratio is obtained. Thirdly, the influence of stirrups is considered differently for joints with low, medium and high amount of stirrup ratios, in a way, which was not considered in previously suggested equations. Finally, the proposed design equation predicts the joint shear strength of exterior beam column connections accurately with minimal standard deviation and is more reliable than the previously suggested equations. Based on the detailed experimental and FEM analysis, a new equation is proposed at the end of the chapter for the determination of joint shear strength for GFRP reinforced beam-column joints.

6. Conclusions

Based on the experimental, theoretical and analytical works the following conclusions are drawn.

- Providing GFRP bars with L steel clamps changes the failure modes of monotonically loaded exterior beam-column joints from joint shear to beam failure. Furthermore, the joint shear strength of joints is increased by 15% if detailed by L bars bent down detail beam reinforcement.
- Anchorage failures are not anticipated in joints with and without stirrups in monotonically loaded exterior beam column joints, with the provision of anchorage coupler at the joint in the GFRP reinforced specimens.
- Column axial compressive load has no influence on ultimate shear capacity of the joint but higher column compressive axial load and high column longitudinal reinforcement ratios are necessary for the concrete joints to avoid column failures.
- Joint shear strength values obtained from the experiments are comparable with the analytical results for both the beam-column joints reinforced with steel and GFRP reinforcements. The joint shear strength predicted by the analytical tool ABAQUS is also validated with experimental results.
- Increasing the beam longitudinal reinforcement ratio increases the joint shear strength. Because the influence of beam longitudinal reinforcement ratio is taken into account in the proposed equation predicts that the joint shear strength.
- The analysis and design of beam-column joints reinforced with GFRP reinforcements is carried out by strut and tie model. Strut and Tie models are based on the models for the steel reinforced beam-column joints. The resulting strut and tie model developed for the GFRP reinforced beam-column joints predicts joint shear strength for varying beam longitudinal reinforcement ratio, joint aspect ratio and stirrup ratio.
- The GFRP reinforced specimens performance is low when compared to the conventional steel reinforcements. But the use of hybrid reinforcements will give similar results as that of steel because of the very high elastic modulus of the hybrid reinforcements.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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