CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Structural Behavior of Eccentric Square Columns having Jute Fibre Reinforced Concrete and GFRP Rebars

by

Hassan Raza

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in the

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I want to dedicate this work to my family, who helped me throughout my education. This is likewise a tribute to our best teachers who guided us to go up against the troubles of presence with ingenuity and boldness, and who made us what we are today.

CERTIFICATE OF APPROVAL

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Abstract

Glass Fibre Reinforced Polymer Rebars (GFRP) can be reliable reinforcement used in concrete structure instead of steel reinforcement due to its properties like high tensile strength, light weight and resistance against corrosion. Addition of fibres in concrete mix are increasing for better achievement of strength and durability results. Vegetable fibres such as jute fibre is an ideal fibre having high tensile strength and economical. Along with this, jute fibres improve the durability and have a good resistance against the crack propagation. They are very much available in tropical regions. The overall objective of the research program is to replace longitudinal steel rebars with FRP rebars in concrete structures with additional use of natural fibres for improved durability and performance. However, in current MS study, only prototype eccentric square columns in lab for the effect of jute fibres addition, and steel rebar replacement with GFRP rebar is being studied. Durability aspect is outside the scope of this thesis due to the time constraints. The steel reinforcement is used for lateral reinforcement.

The mix design ratio of 1:2:3:0.6 for PC and JFRC which is used. Addition of 5% jute fibre by mass of cement having length of 50 mm. Splitting tensile, toughness energy, flexural and compressive strength are investigated as per ASTM standard. The dynamic characteristics of PC and JFRC are also measured. Sixteen prototype specimens of PRC and JFRC (Eight each) having a square cross section 100 x 100 mm and height of 450 mm were cast and tested under uniaxial eccentric load condition.

As in case of PC the slump value of PC is 40% greater as compared to JFC materials. In JFRC specimen the density is less due to light weight of jute fibres. The damping ratio of the JFRC specimen is greater than PC that has more energy dissipation. Both PC and JFRC samples are tested in servo hydraulic testing machine. It is observed that by using jute fibres in concrete, the failure mode of concrete is converted from crushing to bridging. It is concluded that jute of with GFRP rebars and concrete showed improved properties and better performance.

Therefore, it is recommended to use jute fibre and GFRP rebars in concrete column under eccentric load condition.

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Abbreviations

A	Aggregate
b	Breadth of Column
C	Cement
C.Em	Compressive Energy-Absorption up to Maximum Load
CE	Total Compressive Energy Absorbed
Cr.E	Cracked Energy Absorption after Maximum Load
Cr.E	Compressive Cracked Energy-Absorption after Maximum Load
CS	Compressive Strength
CTI	Compressive Toughness Index
e	Eccentricity
$\mathbf{E}_m$	Energy-Absorption up to Maximum Load
fl	Longitudinal Frequency
fr	Torsional Frequency
FRC	Fibre Reinforced Concrete
FS	Flexural Strength
ft	Transverse Frequency
GFRP	Glass Fibre Reinforced Polymer
GPa	Giga Pascal
Hz	Hertz
J	Joule
JF	Jute Fibre
JFC	Jute Fibre Concrete
JFRC	Jute Fibre Reinforced Concrete
kg	Kilogram

kN	Kilo Newton
m^3	Cubic Meter
MJ	Million Joule
mm	Millimeter
MPa	Mega Pascal
NFRC	Natural Fibre Reinforced Concrete
PC	Plain Concrete
P$_{max}$	Maximum Load
PRC	Plain Reinforced Concrete
S	Sand
s	Second
STM	Servo Hydraulic Testing Procedure
STS	Splitting Tensile Strength
TE	Total Energy Absorbed
TTI	Total Toughness Index
w/c	Water Cement Ratio

Symbols

ξ	Damping Ratio
Ø	Diameter
T.I (-)	Toughness Index
Hz	Unit of Frequency
E	Energy Absorption
m	Micro Meter
$\boldsymbol{\rho}$	Reinforcement Ratio
%	Percentage
$\mathbf{\frac{l_f}{\emptyset}}$	Aspect Ratio of Fiber
$\mathbf{A'_g}$	Area of GFRP in Compression Portion
$\mathbf{A'_s}$	Area of Steel in Compression Portion
$\mathbf{A_g}$	Area of GFRP in Tension Portion
$\mathbf{A_s}$	Area of Steel in Tension Portion
$\mathbf{P_n}$	Nominal Load
$\mathbf{T_f}$	Tensile Strength of Fiber
$\mathbf{V_f}$	Volume Fraction
ε'_s	Strain of Steel in Tension Portion
ε_s	Strain of Steel in Compression Portion
ε_u	Crushing Strain of Concrete

Chapter 1

Introduction

1.1 Background

For carrying compressive load structural reinforced concrete column are designed. Compressive loading make them important structural members. These columns transmit the load to the lower level from the slabs and beams. Having end restraint, joints between concrete beams, floors and column are fixed in reinforced concrete building causing some moments in the columns. Construction of perfect vertical alignment of columns in multistory building is not possible. Therefore, if vertical alignment of column are incorrect, then eccentric loading conditions are produced. Eccentric load does not act exactly at the centre of column, it acts at some eccentricity as shown in Fig. 1.1. If centric load occurs in the column, then column will fail purely in compression form and produce moments in column. The compression will occur in one face and tension will occur in another face of the column. The buckling failure may occur in the column. Failure of one of the columns in any multistory building can lead to the total collapse of the structure. Hence, columns are usually reinforced with spirals or ties and conventional steel bars. But main problem with steel reinforcement is that corrosion occurs and has a limited service life [1]. According to Nilson, there are two types of eccentricities in the column, one is smaller and other is larger. Due to smaller eccentricity, crushing failure occurs in column. Whereas, distant part of the section may fail due to tensile yielding of steel in columns when columns are subjected to large eccentricity [2]. Liu et al. [3] investigated the failure mode under eccentric loading that can be categorized as bending failure due to decrease in the stiffness and low ultimate axial resistance. El din et al. [4] concluded that under the same eccentricity the GFRP- reinforced concrete columns were more ductile as compared to steel reinforced columns. In strength point of view for all the eccentricities, the GFRP reinforced columns had smaller loss and a longer post peak than that of steel reinforced columns. Tobbi et al. [5] performed experimental investigation on compressive member reinforced with steel rebars, GFRP rebars and GFRP rebars as transverse reinforcement under eccentric loading. The study revealed that the use of GFRP transverse reinforcement and steel longitudinal bars offered positive response in strength and ductility behavior. Khorramian and Sadeghian [6] studied experimental and analytical behavior of short concrete columns under eccentric load condition reinforced with GFRP rebars. The study revealed that behavior of GFRP reinforced eccentric square concrete column had a gradual deformation instead of sudden failure. The results depicted that GFRP rebars sustained high strain without decreasing the compressive strain capacity of bars. The GFRP reinforced columns demonstrated to be reliable to bear the load longitudinal reinforcement in concrete columns. Therefore, to tackle these issues, use of non-corrosive material is necessary as reinforcement in concrete members. Various composites such as fibre reinforced polymers are recommended to enhance strength and avoid corrosion. Besides this, use of these composites in infrastructure development projects also seems to be beneficial in terms of cost and durability. GFRP rebar is a distinctive substitute reinforcement solution for the concrete structure. GFRP rebar is not only considered to be substitute for concrete solution, it also has more characteristics such as high tensile strength, weathering resistance, low density, thermal expansion, stiffness, and damping properties. These benefits improve life cycle, equipment functioning and safety precaution [7]. Many researchers investigated the behavior of GFRP rebars under eccentric loading in square concrete column. GFRP rebars under the eccentric loading gave better results as compared to the steel rebars in square concrete columns. Many researchers recommended use of GFRP rebars in concrete structure for shear and flexural reinforcement [8]. Increased reinforcement ratio of GFRP rebars performed better in terms of deformation and confinement of concrete than steel rebars [9].

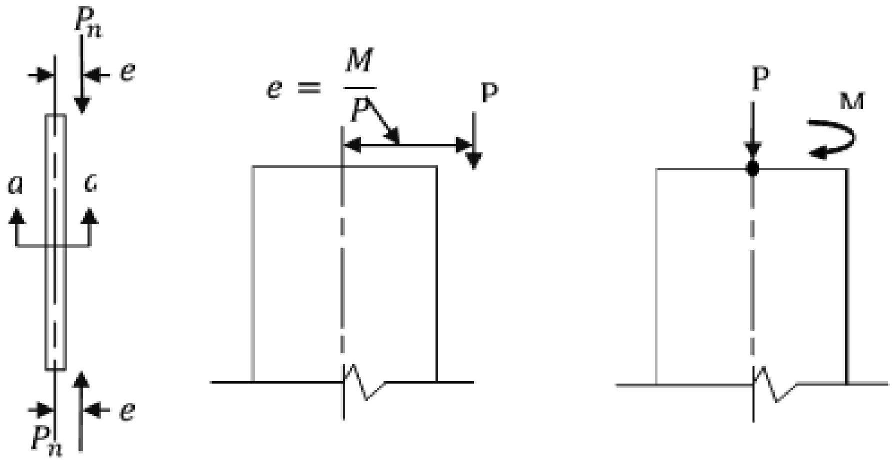


FIGURE 1.1: Column under eccentric load condition

Concrete is an extensively used construction material having high compressive strength but low tensile strength, only ten times of compressive strength. Because of low tensile strength it has brittle nature, along with this low strain capacity is also observed in tension. This results in ultimately low toughness. Concrete is failed in brittle mode. Addition of natural fibres in concrete can minimize and convert brittle behavior into ductile behavior. Natural fibres are also economical and environment friendly. Now a day's natural fibres are used for improving the properties of concrete such as toughness, shrinkage and crack propagation as well as their durability [10-14]. Ferreria et al. [15] proposed the bond behavior of jute fibre in cement matrix. It was observed that the bond behavior of jute fibre in cement matrix was significantly improved. Islam and Ahmed [16] conducted studied on concrete behavior with jute fibres. It was observed that little amount of jute fibres of 0.25% had positive influence on compressive strength and also controlled the cracks propagation. Zakaria et al. [17] investigated the performance of jute fibres for concrete material strengthening. It was concluded that the compressive strength, splitting tensile strength and flexural strength was improved meaningfully. Kesikidou and Stefanidou [18] conducted experiments on jute, coconut, and kelp fibre to investigate its effectiveness in cement and mortars. It was concluded that utilization of natural fibres enhanced the mechanical properties in terms of strength and durability.

In present research, the behavior of small prototype JFRC specimens reinforced with glass fibre reinforced polymer (GFRP) rebars and steel rebars under eccentric load will be investigated and compared. Mechanical properties, axial load capacities will be determined and crack pattern will be observed with a naked eye alongside the detailed failure mechanism. The critical literature review perceived that experimental investigation on GFRP with jute fibre reinforced concrete square columns, especially columns supposed to uniaxial eccentric loading is lacking. On the other hand, existing design practices do not support the design of columns with GFRP rebars as longitudinal reinforcement. Therefore, detailed investigations need to be concluded on awareness of behavior of jute fibre reinforced concrete with GFRP rebars as longitudinal reinforcement. However, there is lack of experimental work to investigate structural behavior of jute fibre reinforced concrete columns with steel and GFRP rebars under uniaxial eccentric load. From critical literature review it is evident that most of the studies limited to observe behavior of columns reinforced with GFRP rebar but no addition of jute fibres.

Hence, the aim of the study is to observe the performance of prototype jute fibre reinforced concrete square column under eccentric loading to enhance the tensile strength and ductility. To the best of author knowledge, no study has been conducted to investigate the structural behavior of eccentric square columns having jute fibre reinforced concrete and GFRP rebars.

1.2 Research Motivation and Problem Statement

The research work aims to expand the load carrying capacity of square column in term of structural load carrying capacity. In all members of a building, eccentric column is critical element due to its load transmission behavior. Columns transfer the load to the foundation and from foundation to the earth. Fig. 1.2 displays real example of eccentric column taken from field as shown below. It can be noted that load transferred from beam to the column is under eccentric condition.

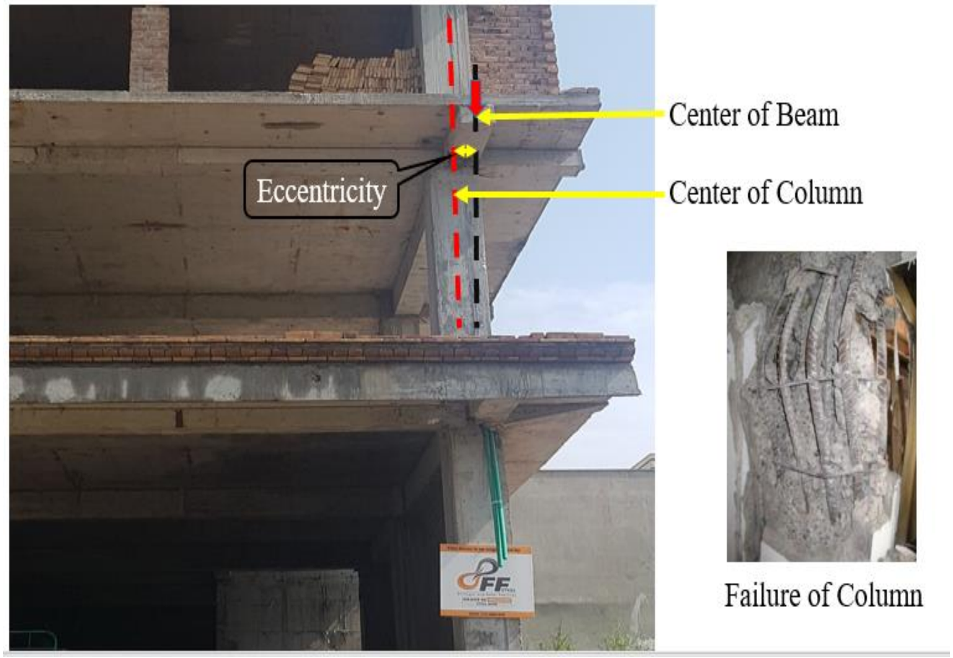


FIGURE 1.2: Real example of eccentric column taken from field

In order to improve the load carrying capacity and to gain safety, the behavior of structural elements which are used in buildings need to be investigated. The modern and proper technique of strengthening may be applied. The verification of failure mechanism before and after FRC strengthening should be kept in mind. Mostly the strengthening technique may improve the load carrying capacities but due to this load transmission mechanism may change. The performance of FRC reinforced with GFRP under eccentric column is important. Thus the problem statement is as follow.

