CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Effectiveness of Jute Fibers and GFRP Rebars on the Structural Behavior of Concentric Rectangular Concrete Columns

by

Fareed Ullah

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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

Corrosion of steel is a major flaw in reinforced concrete (RC) structures predominantly in regions of harsh environment and marine structures. The repair and rehabilitation of these RC-structures are costly. Since last three decades a huge demand in utilization of FRP rebars has been observed. Utilization of FRP rebars is valid to be effective in flexure members. However, utilization of FRP rebars is not considered to be effective in compression members. ACI440.1R-15 and CSA S806-12 avoids deployment of FRP rebars in compression members. However recent studies demonstrated significant outcomes with of GFRP rebars in load carrying capacities of RC-columns.

The overall aim of the research program is to use environment friendly and cost effective natural materials for better serviceability and structural performance of RC-columns. The specific aim of this research work is to deploy jute fibers with GFRP rebars in prototype columns to investigate the structural behavior under concentric load conditions. A total of 8 prototype rectangular columns of 100 x150 x 450 mm are cast and tested under concentric load conditions. Investigational variables include load carrying capacities, dynamic properties, compressive properties, failure modes and fiber bonding.

Results demonstrate that jute fibers and GFRP rebars effectively contribute in enhancement of structural behavior of RC-columns. Jute fibers have significantly enhanced the damping ratios of RC-columns and changed the mode of failure from crushing to bridging. Jute fibers also indicate better crack restraining capacity through bridging mechanism of fibers. Compressive properties depict enhancement in energy absorption and toughness index. The contribution of GFRP rebars in load carrying capacity is 35% of the total capacity of GFRP RC-columns. Based on experimental and predicted outcomes a new reduction factor $(\propto_c = 0.30)$ is introduced in the nominal capacity equation. Moreover, better bonding and bridging effect is evident from the SEM images. Thus, it is recommended to consider the contribution of longitudinal GFRP rebars in the ultimate capacity of column with

a reduction factor of ($\propto_c$ = *0.30)* in the design codes. Furthermore, investigations are encouraged to explore GFRP rebars under various load conditions.

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Abbreviations

A	Aggregate
A_f	Area of FRP Longitudinal Bar
A_g	Gross Cross Sectional Area
C	Cement
E	Energy Absorption
E1.C	Energy Absorption up to Maximum Load in Compression
EI.S	Energy Absorption up to Maximum Load in Splitting
EI.F	Energy Absorption up to Maximum Load in Flexure
Ecr.E	Cracked Energy Absorption after Maximum Load
f'_c	Compressive Strength of Concrete
f_{fu}	FRP Tensile Strength
f_l	Longitudinal Frequency
f_r	Torsional Frequency
FRC	Fibre Reinforced Concrete
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
PRC	Plain Reinforced Concrete
P.m	Maximum Load
P_{pred}	Predicted Theoretical Value
P_O	Nominal Capacity
S	Sand
s	Second
S.C	Strength in Compression
S.S	Strength in Splitting
S.F	Flexural in Strength
S.S	Total Energy Absorption in Splitting
S.F	Total Energy Absorption in Flexure
STM	Servo-Hydraulic Testing Machine
T.E.C	Total Energy Absorption in Compression
T.E	Total Energy
T.I	Toughness Index
T.T.I	Total Toughness Index
W/C	Water Cement Ratio

Symbols

$\boldsymbol{\xi}$	Damping Ratio
$\boldsymbol{\O}$	Diameter
$\boldsymbol{Hz}$	Unit of Frequency
$\boldsymbol{\mu m}$	Micro Meter
$\boldsymbol{\rho}$	Reinforcement Ratio
$\boldsymbol{\%}$	Percentage
$\boldsymbol{\alpha}_1$	Reduction Factor
$\propto_c$	Reduction Factor for GFRP Rebars in Compression
$\propto_f$	Reduction Factor for FRP Rebars in Compression

Chapter 1

Introduction

1.1 Background

Columns are critical structural members in reinforced concrete (RC) structures. Columns are responsible to transmit loads to the earth through foundation. The structural response of RC-columns are of great significance as short RC-columns under concentric load condition may fail due to crushing of concrete or buckling of steel [1-2]. During any seismic event ductility, energy dissipation and damping of RC-columns were of major significance [3]. Whenever RC-structure engaged to large external dynamic force there was possibility of occurrence of structural collapse, specifically in regions of high seismicity where fault lines were active. Therefore, columns should have enough design capacity to sustain any probable major hazard during strong ground motions [4]. Furthermore, development of cracks in columns due to seismic events facilitated penetration of water and moisture and resulted in corrosion of steel rebars. Reduction in axial strength and serviceability was observed due to corrosion of steel rebars that ultimately resulted in failure of RC-columns [5]. This corrosion issue of steel rebars were of chief concern in RC-structures, specifically in buildings exposed to harsh environment, marine structures and structures near coastal areas [6].