"Corrosion of steel rebars affect life span and strength of RC columns. It is also observed from literature and field practice exact vertical alignment of column is not possible. However, eccentric loading causes buckling failure. GFRP are popular for tensile strength and corrosion resistance while addition of jute fibre reduces crack propagation and increase ductility of column. Behavior of GFRP rebars in jute fibre reinforced concrete (JFRC) is still needed to be explored for concrete eccentric square column."

1.3 Overall Objective and Specific Aim

The overall objective of the research program is to replace longitudinal steel rebars with FRP rebars in concrete structures with additional use of natural fibres for improved durability and performance.

"The specific aim of this MS research work is to investigate prototype eccentric square columns in laboratory for the effect of jute fibres addition and steel bar replacement with GFRP rebars."

1.4 Scope of Work and Study Limitation

In this research, jute fibre reinforced concrete (JFRC) reinforced with GFRP rebars and steel rebars is examined for the eccentric square column application. The jute fibres content is 5% by mass of cement. The mix design proportion is 1:2:3 (cement: sand: aggregate) with a water-cement ratio of 0.60. Relative comparison between steel reinforced prototypes and GFRP rebar reinforced prototypes with jute fibres are investigated. Dynamic testing of specimens (i-e PC and JFC cylinders and beam-lets) and prototype square columns is performed by using resonance apparatus as per ASTM C215-02. Post dynamic testing, prototypes are tested in Servo hydraulic testing machine (STM) as per ASTM standards to obtain strength, energy absorption and toughness index.

Eccentric load is applied only in one direction on prototype specimens and uniform steel stirrups are used with uniform spacing for all prototype specimens. Durability is not considered in this study due to time constraints.

1.5 Methodology

Prototype specimen has been used with GFRP rebars and steel rebars. Effectiveness of jute fibres in improving the load carrying capacity and overall failure is investigated and comparison between prototype columns of PRC and JFRC is performed. Load carrying capacity is measured alongside the detailed failure mechanism, the cracking is judged with the naked eye. Different tests are performed to calculate the compressive strength, modulus of rupture and split tensile strength. The mix design ratio of (1:2:3:0.6) (Cement, sand, aggregate, water) is used. The target compressive strength of concrete is greater than 15 MPa. . For preparation of JFRC jute fibres of length 50 mm with a content of 5% fibres by mass of cement is added in concrete. The standard specimens are cast by using ASTM standards.

1.6 Thesis Layout

There are six chapters in this thesis, which are as follows:

Chapter 1 is related to introduction, background, research work and problems which are produced, scope of work, method of completing the research work and thesis outline.

Chapter 2 tells the literature review, failure in eccentric square concrete columns, use of natural fibers in concrete, use of jute fibers in concrete, Fiber reinforced polymers, use of GFRP rebars in concrete structures, testing procedure and summary.

Chapter 3 is related with the experimental procedure. It is related with background, raw materials, mix design, casting and selection of mix design, specimens, testing procedure and summary.

Chapter 4 is related with experimental evaluation. It contains background, frequency and damping ratio of prototypes, behavior of prototype square columns under eccentric loading, SEM analysis of prototype and summary.

Chapter 5 contains discussion. It involves background, modification in nominal strength and nominal moment, relation between material properties and performance and summary.

Chapter 6 is related to conclusion and recommendation.

Bibliography is presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

In last few decades fibres have been used to enhance the behavior and performance of concrete structures. Natural fibres are environment friendly, economical and easily available materials. Fibres such as jute fibres are utilized to upsurge the toughness, durability, and crack restraining properties of concrete. Jute fibres possess high tensile strength, low cost, and easily available in local market. Glass fibre reinforced polymer (GFRP) rebars are alternatives to steel rebars in concrete structures due to its improved properties such high tensile strength, low density, and better corrosion resistance.

2.2 Failure in Eccentric Square Concrete Columns

The behavior showed that GFRP reinforced eccentric square concrete column had a gradual deformation instead of sudden failure. It is also observed that concrete undergoes from crushing to bridging during the tests [6]. El din et al. [4] investigated the performance of GFRP rebars and ties in HSC columns (400 x 400 x 2000 mm) under eccentric load. Different reinforcement rebars and tie numbers were used in specimens with different eccentricities (0.2, 0.3, 0.4 and 0.60) and comparison was done with steel rebars and GFRP rebars. It is concluded that under the same eccentricity the GFRP- reinforced concrete columns were more ductile as compared to steel reinforced columns. In strength point of view for all the eccentricities, the GFRP reinforced columns had smaller loss and a longer post peak than that of steel reinforced columns. Tobbi et al. [5] performed experimental investigation on compressive member reinforced with steel rebars, GFRP rebars and GFRP rebars as transverse reinforcement under eccentric loading. Twenty (350 x 350 x 1400 mm) concrete columns were tested to obtain the data regarding variables like transverse reinforcement configuration, spacing, material type, longitudinal reinforcement ratio and confining volumetric stiffness. The study revealed that the use of GFRP transverse reinforcement and steel longitudinal bars offered positive response in strength and ductility behavior. The study enhanced the worth of GFRP as transverse reinforcement under eccentric loading.

Haddi and Youssef [19] conducted study on GFRP encased square concrete columns under eccentric and axial load. Point loading test was used to study the influence of utilization of the type of reinforcement and magnitude of load eccentricity on the flexural and compressive behavior of square concrete member. Twelve specimens were tested as compressive member, while 4 specimens were tested under flexural loading. A size of square column 210 x 210 x 800 mm was used. It was perceived that specimens with steel reinforcement had more load carrying capacity and similar ductility as compared to GFRP reinforced specimens. But specimen encased with GFRP structural section have high load carrying capacity but lesser ductility. The study helps to improve knowledge on performance of steel and GFRP under different load conditions. Khorramian and Sadeghian [6] studied experimental and analytical behavior of short concrete columns under eccentric load condition reinforced with GFRP rebars. The 14 specimens (150 x 150 x 500 mm) were constructed from which nine specimens were of GFRP reinforced (6#5) and five specimens were of plain concrete under concentric and eccentric loading up to failure with eccentricity at 0.1, 0.2, 0.3. The analytical model helped to observe effect of eccentricity, reinforcement ratio, and concrete strength. The study revealed that behavior of GFRP reinforced eccentric square concrete column had a gradual deformation instead of sudden failure. The results depicted that GFRP rebars sustained high strain without decreasing the compressive strain capacity of bars. The GFRP reinforced columns demonstrated to be reliable to bear the load longitudinal reinforcement in concrete columns. Liu et al. [3] performed experimental and theoretical study in square tubed reinforced short columns under eccentric load. The specimens used was 200 x 200 x 600 mm for different eccentricities of 0, 25, 50 mm. The study also investigated eccentricity and width to thickness ratio of steel tube. The comparison on axial and lateral deformation curves and stress in steel tubes and failure modes were observed. The study revealed that steel tubes exhibit good ductile behaviors. The failure mode which was occurred in TRC short columns under eccentric loading was characterized by bending failure, with the increase of eccentricity the stiffness and axial resistance were decreased. The study helped to determine the effective lateral confining pressure for TRC columns. Numerical analysis method was developed to simulate the mechanical behavior of TRC columns. Elmessalmi et al. [20] performed experimental study on performance of fibre reinforced polymer rebars under different load conditions. Three hundred renewed test performed to observe polymer rebars in compression members. The observations were also made for different columns under different slenderness, load conditions and cross sections to identify the gap in design equations. The study helps to identify better performance of fibre reinforced polymer rebars and also mitigate the gap in design equations to support the use of fibre reinforced polymer in compression member in real life field. It would be better to conduct study on comparison of different fibre reinforced polymer rebars for better results.

2.3 Use of Natural Fibres in Concrete

In ancient times for the enhancement in performance of concrete fibres had been used to improve its behavior and mechanical properties. Fibres can be a solution for enhancing energy absorption capacity, toughness and crack propagation. Researchers were interested in fibres due to their enhanced properties such as low cost, local availability, high strength were the causes behind the use of natural fibres. Sisal, jute, flax, isora, and hemp fibres are easily available in nature. Natural fibres had some defects such that they cannot be used in elevated temperatures [9]. Khan and Ali [21] investigated behavior of coconut fibres in fly ash silica fume concrete. A total of ten batches were prepared. Different fly ash dosages of 0%, 5%, 10%, and 15% with uniform content of silica fume i.e. 15% is used for fly ash silica fume plain concrete (FA-SPC) while same configuration is used with the addition of 2% coconut fibres with 50mm length for fly ash silica fume coconut fibre reinforced concrete (FA-SCFRC). It was concluded that FA-SCFRC demonstrated better performance at 10% content of fly ash as compared to other contents of FA-SCFRC and FA-SPC. Momoh and Osofero [22] investigated the effects of oil palm broom fibres (OPBF) on mechanical properties of concrete at 7, 14, 28, 56 and 112 days. Fibre length of 50 mm with mix design ratio of 1:1.5:3 cement, sand and aggregate were used in preparation of the concrete mix. It was concluded that compressive, flexure and splitting tensile strength of OPBF-concrete does not improved significantly but energy absorption capacity between 70 and 320% at 112 days. Hari and Mini [23] investigated effects of sisal and nylon hybrid fibres on mechanical and durability properties of self-compacting concrete. Different proportions of hybrid fibre proportions 0/100, 25/75, 50/50, 75/25 and 100/0. It was deduced that fibre deterioration reduced due to water absorption and effected durability. Nylon fibre enhances the durability and mechanical properties when hybridized with sisal in concrete.

Chin and Nepal [24] conducted tests on straw fibre reinforced concrete to examine the behavior of concrete. It was concluded that compressive and flexural strength of wheat straw fibres enhanced at 0.25% volume fraction than plain concrete. Plant fibres importance was studied by such as wheat straw and determined flexure and shear reinforcement. Wheat straw was taken by mass of concrete; fibre length was 25 mm with mix design ratio of (1:2:4) for PC. Properties such as energy absorption, flexure strength and toughness index were improved up to 7.5 %, 30.4 %, and 11.1% respectively. Crack propagation was reduced up to some extent with use of wheat straw. In rigid pavements wheat straw fibres showed better behavior and can yield comparable design [5]. The dynamic and mechanical properties of coconut fibre reinforced concrete showed better results. Different fibre lengths of 25 mm, 50 mm and 75 mm were used and different fibre contents of 1%, 2% and 3% were used in concrete. It is observed that 50 mm length of fibre with 5% content showed improved results [26]. Elsaid et al. [27] investigated the natural fibre and kenaf fibres mechanical properties such as resistance of concrete. To investigate the properties of fibres almost 53 samples of standard size 22 samples were casted, while for splitting tensile strength 12 samples and 19 samples were casted to check for the modulus of rupture. For concrete almost 1.2%-2.4% fibres by volume fraction was considered. So, it is indicated that the kenaf fibre toughened the concrete, significantly improved the tensile strength, improved crack behavior and was responsible to provide three times more toughness than the plain concrete. Wahyuni et al. [28] investigated the splitting-tensile strength of concrete using 0.5% of bamboo fibre by weight of cement while length of bamboo fibre was 2cm. Splitting tensile strength of cylinder after 28 and 90 days was also tested. It was observed that the tensile strength of BFRC increased 26 % as compared to the PC.

2.4 Use of Jute Fibres in Concrete

Ferreria et al. [15] proposed the bond behavior of jute fibre in cement matrix. It was observed that the bond behavior of jute fibre in cement matrix was significantly improved. Islam and Ahmed [16] conducted studied on concrete behavior with jute fibres. Jute fibres content of 0%, 0.25%, 0.50% and 1.0% with the length of 10 mm and 20 mm were used to prepare the cylinders and beams. It was observed that little amount of jute fibres of 0.25% had positive influence on compressive strength and also controlled the cracks propagation. Alam and riyami [29] investigated the shear strength of reinforced concrete beam using jute fibre, kenaf and jute fibre rope reinforced polymer lamination. It is observed that natural fibres such as jute fibres, kenaf and jute fibre rope polymer lamination enhanced the shear strength by 35%, 34% and 36%, as compared to control beam, respectively. Zakaria et al. [17] investigated the performance of jute fibres for concrete material strengthening. Two different mix design proportion 1:2:4 and 1:1.5:3 with the volumetric fraction of jute fibres having varying length 10 - 25mm were used. It was concluded that the compressive strength, splitting tensile strength and flexural strength was improved meaningfully. Zia and Ali [30] performed experimental work on natural fibre reinforced concrete to investigate the behavior of jute fibre reinforced concrete (JFRC), nylon fibre reinforced concrete (NFRC), and polypropylene fibre reinforced concrete (PPFRC). Mix design ratio of 1:3:1.5:0.7 (cement, sand, aggregate, water) is used for plain concrete and fibre reinforced concrete. Fibre content of 5% with 50 mm fibre length was used. It was concluded that compressive strength of JFRC and NFRC was reduced 36% while PPFRC enhanced by 1% than that of PC. Splitting tensile strength of JFRC and NFRC reduced by 21% and 11% while 5% enhancement for PPFRC respectively. Tan et al. [31] conducted experiments to examine the effectiveness of sisal fibres in concrete externally wrapped with jute fibres. Twenty-four specimens were casted and tested up to the failure. It was concluded that the utilization of jute fibre as a confinement enhanced the compressive strength of both plain concrete and sisal fibre reinforced concrete. Kundu et al. [32] investigated the effect of utilization of jute fibres in concrete pavers. The jute fibres length were 3 to 5 mm with 1% weight of cement in concrete. It was concluded that the use of jute fibres enhanced that compressive, flexure and flexure toughness index by 30%, 49, and 166% respectively. It was also concluded that jute fibres was effective to be used for long term service life of concrete paver block. Kesikidou and Stefanidou [18] conducted experiments on jute, coconut, and kelp fibre to investigate its effectiveness in cement and mortars. It was concluded that utilization of natural fibres enhanced the mechanical properties in terms of strength and durability. Sen et al. [33] conducted experiments on variance in mechanical properties of jute fibres under different period of time. Jute composites were immersed in water up to 2736 hours. Based on the time of immersion of jute fibres it was concluded that tensile strength and flexure strength of jute composites were reduced. Liu et al [3] investigated behavior of jute fibres in cement based materials to improve the mechanical properties and crack restraining mechanism. Jute fibres of length 30mm with 0.5 to 0.6 kg.m^3 was used. It was concluded that the compressive and tensile strength of jute fibre reinforced concrete while the crack restraining mechanism was more effectively improved at 20 mm fibre length.

2.5 Fibre Reinforced Polymer Rebars

The use of Fibre reinforced polymer (FRP) rebar has been remarkably increased in last two decades due to their improved properties such as excellent corrosion resistance, high tensile strength, low weight and low maintenance cost. FRP bars has been used as reinforcement in bridges, buildings and other structures [34]. FRP bars are made of fibres embedded in the polymer resin while these fibres carry load and resin bonds the fibre to transfer the load. FRP bars such as Glass fibre reinforced polymer (GFRP) rebars are more commonly used bars as a replacement to steel bars due to their cheap cost. GFRP rebars are non-corrosive, environment friendly and non-hazardous in severe environments conditions [35]. Sadrie et al. [36] explored that the use of GFRP rebars in concrete structures in harsh environmental conditions extends the life duration of the structure and the overall maintenance cost of the structure. The use of GFRP rebars with high strength concrete will solve the solution of strength and corrosion problems in harsh environments. Furthermore, with adjustment in spacing of transvers reinforcement strength problems can be solved to gain high strength and ductility [37]. Mechanical properties of GFRP rebars investigated by previous researches is shown in Table 2.1.

TABLE 2.1: Summary of the mechanical properties of GFRP rebars as stated in previous literature

Reference	**Diameter (mm)**	**Length (mm)**	**f_{uT} (MPa)**	**E_{ft} (GPa)**	**F_{uC}/f_{uT}**	**E_{fc}/E_{ft}**
Muhammad et al. [8]	19.1	-	729	44	0.38	0.91
Khuramian et al. [6]	16	32	629	38.7	1.24	1.06
Hadi and Yousif [19]	10	6.25	1103	92.4	0.62	0.65
Xue et al. [38]	15.9	-	654	39	0.36	0.92

f_{ut} = Maximum tensile strength of GFRP rebars, E_{ft} = Elastic modulus of GFRP rebars, F_{uC}/f_{Ut} = compressive strength to tensile-strength ratio of GFRP rebars, E_{fc}/E_{ft} = compressive elastic modulus to tensile elastic modulus ratio of GFRP rebars.

2.6 Use of GFRP rebars in Concrete Structures

Rizkalla et al. [39] conducted study on design of FRP for strengthening of concrete structures. Different FRP bars such as aramid and glass fibre polymer rebars were used in concrete. It was concluded that high temperature 20 to 250 ^oC easily effected the bonding of FRP bars in concrete as 80% to 90% reduction was observed in bonding strength while steel bars showed 38% reduction in bonding strength. Deitz et al. [40] investigated physical properties of GFRP bars in compression. The diameter of bar used was 15mm with different effective length of 50 mm to 380mm. A total of 45 rebars were tested under compression load. It was concluded that ultimate compressive strength of 15mm diameter GFRP rebar was 50% of its ultimate tensile strength. Tensile modulus of elasticity was found equal to the compressive modulus of elasticity. Almusallam and Al-salloum [41] studied durability of GFRP rebars in concrete beams under sustained loading. A total of 36 beams with dimensions of 100 x 100 x 2000 mm were casted and tested up to the failure. The diameter of bar used was 10mm for all the specimens. It was concluded that the tensile strength of GFRP rebars were decreased due to sustained load condition. The tensile strength was reduced from 743 MPa to 622 MPa almost 16.3% loss in tensile strength. Hadi et al. [19] investigated circular columns reinforced with GFRP rebars. A total of twelve specimens with 205mm diameter and 800mm height were casted and tested up to failure. The results concluded that reduction in axial load carrying capacities was due to increment in spacing of transverse reinforcement as compared to steel reinforced specimens. However, the ductility of concrete column specimens were increased with the reduction in spacing of spirals. Karim et al. [42] studied load and moment interaction diagrams of circular concrete columns with GFRP rebars. Twelve specimens were casted with #4 GFRP rebars and #3 helices in concrete. It was concluded that GFRP reinforced specimens showed decrement in load carrying capacity than steel reinforced specimens. Furthermore, it was also concluded that insufficient longitudinal reinforcement led to brittle failure of GFRP reinforced specimen before moment interaction diagram approach reached the pure flexure strength. Vakili et al. [43] investigated effects of glass fibres on the shear strength of GFRP reinforced concrete beams. Three beams with rectangular cross section of 100 x 200 x 1500mm were reinforced with 8mm diameter GFRP rebars. It was shown that addition of glass fibre enhanced the shear strength of GFRP reinforced beams up from 55% to 233% as compared to the beams reinforced without addition of glass fibres. Maranan et al. [44] under four-point bending test evaluated the flexural strength and service ability performance of geo polymer concrete beam having GFRP rebars. It concluded that when the reinforcement ratio of glass fibre increased, the efficiency of a beam also improved, which was based on experimental results. Geo-polymer concrete beams response higher than GFRP encouraged concrete beams that was strengthen by the bending capacity of the GFRP. The geo-polymer concrete as compared to the orthodox concrete of the same review was initially improved by the mechanical properties of geo-polymer. Improve efficiency including post crack, stiffness, load capacity and deformation that was resulted by the addition in the reinforcement ratio of GFRP rebars. Zhu et al. [45] investigated effectiveness of fibre reinforced polymer rebars and partially steel fibre reinforced high strength concrete, the flexural behaviors was also investigated. Under four-point bending load, twelve beams specimens were tested. The tension zone of the beam reinforced by steel fibres of different percentages. The tension zone was successfully expanded by the steel fibres and took large bending moments. With FRP rebars ductility decreased with increased thickness of layers fibre reinforced high strength concrete (FRHSC). Division of the steel fibre volume in FRHSC. The full depth of the structure with high ductility essential to equipped by steel fibres. Mohamed et al. [46] examined the behavior of concrete columns with GFRP and CFRP rebars and reported a considerable reduction in compressive strain for GFRP specimens.

Eccentricity in square concrete columns causes bending moments in columns which reduces the load carrying capacity of columns due to which column failure occurs. Corrosion of steel rebars is one the dominant factors in reduction of axial load carrying capacity which ultimately reduced the strength and causes the failure of columns. In current study GFRP rebars are utilized in jute fibre reinforced concrete (JFRC) column prototypes to investigate the behavior of eccentric square columns. The behavior of prototype columns of PRC and JFRC with GFRP rebars under eccentric loading will be investigated and compared. According to the best knowledge of author no study has been performed on square eccentric concrete columns with jute fibres and GFRP rebars as a reinforcement.

2.7 Testing Practice

The behavior of a structure can be predicated by four methods. These methods include (i) full scale testing in actual site scenarios [47], (ii) specified boundary conditions for a full scale element [48], (iii) either scale down the prototype structure or other typical structural elements such as raw material, different cases of loading, and boundary conditions [49], (iv) to scrutinize the effectiveness small prototypes elements for comparison purposes, one variable while rest of the conditions are same with differ conditions [26, 50]. Among these conditions 4^{th} (iv) is adopted. The behavior of small prototype square columns under eccentric load condition reinforced with steel and GFRP rebars are compared.

2.8 Summary

From the literature review natural fibres can be used to enhance the mechanical properties of concrete. Fibres such as jute fibres have high tensile strength, low cost and easily available. Jute fibres increases the mechanical properties. GFRP rebars are corrosion less with high tensile strength, low weight and low maintenance cost as compared to steel reinforcement bars. GFRP rebars can be effective in harsh environment.

To the best of author knowledge, on the basis of literature review, no research has been performed on eccentric square columns with the addition of jute fibres and GFRP rebars as a reinforcement. In current research work, a total of sixteen prototype columns under eccentric load condition with different reinforcement ratio and longitudinal reinforcement types have been casted and tested. Reinforcement details used for PRC and JFRC prototypes are (4- Ø6, 8-Ø6 with Ø6-64 mm spacing) respectively. A cover of 12.5 mm is provided on the top and bottom of prototype columns while 12.5 mm distance on both sides of prototype columns. A cut length of 430 mm is used for GFRP rebars. Mechanical properties, different frequencies, damping ratios and strength of PRC and JFRC prototype columns are determined.

Chapter 3

Experimental Program

3.1 Background

The mechanical properties of jute fibre reinforced concrete with glass fibre reinforced polymer (GFRP) rebars are investigated. The main outcomes in fibre reinforced concrete are increment in mechanical properties, toughness and energy absorption. Jute fibres are used to enhance the crack resistance along with GFRP rebars through the experimental test setup. This chapter includes the detailed selection of mix design, raw materials, and casting procedure and testing procedure for all the specimens.

3.2 Raw Materials

The ingredients for the preparation of plain concrete includes fresh drinking water, ordinary Portland cement, locally available sand and standard aggregates. While, preparation of JFRC consists of same ingredients with an extra addition of one ingredient named as jute fibres (JF). It can be noted that jute fibres possess very high tensile strength whereas its elongation is 1.5 to 1.8%. Table 3.1 also illustrates high stiffness values. Conditioned jute fibre having 0.4 mm diameter purchased from local market in Pakistan and by hand cut to a length of 50 mm. With the help of scanning electron microscope images the microstructure of jute fibre is examined.

Table 3.1: Mechanical properties of jute fibres

Properties	**Values**
Length (mm)	50
Diameter (mm)	0.40
Aspect ratio	125
Density (kg/m^3)	1460
Specific gravity	1
Water absorption (%)	13
Tensile strength (MPa)	393-773
Elongation (%)	1.5-1.8

Table 3.2 shows mechanical properties of GFRP rebar and steel rebar. Both bars have same diameter of 6 mm. The test is performed by using STM machine in the laboratory. The ultimate tensile strength of steel rebar (fs) and GFRP rebar (fg) after testing is 505 MPa and 859 MPa respectively. The steel rebar has the yielding point before rupture point which indicates ductile behavior, whereas GFRP rebar ruptures without yielding point which indicates brittle behavior. Regardless of

Table 3.2: Mechanical properties of rebars

Properties	**GFRP**	**Steel**
Diameter (mm)	6	6
Cross sectional area (mm^2)	28.27	28.27
Density (kg/m^3)	2200	7850
Weight (kg/m)	0.05	0.22
Ultimate strength (MPa)	859.78	505
Elastic nodulus (GPa)	46	200
Ultimate tensile strain (%)	1.2-3.1	6-12

yielding point GFRP rebar possess benefits over steel rebar such as higher tensile strength, non-conductivity, non-magnetic properties especially in hospitals where

X-Rays machines are highly magnetic and electric conductive. It also has the properties such as lightweight, corrosion resistance and high tensile strength which makes it utilizable under eccentric load condition. It can be noted that the ultimate tensile strength of GFRP rebar is 70% greater than that of normal steel rebar.

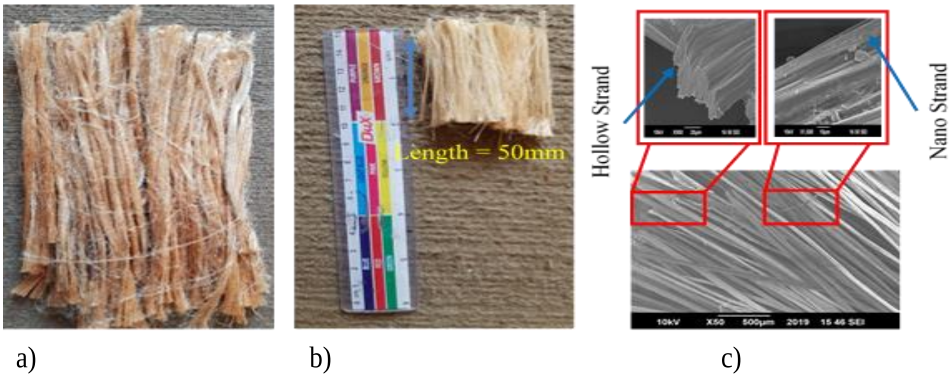


FIGURE 3.1: Jute fibres; a) raw fibres, b) prepared fibres and c) 50m SEM view

Fig. 3.1 shows the raw form of jute fibres as cut to 50 mm length with the SEM view showing. From Fig. 3.1 (c), it is observed that jute fibre comprises of micro tubes character laid together in the longitudinal direction. The edges of fibre shows that these micro tubes (jute fibres) are hollow. It is evident that it can be the source of water absorption of jute fibre. Commonly jute fibres have an average diameter of 0.4 mm. Fig. 3.2 (a) shows diameter, length and of GFRP rebar along with stress strain graph of steel and GFRP rebar. It can be noted that Figure 3.2 (b) that the curve of GFRP rebar do not show yielding stress point which shows its brittle behavior.

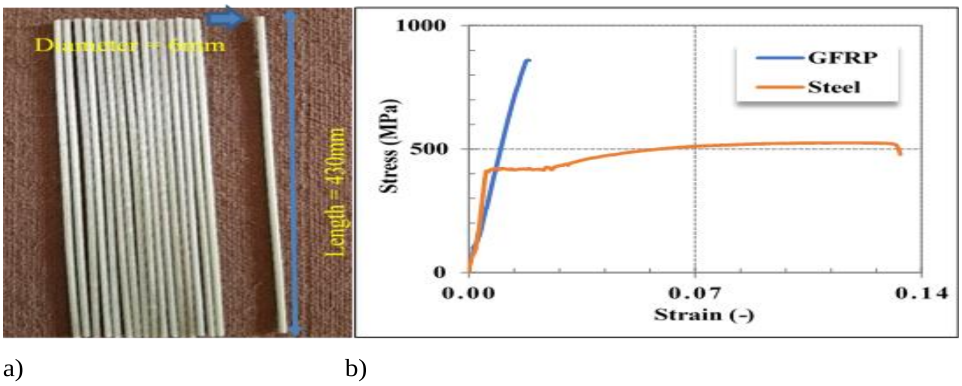


FIGURE 3.2: GFRP rebars; a) naked eye and b) relative strength of steel and GFRP rebar

3.3 Selection of Mix Design and Casting Procedure

The proportion of 1:2:3:0.60 (Cement: Sand: Crush: Water cement ratio) is used for the preparation of plain concrete as well as for JFC as shown in Table 3.3. The length of jute fibre is 50 mm while 5% content is used by mass of cement. The targeted compressive strength at 20 MPa in order to enactment of fibres reinforced concrete practically in the field to use this mix design proportion is the main purpose. All the ingredients have to be measured in kg (mass) but for the exception of water which was measured in liters. The non-tilting rotary type drum concrete blender has been used to prepare JFC and PC. By blending all the materials along with water by pouring it in the drum for three minutes the preparation of PC is done. A different type of method is used for the preparation of JFC [32]. To prevent the balling effect, the ingredients has to be placed in layer by layer form into the blender. In the blender drum the one third part of materials listed as (cement, sand, aggregate and jute fibres) are placed turn by turn. Initially after the insertion of material entirely into the blender drum the amount of 33% of total water is spread on all materials. After that during the rotation of the machine slowly and gradually addition of 67% the remaining amount of water in the drum. To get a homogenous concrete the blender has to be rotated for six minutes in which two minutes is for each layer. With the help of 25 number of

Table 3.3: Mechanical properties of PC and JFC with mix design ratio of (1:2:3:0.6)

Property	**Fibre**	**Cement**	**Fibre**	**Fine Aggregate**	**Coarse Aggregate**	**Water**	**w/c**
	(%)	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(ltr/m^3)**	
PC	0%	333.33	0	666.66	1000	200.00	0.6
JFC	5%	330.81	16.67	661.61	992.42	198.48	0.6

blows which With the help of 25 number of blows which are done with the help of temping rod as per ASTM standard are filled in each three layers in case of molds, to reduce the air voids 75 to 100 mm molds are free felled. By utilization of the following process, the specimens of PC and JFC are casted. For labelling the molds they are extracted after 48 hours. Then they are placed into a water container for the curation of specimens for 28 days.

3.4 Specimens

In current study for determination of mechanical properties of PC and JFC, cylinders and beam-lets were casted. Cylinder molds had the dimensions of 100 mm diameter and 200 mm height whereas for beam-let molds had 100 mm width, 100 mm height and 450 mm length. Twelve specimens (i.e. six for PC and six for JFC) has to be casted for compressive strength and splitting tensile strength testing. Six specimens (i.e. three for PC and three for JFC) was casted for flexural strength testing. As per ASTM standards C-39M-18 [51], C-496M-17 [52] and C-293M-16 [53] three different minimum loading rate 0.15 MPa/s for splitting-tensile test, 0.78 MPa/min are used for compressive test and 0.86 MPa/min were used for flexural test. By taking average of three samples values. Dynamics testing is performed according to ASTM C215-02 [54]. It can be seen from Table 3.4 the damping ratio for JFC cylinders and beams are more than that of cylinder and beams of PC. In comparison with PC the JFC specimens demonstrated more energy dissipation. In both cases up to 1.76 and 1.43 correspondingly as related to PC cylinder and beams the damping ratio is increased for JFC specimens. For all PC and JFC specimens mechanical tests have been done to determine the mechanical properties.

In Fig. 3.3 (a) shows compressive behavior. Compressive strength is taken from the stress stain graph. The area under curve from zero to the peak load is considered as the initial energy absorption (E_m). The area under curve from peak load to ultimate load is considered as post cracking energy absorption (C_{cr}.E). The total energy absorption (TE) is taken as the total area under the curve. The toughness index (TI) is the ratio between total energy absorption to initial energy absorption

TABLE 3.4: Resonance frequencies and damping ratios for beam and cylinder specimens

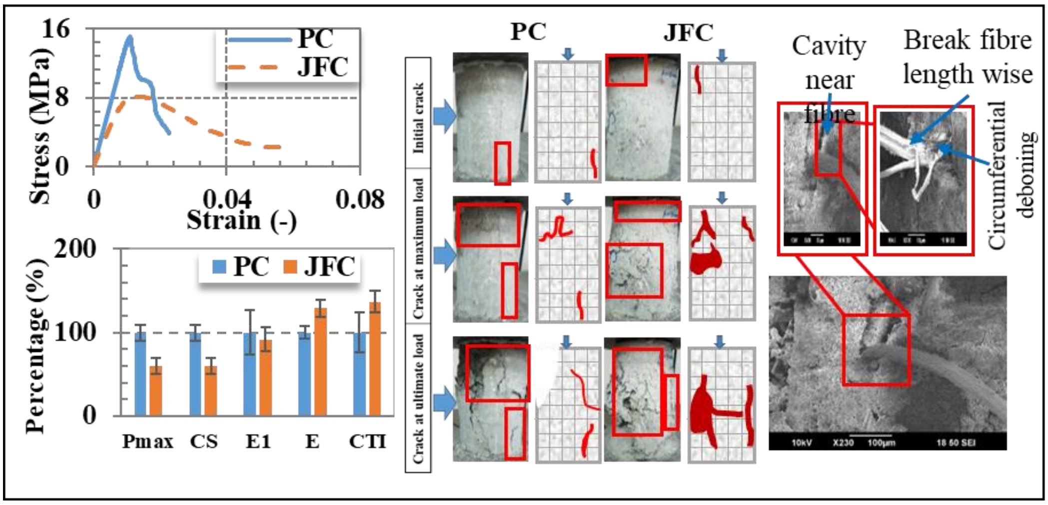
Specimen	No.		Resonance Frequency			Damping Ratio
			$\mathbf{f}_l$	$\mathbf{f}_t$	$\mathbf{f}_r$	
Beam	PC	3	1511 ± 173	1642 ± 44	1592 ± 125	2.78 ±0.45
	JFC	3	1200 ± 48	1242 ± 76	1227 ± 92	4.21 ± 1.05
Cylinders	PC	6	3217 ± 615	1685 ± 226	1516 ± 12	2.62 ± 0.14
	JFC	6	1767 ± 317	1043 ± 202	1509 ± 0	4.38 ± 0.93

((E_m+C_{cr}.E)/E$_m$). Table 3.5 shows the mechanical properties of PC and JFC with mix design ratio of (1:2:3:0.6). The cracked energy absorption and toughness index of JFC specimens are increased up to 37% and 32%, respectively as compared to PC specimens. Toughness index has been also increased up to 22.10% as related to PC. Although there was considerable decrease in compressive strength. The values of energy absorption and toughness index have been considerably increased in all JFC specimens. It can be noted that under compression loading the PC specimens should brittle behavior while JFC showed bridging effect due to jute fibre. In PC some of the fragments have fallen down. The stress strain curve, compressive properties and comparison of mechanical properties are shown in Fig. 3.3 (a). The results are analyzed through SEM images at failure surface, refer Fig. 3.3 (a). These images assisted in studying fibre and concrete matrix bonding. SEM images shows the conditions resulted at tested surface of JFRC specimen under compressive load. Fibre pull-out is clearly evident from the SEM images. It can also be noted that there is a circumferential debonding at fibre. Similarly, fibre break length wise is visible from SEM images. While analyzing images cavity near fibre is observed. Fig.3.3 (b) shows split tensile properties for all PC and JFC specimens. The comparison of splitting properties shows that Pmax, E1 and STS reduced 62.05%, 62.05%, 30.55% whereas E and STI increased 187.16% and 259%. Specimens under splitting loading showed sudden failure and broken into two pieces are PC while bridging effect was noticed for JFC specimens. The crack propagation of specimens are shown through schematic diagram. The PC specimens broke into two pieces at the maximum load whereas JFC specimens showed bridging effect. SEM images at failure surface of tested JFC specimen are shown under splitting load. The cause of failure observed through analysis is fibre pull-out. The visible cavity at the toe of fibre is indication of improper bonding of fibre and concrete matrix. On the other hand, cavity is not much deep, so it can be assumed that the reason behind the cavity is air entrapped near the surface of fibre. In Fig. 3.3 (c) shows flexural behavior. Similar behavior was noticed under flexural loading. Flexural strength, Em, Cr. E, TE and TI of PC and JFC are shown in Table 3.5. The flexural strength of JFC specimens are decreased by 0.59 MPa than PC specimens. The Cr. E, TE and TI 7.38J, 6.66J and 2.13 respectively than PC specimens.

TABLE 3.5: Mix design ratio for PC and JFC (1:2:3:0.6)

Properties	**Compressive**		**Splitting Tensile**		**Flexural**	
	PC	**JFRC**	**PC**	**JFRC**	**PC**	**JFRC**
Pmax (kN)	131.26 ± 12.49	79.20±10	76.33 ± 14.86	47.10 ± 7.85	7.39 ± 0.54	6.06 ± 0.99
Strength (MPa)	16.19 ± 1.59	9.77 ± 1.27	2.43 ± 0.47	1.50 ± 0.24	3.32 ± 0.25	2.73 ± 0.44
Em	0.08 ± 0.02 MJ/m^3	0.07 ± 0.01 MJ/m^3	29.61 ± 5.35 J	22.68 ± 1.01 J	5.10 ± 0.20 J	4.11 ± 0.26 J
Ccr.E	0.13 ± 0.02 MJ/m^3	0.18 ± 0.02 MJ/m^3	0 J	61.35 ± 2.05 J	0 J	7.38 ± 1.41 J
TE	0.19 ± 0.01 MJ/m^3	0.25 ± 0.03 MJ/m^3	29.61 ± 5.35 J	85.03 ± 2.05 J	5.10 ± 0.20 J	11.76 ±1.41 J
TTI	2.76 ± 0.70	3.37 ± 0.22	1	3.59 ± 0.25	1	3.13 ± 0.67

Application of flexural load resulted in pull-out of fibres and along with splitting of fibre. The splitting of fibre is like threads. Existence of concrete matrix is clearly visible through SEM images. Presence of small cavity on tested surface indicates good bonding among concrete and fibre, whereas propagation of cavity resulted



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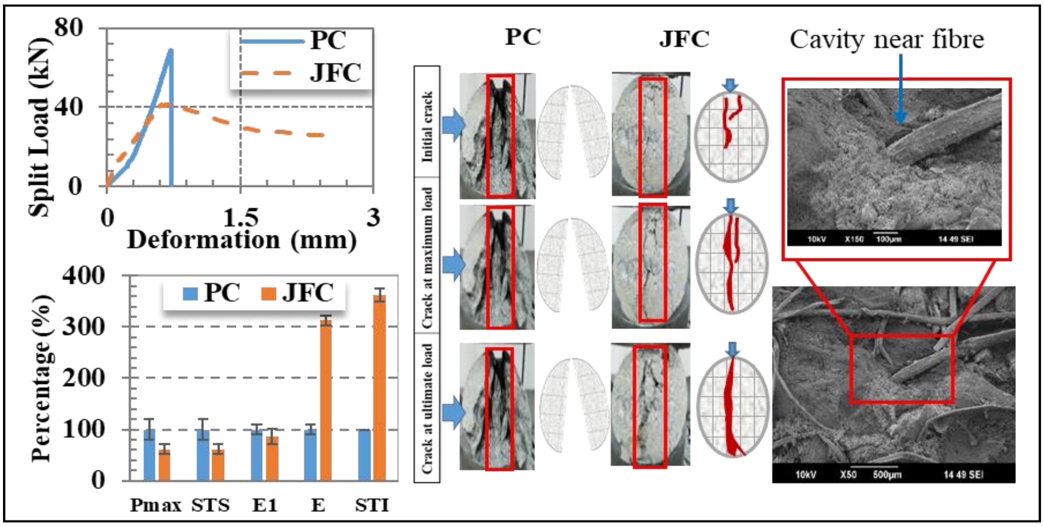

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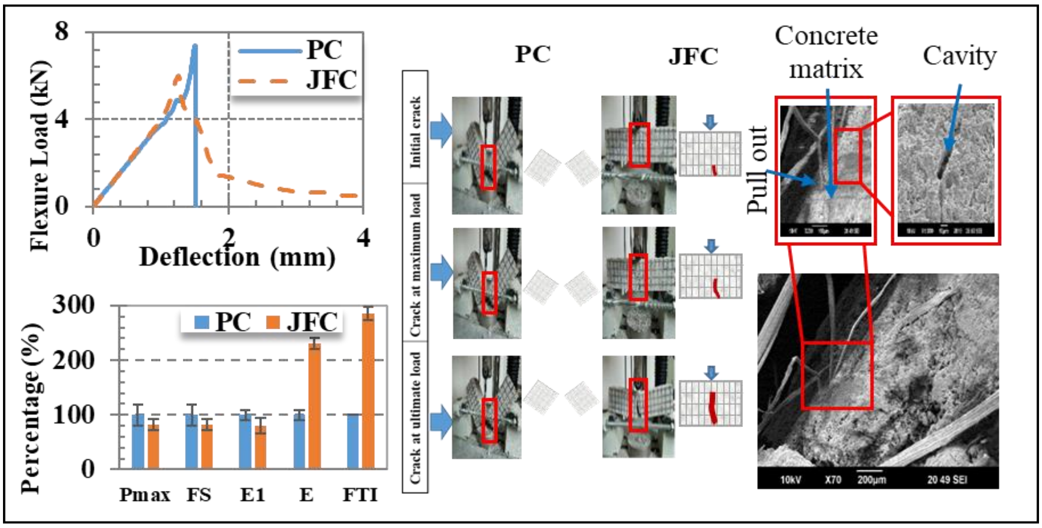


c)

FIGURE 3.3: Mechanical properties; a) compressive behavior, b) split tensile behavior and c) flexural behavior

Under eccentric load condition a total of sixteen prototype column samples were casted and tested. Detailed of specimens and reinforcement arrangement for steel-reinforced and GFRP-reinforced prototype to be tested to the laboratory are shown in Table 3.6.

Table 3.6: Test matrix with labelling for prototype

S. No	**Longitudinal Rebars**	**Steel Ties**	**Ratio**	**Labels**	
				PRC	**JFRC**
1	4-Ø6	Ø6-64mm	0.011	4SPC-A/B*	4SJC-A/B*
2	4-Ø6	Ø6-64mm	0.011	4GPC-A/B*	4GJC-A/B*
3	8-Ø6	Ø6-64mm	0.022	8SPC-A/B*	8SJC-A/B*
4	8-Ø6	Ø6-64mm	0.022	8GPC-A/B*	8GJC-A/B*

*Note: A & B represents different load rate (0.19 MPa/s and 0.31 MPa/s) applied on specimens.

in air entrapped in voids. It can be noted that strong bonding between concrete matrix and jute fibre is present. That has been weaken by flexural load. Thus debonding is the key cause in fibre flexural. Under mechanical loading proper mixing of jute fibre with concrete is seen in SEM results.

For eccentric testing and material (that is PC and JFRC) the set of two specimens are considered. Width of 100 mm, height of 100 mm and length of 450 mm were used for all samples. To meet the condition and capacity of the available testing apparatus the size of prototype specimens was selected in the laboratory. All specimens in the shape of beam were prepared and tested as a column. By the longitudinal GFRP rebars, material and its numbers the specimen are identified. Smaller diameter of 6 mm are used in the prototype specimens. The same steel reinforcement spacing at the rate of 64 mm for the four and eight number of longitudinal GFRP rebars is used. The loading rate was 0.19 MPa/s and 0.31MPa/s for eccentric load test. ASTM C39M-18 was used for taking the average of two values that can also be verified. The reinforcement detailing for steel and GFRP reinforced concrete column is shown in Fig. 3.4.

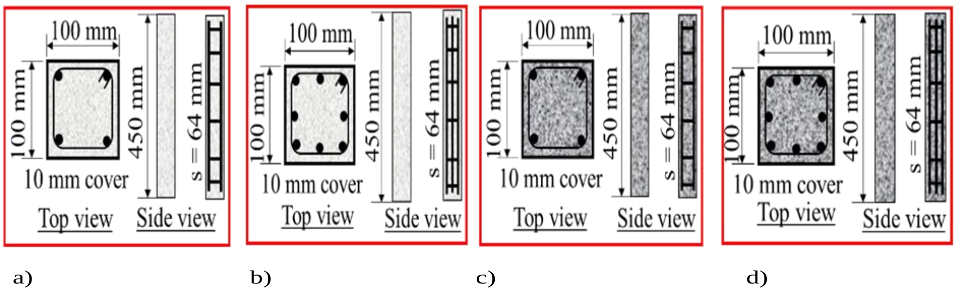


FIGURE 3.4: Reinforcement detailing for; a) steel and GFRP in RC with 4 rebars, b) steel and GFRP in RC with 8 rebars, c) steel and GFRP in JFRC with 4

3.5 Testing Procedure

3.5.1 Dynamic Properties of Prototype

In current research work, dynamic testing is performed for prototype columns of PRC and JFRC. Properties such as torsional frequency, transverse frequency, longitudinal frequency and damping ratios have been determined as per ASTM standard C215-02 [54]. Figure 3.5 shows resonance apparatus for dynamic testing.

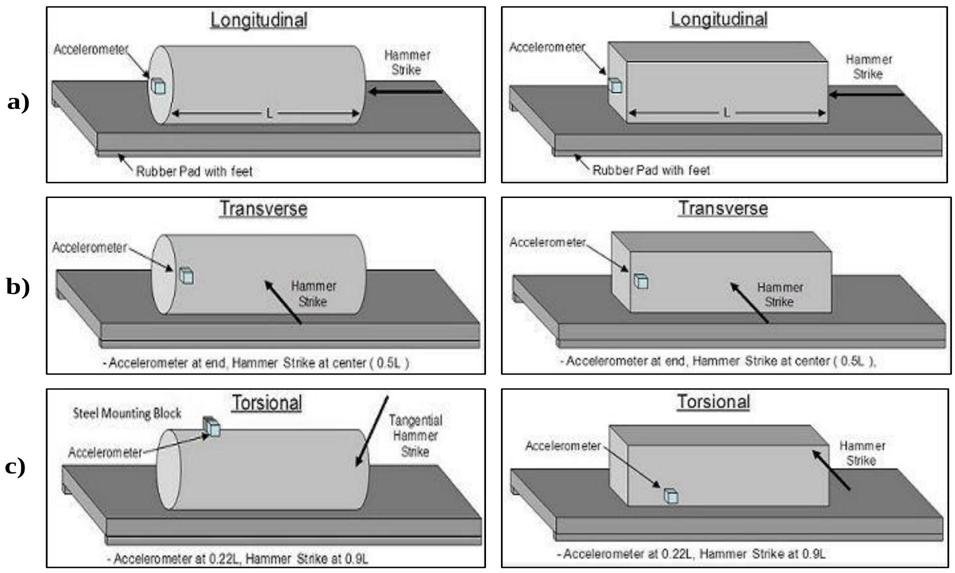
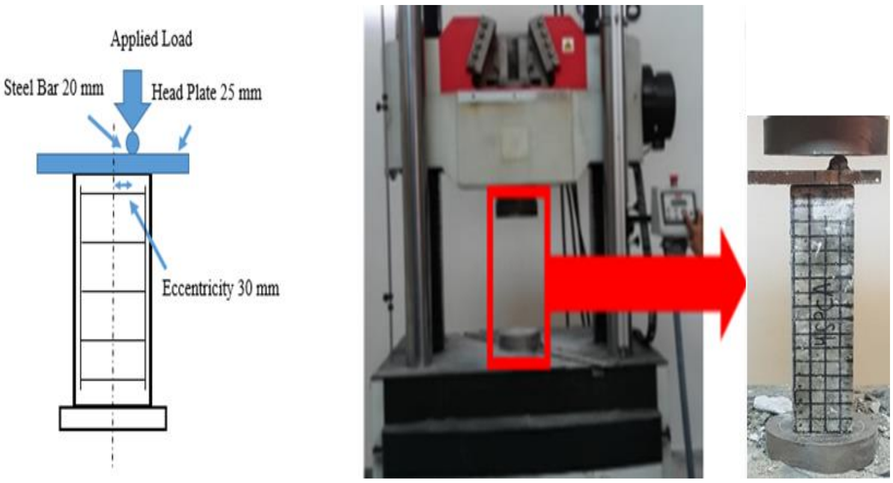


FIGURE 3.5: Resonance apparatus for dynamic testing as per ASTM C215 [54] for; a) Longitudinal frequency, b) Transverse frequency and c) Torsional frequency.

3.5.2 Eccentric Load Test

In the testing procedure for eccentrically loaded columns the same method used is similar to that of concentrically loaded column. A 25 mm thick steel plate and 25 mm diameter round bar is placed between the specimen and the head of Servo testing machine (STM). Load mechanism and experimental test setup for prototype columns to be tested under eccentric condition are shown in Fig. 3.6. Elchalakani et al. [56] used 30 mm eccentricity in testing of glass fibre reinforced concrete columns subjected to eccentric axial loading. In this study load mechanism described by Elchalakani et al. [56] is adopted to carry out the testing for prototype square columns. The total width of the square prototype column is 100 mm, half of the prototype is 50 mm, after minus of 10 mm concrete cover, the remaining is 40 mm. The applied load is at 30 mm eccentricity on the inner part of 40 mm, because the applied load is inside the concrete core. A head plate of steel having 25mm thickness is placed only on the top surface of prototype and a rod of steel rebar having 20 mm diameter is placed on the steel head plate. The load is applied only in one direction from the top surface on the prototype at an eccentricity of 30 mm. Fig. 3.6 (a) shows the load mechanism it can be seen that the load is applied at eccentricity of 30 mm. The steel bar should be 30 mm apart from the center of the steel plate.



a) b)

FIGURE 3.6: Eccentric load mechanism; a) schematic view and b) test set up

3.6 Summary

With the mix design ratio of 1:2:3:0.6 PC specimens are prepared. With the same mix design by the addition of 5% jute fibre content by mass of cement the preparation of JFRC is done. To determine the eccentric behavior of RC column with jute fibers a total of 16 prototype square eccentric columns are used to determine the compressive properties, failure mode under SEM analysis and overall structural behavior.

Chapter 4

Experimental Evaluation

4.1 Background

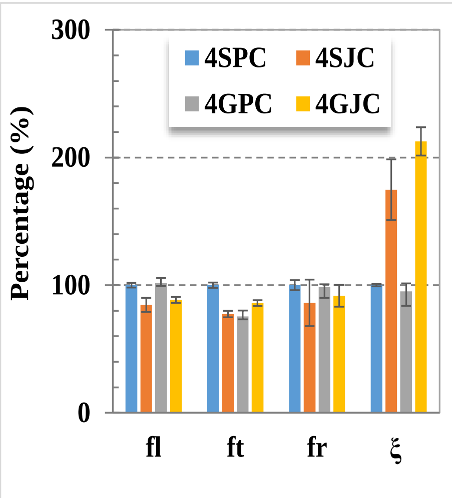
PC is prepared by using a mix design ratio of 1: 2: 3: 0.6 whereas for JFC similar mix design is selected along with the addition of 5% jute fibres by mass of cement having a length of 50 mm. To examine the dynamic properties and behavior of prototype columns with experimental results of PRC and JFRC prototype specimens are being discussed in this chapter.

4.2 Frequencies and Damping Ratio of Porotypes

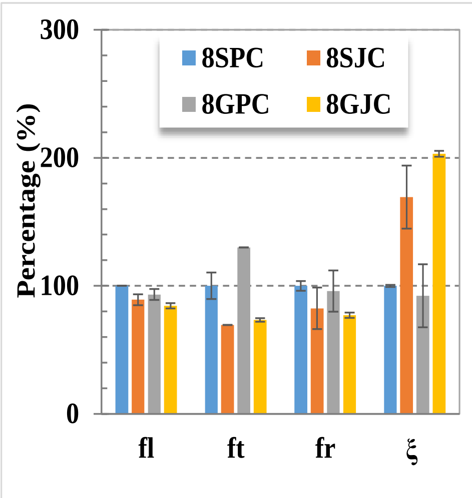
Resonance frequencies and damping ratios of PRC, JFRC prototype specimens are determined which are presented in Table 4.1. Methodology used for obtaining the frequencies and damping ratios of JFRC is similar to PRC [55]. The reason behind this selection is non-availability of any separate criteria for fibre reinforced concrete (FRC) in codes. For PRC prototype specimens longitudinal, torsional and transverse frequencies are greater than JFRC specimens. The prime objectives for performing the dynamic test is to investigate the internal properties and to check any increase in dampness by the addition of jute fibres. It can be seen from Table 4.1 the damping ratio for JFRC prototypes are more than that of PRC prototype specimens. In comparison with PRC the JFRC specimens demonstrated more energy dissipation. The damping ratio of 4SJC is more up to 74.58% than 4SPC prototype specimen. The damping ratio of 4GJC is more up to 123.52% than 4GPC prototype specimen. The damping ratio of 8SJC is more up to 69.39% than 8GPC prototype specimen. The damping ratio of 8GJC is more up to 120% than 8GPC prototype specimen.

TABLE 4.1: Resonance frequencies and damping ratios for prototypes specimens

Specimen	**No.**	**Resonance Frequency**			**Damping Ratio**
		f_l	f_t	f_r	
4SPC	2	1529 ± 23	1575 ± 31	1597 ± 62	3.58 ± 0.03
4SJC	2	1292 ± 71	1220 ± 31	1375 ± 250	6.25 ± 1.48
4GPC	2	1553 ± 63	1191 ± 54	1575 ± 33	3.40 ± 0.21
4GJC	2	1353 ± 32	1353 ± 32	1464 ± 125	7.60 ± 0.84
8SPC	2	1642 ± 0	1724 ± 178	1642 ± 62	3.79 ± 0.03
8SJC	2	1464 ± 63	1198 ± 0	1354 ± 219	6.42 ± 1.58
8GPC	2	1531 ± 31	2241 ± 31	1575 ± 31	3.50 ± 0.08
8GJC	2	1386 ± 203	1264 ± 31	1264 ± 31	7.70 ± 1.78



a)



b)

FIGURE 4.1: Prototypes dynamic results; a) 4-longitudinal rebars and b) 8-longitudinal rebar

Fig. 4.1 shows results of dynamics results of prototypes for PRC and JFRC. It can be noted that energy dissipation has increased by the addition of jute fibres in JFRC prototypes as compared to PRC prototypes. The damping ratio has been increased for 4SJC, 4GJC, 8SJC,8GJC as compared to 4SPC, 4GPC, 8SPC, 8GPC. Chopra [55] reports that greater damping ratio significantly reduces response of the structure against dynamic loading. This damping relates to the energy losses due to material type as more energy absorption produces greater damping ratios. Thus, more energy absorption results in greater damping. Since JFRC prototypes has more energy absorption due to jute fibres incorporation. Thus it increases the damping ratio. This increment in energy absorption results in better structural performance. The trend of increment in frequencies and damping ratios in prototype columns is similar to that of cylinder and beam specimens. The energy dissipation of JC and JFRC specimens are increased as compared to PC and PRC specimens due increment in damping ratios.

4.3 Behavior of Prototype Square Columns under Eccentric Loading

The results of the two different loading rates are close to each other. Thus, average stress value is taken. Strength is obtained as the peak stress from the stress strain curve. Energy absorption for the compressive behavior is obtained as area under the stress strain curve. The units of energy absorption is given as MJ/m^3. The strength, C. Em, Ccr.E, CE and CTI of PRC and JFRC are shown in Table 4.2. JFRC prototype with GFRP rebars eccentric columns shows more load than JFRC prototype with steel rebars specimens. Prototype 4GJC showed 8.46 kN more load than 4SJC. Similarly, 8GJC showed 17.83 kN more load than 8SJC. JFRC prototype with GFRP rebars eccentric columns shows more compressive strength than PRC with steel rebars prototype specimens. Prototype 4GJC showed 0.84 MPa more compressive strength than 4SJC. Similarly, 8GJC showed 1.58 MPa more compressive strength than 8SJC. Prototype 8SPC showed 2.56 MPa more

Table 4.2: Experimental outcomes of tested prototypes with different longitudinal rebars

Spec.	**Load (kN)**	**Strength (MPa)**	**C.Em (MJ/m^3)**	**Ccr. E (MJ/m^3)**	**CE (MJ/m^3)**	**CTI (-)**	**Failure Mode**
4SPC	120.02±9.5	12.02±0.9	0.03±0.01	0.04±0.01	0.07±0.01	2.37±0.04	Crushing
4SJC	73.57±4.54	7.36±0.45	0.04±0.01	0.09±0.01	0.13±0	3.25±0.08	Bridging
4GPC	97.71±3.61	9.77±0.36	0.05±0.01	0.04±0	0.09±0.01	2.33±0.29	Crushing
4GJC	82.03±2.78	8.20±0.27	0.04±0.01	0.12±0.01	0.16±0.01	4.00±0.33	Bridging
8SPC	145.87±1.6	14.58±0.1	0.04±0.01	0.05±0.01	0.09±0.01	2.07±0.15	Crushing
8SJC	71.00±2.52	7.1±0.25	0.04±0.01	0.12±0.01	0.16±0.02	4.00±0.16	Bridging
8GPC	111.63±1.8	11.16±0.1	0.05±0.01	0.09±0.01	0.14±0.02	2.80±0.02	Crushing
8GJC	88.83±3.00	8.68±0.3	0.04±0.01	0.15±0.01	0.19±0.01	4.45±0.22	Bridging

compressive showed 2.56 MPa more compressive strength than prototype 4SPC. Prototype 8GPC showed 1.39 MPa more compressive strength than 4GPC. Prototype 8GJC showed 0.48 MPa more compressive strength than prototype 4GJC. Prototype 4GJC showed negligible difference in compressive strength as compared to prototype 8SJC. JFRC prototype eccentric square columns showed more compressive toughness index than PRC prototype eccentric square column. Prototype showed highest toughness index of 4.45 than all other prototypes. Prototype 4SJC showed 0.88 more compressive toughness index than 4SPC. Prototype 4GJC showed 1.67 more compressive toughness index than prototype 4GPC. Prototype 8SJC showed 1.93 more compressive toughness index than 8SPC. Prototype 4SPC showed 0.3 more compressive toughness index than 8SPC. Prototype 8SJC also showed more compressive toughness index than 4SJC up to 0.75. Prototype 8GPC showed 0.47 more compressive toughness index than 4GPC. Prototype 8GJC showed more 0.45 compressive toughness index than 4GJC. Strength of 8SPC is greater up to 30% as compared to 8GPC. This is due to lesser relative strength of GFRP rebar in compression than steel rebar, which ultimately effects the load carrying capacity of columns. But 8GPC shows better performance in post cracking region because GFRP-RC prototype absorbed 80% more energy in post cracking region as compared to the RC prototype. The overall performance in terms of damping ratio, compressive strength, compressive post cracking energy absorption and compressive toughness index of 8GJC is better as compared to the 8SJC. The damping ratio of 8GJC is up to 20% greater as compared to 8SJC due to addition of jute fibres and also due to lower density of GFRP rebars as compared the steel rebars. Prototype 8GJC shows better performance in post cracking region because GFRP with jute fibres absorbed 25% more energy in post cracking region as compared to the 8SJC. The compressive toughness index of 8GJC is greater than 12% as compared to the 8SJC. This is due to more energy absorption in post cracking region in GFRP-RC prototype. Development of jute fibres produces bridging and resists crack initiation, crack propagation and ultimately results in better structural performance.

In Figure 4.2 (a) stress strain graph for prototype square eccentric column is shown.

It can be seen that strain for JFRC is increased as compared to the PRC strain. The energy absorption is greater for JFRC as compared to PRC. It means that JFRC show more ductile behavior than PRC. PRC shows sudden drop whereas JFRC show gradual decrease in curve. In Fig. 4.2 (b) crack propagation behavior is explained for prototypes with 4 and 8 longitudinal rebars and crack pattern is shown through schematic diagram. It can be seen that cracks has occurred on the top portion of prototypes where load has been applied on the edges on some eccentricity. For maximum load the cracks has propagated up to 3 inch from the top position. Furthermore, at ultimate load crack has occurred at left bottom for all prototypes. Bridging effect is also seen for JFRC prototypes as compared to PRC prototypes where some particles of concrete has broken and fallen down. In Fig. 4.2 (b) crack propagation behavior is explained for prototypes with 8 longitudinal rebar and crack pattern is shown through schematic diagram. It can be seen that cracks has occurred on the top portion of prototypes where load has been applied on the edges on some eccentricity. For maximum load the cracks has propagated up to 3 inch from the top position. Furthermore, at ultimate load crack has occurred at left bottom for all prototypes. Bridging effect is also seen for JFRC prototypes as compared to PRC prototypes where some particles of concrete has broken and fallen down. Fig. 4.3 (a) shows comparison of properties for prototypes with 4-longitudinal rebar. It can be noted that from the graph the percentage of compressive crack energy, total compressive energy and compressive toughness index of 4SJC is greater up to 125%, 85.71% and 37.50% respectively than that of 4SPC. The percentage of compressive crack energy of 4GPC is equal to 4SPC prototype, the percentage of total compressive energy of 4GPC is greater up to 28.57% as compared to 4SPC, the percentage of compressive toughness index of 4GPC is less up to 4.16% than that of 4SPC prototypes. The percentage of compressive crack energy, total compressive energy and compressive toughness index of 4GJC is greater up to 200%, 128.57% and 66.67% respectively than that of 4SPC prototype. It can be noted that prototype 4GPC showed reduction of strength up to 22.83% as compared to 4SPC. The compressive energy absorption of 4GPC is increased up to 28.57% than 4SPC and compressive toughness index has decreased up to 1.71%. Prototype 4GJC showed better mechanical properties as compared to 4SJC. Compressive strength has increased up to 11.49%, compressive energy absorption up to 23.07% and compressive toughness index has increased up to 23.07% for Prototype 4GJC as compared to 4SJC. Prototype 4SPC showed increased strength of 63.13% as compared to 4SJC. While the compressive energy absorption and compressive toughness index has increased up to 85.71% and 37.13% respectively for 4SJC than 4SPC. Prototype 4GPC showed increment of 19.11% in strength than 4GJC. Prototype 4GJC showed increment of 77.77% and 71.67% in compressive energy absorption and compressive toughness index as compared to 4GPC. Prototype 4GPC showed increment of 32.81% in strength than 4SJC. Whereas for 4SJC compressive energy absorption and compressive toughness index has increased up 44.44% and 39.48% as compared to 4GPC prototype. 4SPC showed increase of 46.31% in strength than 4GJC. Prototype 4GJC showed increase of 128.57% and 68.77% in compressive energy absorption and compressive toughness index than 4SPC. Fig. 4.3 (b) shows comparison of properties for prototypes with 8-longitudinal rebar. It can be noted that from the graph the percentage of compressive crack energy, total compressive energy and compressive toughness index of 8SJC is greater up to 140%, 77.77% and 90.47%, respectively than that of 8SPC prototype. The percentage of compressive crack energy, total compressive energy and compressive toughness index of 8GPC is greater up to 80%, 55.55% and 33.33% respectively than that of 8SPC prototype. Strength of 8SPC is greater up to 30% as compared to 8GPC. This is due to lesser relative strength of GFRP rebar in compression than steel rebar, which ultimately effects the load carrying capacity of columns. But 8GPC shows better performance in post cracking region because GFRP-RC prototype absorbed 80% more energy in post cracking region as compared to the RC prototype. The percentage of compressive crack energy, total compressive energy and compressive toughness index of 8GJC is greater up to 200%, 111.11% and 114.28% respectively than that of 8SPC prototype. The overall performance in terms of damping ratio, compressive strength, compressive post cracking energy absorption and compressive toughness index of 8GJC is better as compared to the 8SJC. The damping ratio of 8GJC is up to 20% greater as compared to 8SJC due to addition of jute fibres and also due to lower density of GFRP rebars as compared the steel rebars. Prototype 8GJC shows better performance in post cracking region because GFRP with jute fibres absorbed 25% more energy in post cracking region as compared to the 8SJC. The compressive toughness index of 8GJC is greater than 12% as compared to the 8SJC. This is due to more energy absorption in post cracking region in GFRP-RC prototype. Development of jute fibres produces bridging and resists crack initiation, crack propagation and ultimately results in better structural performance. It can be noted that prototype 8GPC showed reduction of strength up to 30.67% as compared to 8SPC. The compressive energy absorption of 8GPC is increased up to 55.55% than 8SPC and compressive toughness index has increased up to 35.26%. Prototype 8GJC showed better mechanical properties as compared to 8SJC. Compressive strength has increased up to 25.11%, compressive energy absorption up to 18.75% and compressive toughness index has increased up to 11.25% for Prototype 8GJC as compared to 8SJC. Prototype 8SPC showed increased strength of 105.45% as compared to 8SJC. Prototype 8SJC showed increment of 77.77% and 93.23% in compressive energy absorption and compressive toughness index than 8SPC. Prototype 8GPC showed increment of 25.66% in compressive strength than 8GJC. Prototype 8GJC showed increment of 35.71% and 58.93% in compressive energy absorption and compressive toughness index as compared to 8GPC. Prototype 8GPC showed increment of 57.23% in compressive strength than 8SJC. Whereas for 8SJC compressive energy absorption and compressive toughness index has increased up 14.28% and 42.86% as compared to 8GPC prototype. Prototype 8SPC showed increase of 64.21% in compressive strength than 8GJC. Prototype 8GJC showed increase of 111.11% and 114.98% in compressive energy absorption and compressive toughness index than 8SPC. Prototype 8SPC and 8GPC showed more strength than 4SPC and 4GPC. Prototype 8SJC and 8GJC showed approximately equal strength as compared to 4SJC and 4GJC.

In dynamic properties of RC column longitudinal frequency and dynamic elastic modulus is more but damping ratio is less. In static properties of RC column

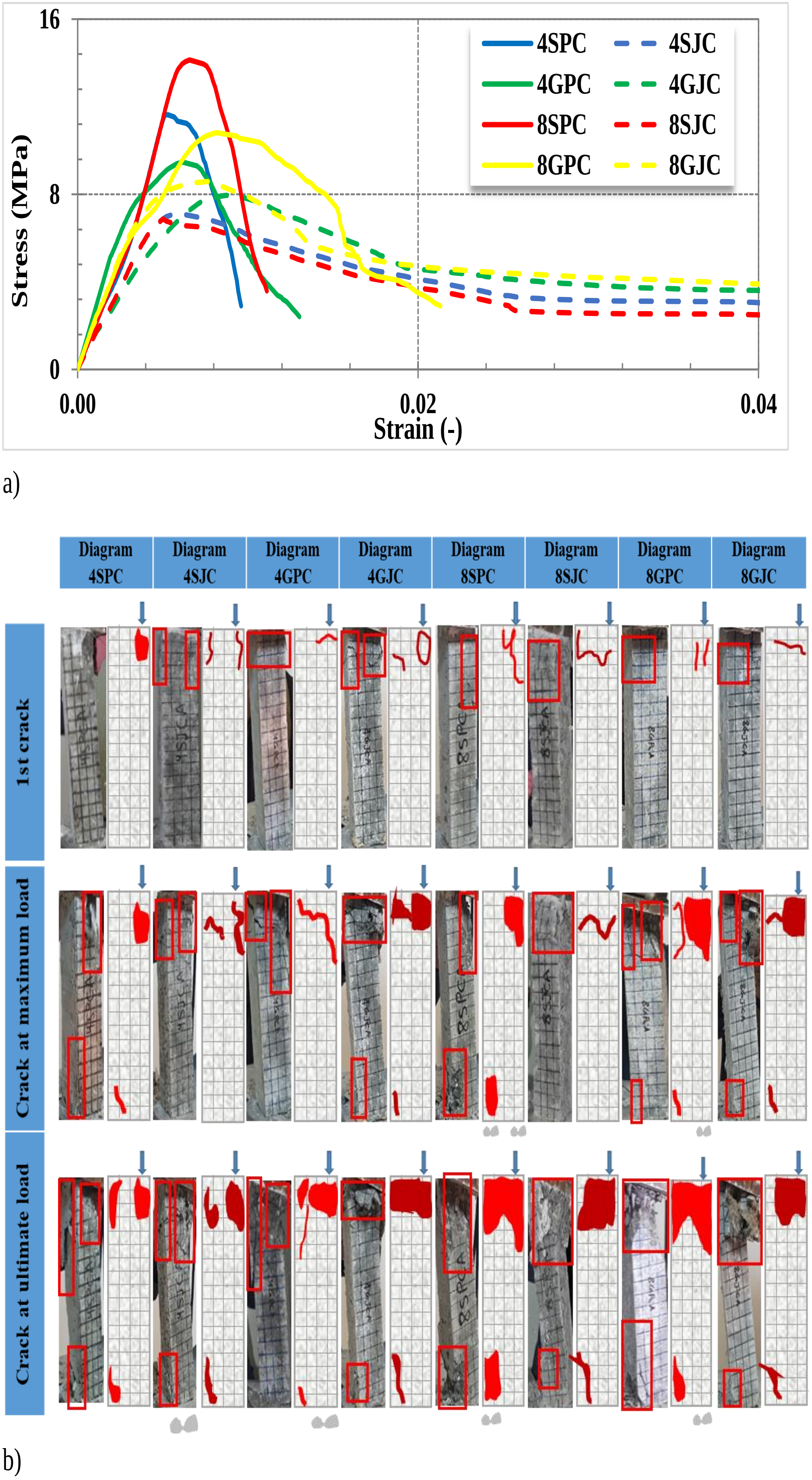
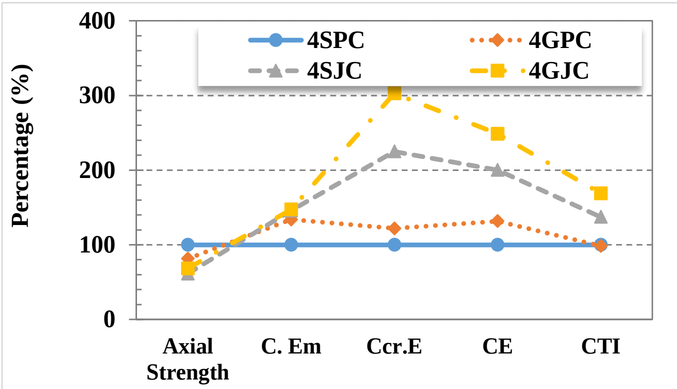


FIGURE 4.2: Compressive behavior of eccentric square prototypes with 4 and 8 longitudinal rebar; a) stress-strain curve and b) tested specimens

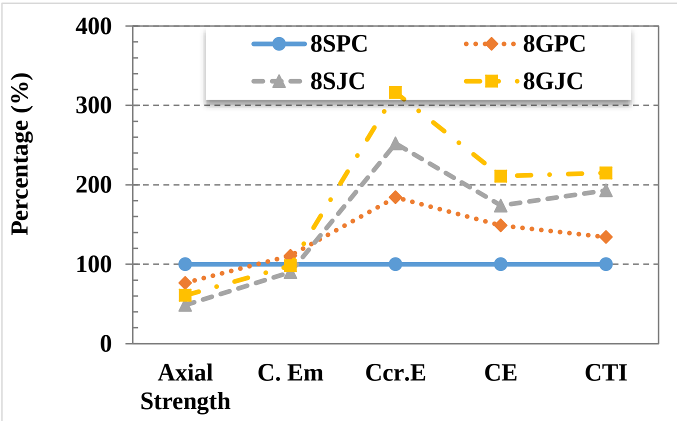
vertical load capacity and lateral load capacity is more but post cracking energy absorption, total compressive energy absorption and compressive toughness index is less. With addition of jute fibres in RC column dynamic properties of JFRC column longitudinal frequency and dynamic elastic modulus reduces up to 18% and 20%, respectively. But damping ratio increases up to 75%. In static properties of JFRC column vertical load capacity and lateral load capacity reduces up to 10% each. But post cracking energy absorption, total compressive energy absorption, compressive toughness index increases up to 125%, 86% and 37%, respectively. The damping ratio helps in dynamic properties and energy absorption helps in static properties which lead towards the better structural performance of columns. There is significant improvement in dynamic and static results for JFRC specimens with GFRP rebars.

Therefore, as eccentric load is applied on the top of the prototype column the compression behavior occurs at the right side of the column while tension is produced at the left side. It means that buckling is occurring due to eccentric loading. Similar behavior is observed for rebars as compression has occurred on the right and tension on the left causing buckling failure. Due to eccentric loading compression is seen in right side and tension is seen in left side of both PRC and JFRC prototypes. The cracks has been observed in most top and left bottom in PRC and JFRC. The tested prototypes columns are short columns due to relatively smaller cross section compared to its length, (i.e. slenderness ratio is 4.5). This slenderness ratio causes failure in top and bottom of prototype column because dominant stresses produces at the top and bottom of the short prototype columns. The stresses are produced due to eccentric loading not because of the concentric loading, so eccentric loading produce moments at the top of the steel plate and cause unbalance and slippage, thus failure occurs at top and bottom near the compression face of prototype eccentric square columns. Similar behavior is observed in previous research work as well. The failure mode in PRC prototypes are crushing whereas in JFRC the failure mode is bridging due to jute fibres. Prototype 8SJC and 8GJC show approximately equal strength as compared to the 4SJC and 4GJC. The failure occurs in prototype columns when the applied load is 60%

of its peak load on the descending side. The failure occurs in prototype column when splitting failure produces in GFRP rebar on the compression side. When significant amount of crushing occurs on the compression side of prototype column then it fails. When applied load on PRC prototypes reach up to peak load then concrete at its compression side starts to crush and the concrete cover starts to spall. When the load reaches to ultimate point then significant crushing produces in compression side of prototype. Concrete section is failed due to these effects. When the spalling occurs in concrete cover, the point of centre of gravity starts to shift away from the applied load and the eccentricity slightly increases. The



a)



b)

FIGURE 4.3: Comparison of properties for prototypes; a) with 4-longitudinal rebar and b) with 8-longitudinal rebar

rebars are exposed now, the weathering effect has taken place in steel rebars and as a result corrosion occurred. On the other side of the prototype, weathering effect will not occur in GFRP rebars. While in JFRC prototypes, the bridging effect occur due to addition of jute fibres and due to this effect, these rebars are not exposed. These prototypes constantly takes ultimate load as compared to PRC prototypes. Similar crushing and bridging trend is observed in prototype columns which was previously observed in cylinders and beams. It is noted that 4GJC and 8GJC showed greater strength and increased strain. The most significant behavior observed during this study is that bending moments considerably decreases load carrying capacities of eccentric columns since non-uniform distribution of stresses ultimately result in higher peak stresses. It is also noted that GFRP-RC columns are more susceptible to buckling on its vertical length due to lower modulus of elasticity of GFRP rebars as compared to steel-RC columns. Furthermore, in current study GFRP-RC prototype columns at smaller eccentricity of 25 mm does not carry equal amount of load carrying capacity than that of steel-RC prototype columns. Whereas at larger eccentricity of 35 mm GFRP-RC prototype columns and steel-RC columns shows approximately equal load carrying capacities as reported by Elchalakani et al. [56]. This shows significance of current study. This shows improved structure performance of prototype column by utilization of GFRP rebar and jute fibre.

4.4 SEM Analysis of Prototypes Specimens

SEM images of failure surface can be seen in Fig. 4.4 for under eccentric loading. Eccentric loading caused failure at center position and also shearing of fibre is observed. While, splitting of fibre is occurred and bonding at toe is observed from SEM images. Concrete matrix along with bonding of fibre is clearly visible from images. After application of eccentric load and observing failure surface resulted formation of small cavity near fibre. A part of fibre extended within the concrete can be seen through the cavity available at the toe of fibre. The pulled out fibre is noticeable through the presence of cavity neat the toe fibre.

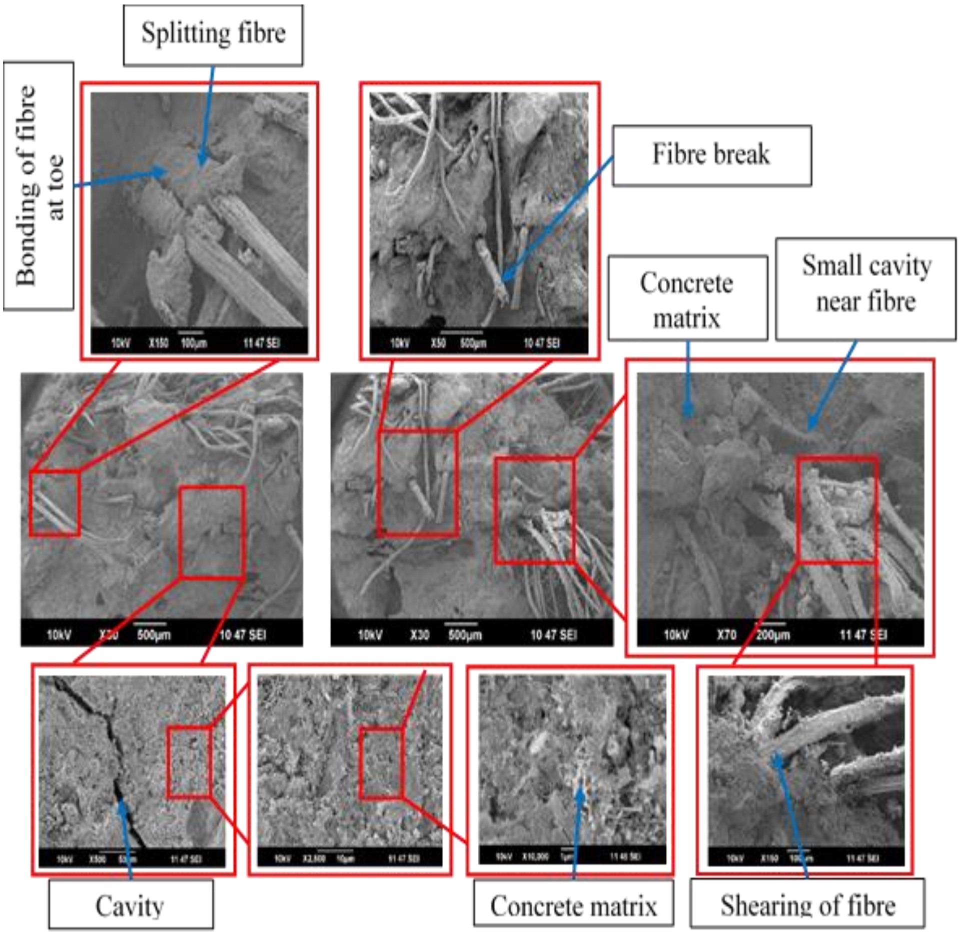


FIGURE 4.4: SEM analysis of failure zones of square prototypes under eccentric loading

4.5 Summary

In case of PRC and JFRC the dynamic properties and behavior of prototype column are determined. As compared to PRC and JFRC specimen the damping ratio of JFRC are much better than PRC specimens. Modification in nominal strength and nominal moment due fiber addition and relationship between material properties and prototypes performance.

Chapter 5

Discussion

5.1 Background

The results of the tests for dynamic and mechanical properties has been elaborated in Chapter 4. Decrement in compressive strength, split tensile strength and flexural strength has been observed in JFC and JFRC specimens. Whereas increment in energy absorption and toughness index has been observed for JFC and JFRC specimens. In this Chapter nominal strength and moment equation are modified and relationship between mechanical and prototype performance is investigated.

5.2 Modification in Nominal Strength and Nominal Moment Due to Fibre Addition

Fig. 5.1 shows modification of nominal strength and moment under eccentric load condition. It can be seen in Fig. 5.1 (a) as a response to the external load the stresses-strain distribution phenomena produced. For steel reinforced concrete Nelson does not considered the tensile strength of concrete due to its brittle behavior as described in Eqn. 5.1. Without considering the concrete strength in tension portion of RC column.

$$P_n = 0.85 f'_c ab + A'_s f'_s - A_s f_s \tag{5.1}$$

$$M_n = P_n\ e = 0.85\ f'_c\ ab\left(\frac{h}{2} - \frac{a}{2}\right) +\ A'_s f'_s\left(\frac{h}{2} - d'\right) +\ A_s f_s\left(d - \frac{h}{2}\right) \tag{5.2}$$

However experimental results demonstrated that with the addition of jute fibres the behavior of concrete are enhanced therefore tensile strength of concrete should be considered. Thus for steel reinforced concrete Eqn. 5.1 is modified and a new equation Eqn. 5.3 and Eqn. 5.4 are proposed for the design of column under eccentric load condition. Considering the concrete strength in tension portion of JFRC column.

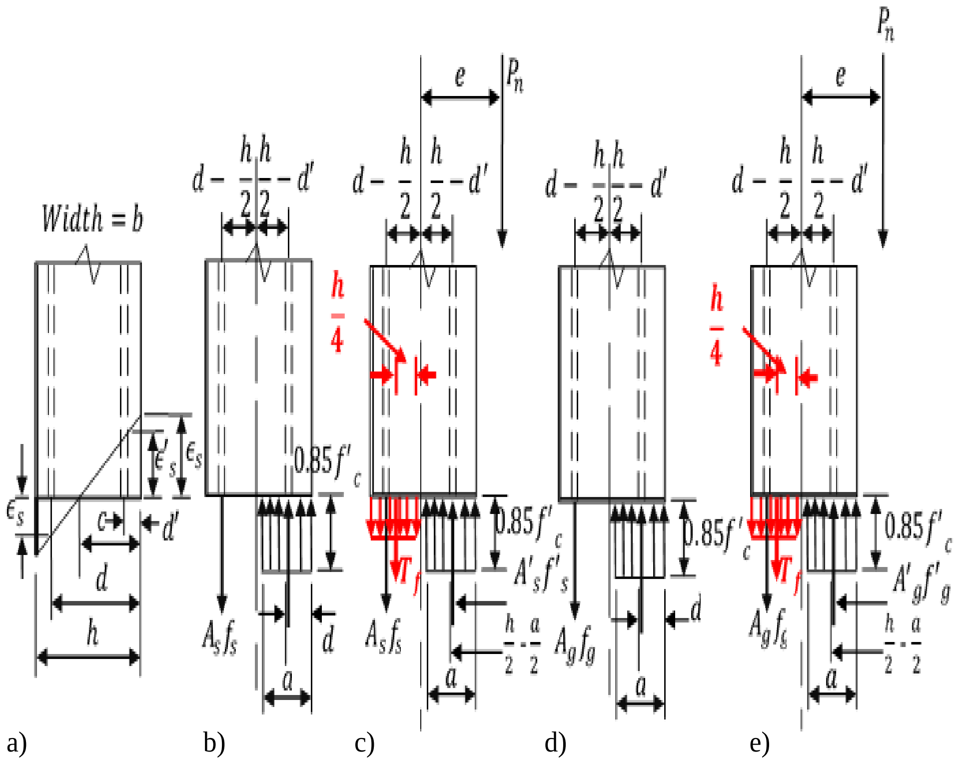


FIGURE 5.1: Nominal strength and moment of eccentric column distribution; a) under eccentric stress strain distribution, b) RC section with steel rebar [1], c) modified for JFRC having steel rebar, d) RC section with GFRP rebar [56] and e) modified for JFRC having GFRP rebar

$$P_n \ = 0.85 f'_c ab + A'_s f'_s - A_s f_s - \ T_f \tag{5.3}$$

$$M_n = 0.85\ f'_c\ ab\left(\frac{h}{2}-\frac{a}{2}\right) + \ A'_s f'_s\left(\frac{h}{2}-d'\right) + \ A_s f_s\left(d-\frac{h}{2}\right) + \ T_f\ \left(\frac{h}{2}\right) \tag{5.4}$$

In Eqn. 5.3 and Eqn. 5.4 the first, second and third part is same as proposed by nelson however the fourth part introduced is concrete strength in tension zone as denoted by T$_f$. The theoretical calculation for $T_f = 1.64 V_f \left(\frac{l_f}{\emptyset}\right) bt_f$ which can be taken from the experimental test results. Proposed Eqn. 5.5 and Eqn. 5.6 by ignoring strength of concrete in tension zone for eccentric column reinforced with GFRP rebars [56]. However, by addition of jute fibres the behavior of concrete significantly improved. The equation proposed by Elahcalani is modified and a new equation for GFRP in jute fibre reinforced concrete is produced. Thus Eqn. 5.5 and Eqn. 5.6 are proposed by considering tension zone of FRC. Without considering the concrete strength in tension portion of GFRP RC column.

$$P_n \ = 0.85 f'_c ab + f_{g'} A_{g'} - a_2 f_g A_g \tag{5.5}$$

$$P_n \ = 0.85 f'_c ab\ \left(\frac{h}{2}-\frac{a}{2}\right) + f_{g'} A_{g'}\left(\frac{h}{2}-d'\right) + a_2 f_g A_g\left(d-\frac{h}{2}\right) \tag{5.6}$$

Considering the concrete strength in tension portion of GJFRC column.

$$P_n \ = 0.85 f'_c ab + f_{g'} A_{g'} - a_2 f_g A_g - T_f \tag{5.7}$$

$$P_n \ = 0.85 f'_c ab\ \left(\frac{h}{2}-\frac{a}{2}\right) + f_{g'} A_{g'}\left(\frac{h}{2}-d'\right) + a_2 f_g A_g\left(d-\frac{h}{2}\right) + T_f\left(\frac{h}{2}\right) \tag{5.8}$$

f_g represents tensile strength of GFRP rebar in tension portion, f'_g represents tensile strength of GFRP rebar in compression portion, fs represents tensile strength of steel rebar in tension portion, fs represents tensile strength of steel rebar in compression portion. The values of fg and fs are obtained after testing rebars in Servo hydraulic machine (STM). The values of f_g, f_g' and fs in equation are 859 MPa, 429 MPa and 505 MPa respectively for experimental and theoretical results. The experimental and theoretical results for eccentric column is shown in Table 5.1. Percentages difference is elaborated in Table 5.1. The minimum difference is 0.23 where is maximum difference in nominal strength is 12.92. The minimum difference is 3.57 where is maximum difference in nominal moment is 24.04.

TABLE 5.1: Experimental and theoretical calculation prototype

Specimen	**Strength**			**Moment**		
	$\mathbf{P}_{exp}$	$\mathbf{P}_{actual}$	**% age diff.**	$\mathbf{M}_{exp}$	$\mathbf{M}_{actual}$	**% age diff.**
4SPC	120.02	111.37	8.66	3600600	3575505	3.57
4SJC	73.57	65.16	12.92	2207100	2737030	24.01
4GPC	97.71	111.37	13.98	2931300	3579230	4.66
4GJC	82.02	81.59	0.52	2460600	2701220	6.27
8SPC	145.87	139.92	4.25	4376100	4454059	17.24
8SJC	71.00	68.99	2.91	2130000	3673371	19.01
8GPC	111.63	111.37	0.23	3348900	3724520	11.21
8GJC	88.83	81.59	8.87	2664900	3195120	19.89

5.3 Relation Between Materials Properties and Prototypes Performance

JFC specimens showed less frequency and greater damping ratio as compared to PC specimens. The increment JFC specimens is up to 1.6 times. Compressive, split and flexural strength of JFC specimens is decreased but the total energy and toughness index is increased. JFRC prototypes demonstrated less frequency and greater damping ratio as compared to PRC prototypes. Damping ratio increased up to 3.4 times for JFRC prototypes as compared to the PRC prototype. Utilization of jute fibres in concrete caused reduction in compressive strength however energy and toughness index significantly increased. Incorporation of jute fibres changed failure mode from crushing to bridging under eccentric compressive load. Both PC and PRC showed similar behavior as some of the fragments are broken down at ultimate load. However, JFC and JFRC due to the addition of jute fibres produced bridging effect. The width of cracks in PRC specimens is greater than JFRC specimens whereas in JFRC specimens hair lines cracks were appeared. Porotypes 4SJC and 8SJC showed lesser compressive energy and lesser compressive index as compared to 4GJC and 8GJC.Prototypes 4SPC, 8SPC,4GPC and 8GPC showed greater load capacity but lesser compressive energy and compressive toughness index as compared to the 4SJC, 4GJC, 8SJC and 8GJC respectively. For restrict the crack propagation and enhancement in damping ratio it is suitable to use jute fibre with GFRP rebars in concrete. Because better performance is observed in experimental work for both 4 and 8 longitudinal rebar of GFRP with jute as compared to 8 and 8 longitudinal rebar with jute fibre.

Better ductility was observed for GFRP prototypes under eccentric load condition due to the high tensile strength of GFRP rebar. Eccentric loading cause compression in one side and tension on the opposite side. The strength of concrete in neglected in tension portion thus by using jute fibre bridging effect produced so we may take in strength (T_f) in tension portion. T_f is obtain directly through the flexural test. After the consideration of concrete strength in tension portion a new factor is introduced for nominal strength and nominal moment equation. If considering the nominal moment equation for both GFRP and steel rebar the nominal moment is increased for eccentric column while reinforcement ratio is decreased. Addition of jute fibre changed the seismic behavior of eccentric column by enhancing the damping ratio. GFRP and jute fibres in concrete showed better performance as compared to steel with jute fibres due to high tensile strength of GFRP and jute fibre.

In a real field scenario for square eccentric column utilization of GFRP rebar with jute fibres under load eccentric condition is suitable. For crack propagation resistance the jute fibre is the best option to used due to its high tensile strength as compared to the other natural fibre.

5.4 Summary

Relationship between damping ratios of JC and JFRC specimens are developed. It is noted that damping ratios increased for JFC and JFRC as compared PC and PRC specimens. In PC and PRC specimens the failure mode is crushing while in JFC and JFRC specimens the mode of failure was bridging due to addition of jute fibres. Jute fibres inclusion produced bridging effect in JFRC specimens and enhanced crack resistance. Prototypes with glass rebars and jute fibres demonstrated better performance than all other specimens. Equations are developed for nominal and strength and moment under eccentric loading and relations developed showed improvement in ductility and toughness for mechanical and prototypes.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In current research work, jute fibre reinforced concrete (JFRC) is studied with the addition of GFRP longitudinal rebars for eccentric square concrete columns. The mix design proportion of 1:2:3:0.6 (cement: sand: aggregate: water) is used for PRC and JFRC. For JFRC jute fibre of 50 mm length having 5% weight by mass of cement is used. Experiments are carried out and conclusions are shown below:

- The energy dissipation of JFC cylinders and beams increased by 16.27% and 17.07% as compared to PC specimens respectively. Splitting tensile strength of JFC specimens decreased up to 38.27% while total tensile energy and toughness index increased up to 187.16% and 259% than PC cylinders respectively.

  - The flexural strength of JFC specimens decreased up to 17.77% while total flexural energy and flexural toughness index increased up to 130.58% and 213% than PC specimens respectively.
  - The compressive strength of JFC cylinder decreased up to 39.65% however the compressive energy and compressive toughness index increased up 31.57% and 22.10% as compared to PC cylinders.

- The application of different loading rates on the prototypes columns (i.e. 0.19 MPa/s and 0.31 MPa/s) demonstrate that an increase in loading rate produces negligible difference in compressive properties of prototypes columns. That is why, an average of two is taken.
- JFRC prototype damping ratio increased 97.4% as compared to PRC prototype. The most suitable result was for GFRP with jute fibre in concrete.
  - Increment in damping ratio helps to reduce the magnitude of lateral load.
  - Energy absorption helps to reduce the impact of applied loading.
- JFRC specimen showed similar behavior to that of PRC with linearity in stress strain graph in raising potion. Increment in reinforcement ratios has a significant effect on the strength of PRC column under eccentric load condition for both steel and GFRP rebar column.
  - For JFRC columns under eccentric loading significant enhancement in strength was not observed due to increment in reinforcement ratio for steel and GFRP rebars.
- Better bonding between jute fiber and concrete is noticed through SEM images.
- Nominal strength and nominal moment equations are developed for eccentric square column of steel and GFRP with jute fiber reinforced concrete.

Therefore, on the basis of above results jute fibres with GFRP rebars in concrete square columns under eccentric load condition can be used for better durability and performance of member as compared to the utilization of jute fibres with steel rebars. So use of natural fibre in concrete improves the seismic behavior of column.

6.2 Future Work

Following recommendations are drawn:

- The experimental work may be carried out on different eccentricities to determine the effectiveness of GFRP rebars.
- Full scale testing may be performed with real field conditions.
- Jute fibres and GFRP bond should be investigated for long term durability.

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