GFRP rebars are new construction materials utilized as a substitute to steel rebars due to its improved properties. GFRP rebars possessed improved properties such as, high tensile strength, corrosion-resistance, cost effectiveness in maintenance and lighter weight (1/4th of steel rebars) [7]. Recent investigations on FRP rebars indicated satisfactory outcomes and expanded utilization of FRP rebars as shear and flexure reinforcement. However, employment of FRP rebars in compression members are not acknowledged. ACI440.1R-15 [8] prohibits employment of FRP rebars in compression members whereas CSA S806-12 [9] ignores contribution of FRP rebars in load carrying capacity in the design equations. However, recent research investigations depicted effectiveness of FRP rebars in load carrying capacities. According to Afifi et al. [10] GFRP rebars contributed 35% in load carrying capacity of RC-column under axial concentric load condition. Natural fibers significantly enhanced the mechanical properties of concrete and overall performance. Alam and Riyami [11] reported improvement in shear capacities, ductility and overall strength by incorporation of jute fibers in concrete. According to Zhang et al. [12] jute fibers significantly enhanced toughness and crack resistance of concrete.

According to the best knowledge of the author, no study has been performed on the combine effectiveness of jute fibers and GFRP rebars on the structural behavior of prototype rectangular RC-columns under concentric load condition.

1.2 Research Motivation and Problem Statement

Columns are critical structural members in RC structures and are responsible for transmission of loads to earth through foundation. During any seismic event, the stability of column is of major importance as failure of column at any critical location may result in total collapse of the building. Steel rebars have a limited service life and may rust due to weathering effects specifically in buildings exposed to harsh environments, marine structures and coastal regions [6]. Maintenance cost, repair and rehabilitation of these structures are costly. To save human lives and infrastructure, and to have more sustainable environment utilization of environment friendly and cost effective construction materials are highly essential. GFRP rebars and natural fibers may be used to achieve this motive. Therefore, experimental investigations are required for better structural performance and serviceability. Thus, the problem statement is as follows;

"In RC-structures, safety of a structure is related with the construction materials. In concentric columns, concrete crushing failure occurs due to its brittle behavior and less toughness. Corrosion of steel rebar is another problem that ultimately results in failure of column. GFRP rebars are used as a substitute to steel rebars to overcome weathering issues [5]. At the same time natural jute fibers are used to enhance the toughness of concrete and convert failure mode from crushing to bridging [11]. Therefore, to enhance concrete properties and structural performance for rectangular RC-column, the overall behavior of prototype column is needed to be explored in detail."

1.3 Overall Objective and Specific Aim

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

"The specific aim of this MS Thesis is to investigate structural behavior of prototype rectangular columns under concentric load condition in laboratory for the effect of jute fibres addition and steel rebars replacement with GFRP rebars."

1.4 Scope of Work and Study Limitation

An average of three specimens are taken for the investigation of mechanical properties of PC and JFC, whereas for prototype rectangular columns, an average of two specimens are taken for structural behavior determination as previously described by Zia and Ali [13] and ASTM C39 standard [14].

The testing of prototypes has been conducted with simplified boundary conditions. The actual infield height of the column is 18 ft whereas scaled down prototype height is 18 inch with the consideration of scale of 1:5. Single mix design ratio, fiber content, and fiber length is utilized as reported by [13]. Relative comparisons between PC, JFC, and PRC, JFRC with steel and GFRP rebars has been performed.

1.5 Methodology

Prototype rectangular columns with GFRP and steel rebars are cast. Comparison between PRC and JFRC prototype columns are performed to investigate the effectiveness of jute fibers on properties of concrete. Axial strength test is performed by utilization of STM machine in CUST laboratory. The crack propagation mechanism is observed through naked eye. Furthermore, for investigation of mechanical properties compressive, split-tensile and flexural strength tests are conducted experimentally. The mix design proportion of 1:2:3:0.6 (cement: sand: aggregate: water) is utilized for PRC whereas addition of 5% jute fibers by mass of cement with 50 mm fiber length is used for JFRC specimens. All tests and preparation of specimens are performed as per ASTM standard guidelines.

1.6 Thesis Outline

This MS thesis research work has six chapters which are summarized here below.

Chapter 1 illustrates introduction. It consist of background, research motivation and problem statement, overall objective, specific aim, scope of work, research methodology and thesis outlines.

Chapter 2 briefs literature review comprehensively. It includes background, failure in RC-columns under concentric load condition, utilization of natural fibers in concrete, use of jute fibers in concrete, fiber reinforced polymers, GFRP rebars utilization in RC-columns, testing practice and summary.

Chapter 3 elaborates experimental program. It involves background, raw material, mix design and casting procedure, mechanical and dynamic properties of PC and JFC, prepared specimens, testing procedure and summary.

Chapter 4 explains experimental evaluation. It contains background, resonance frequencies and damping ratios of prototypes, structural behavior of prototype rectangular columns for PRC and JFRC, SEM analysis of prototype and summary.

Chapter 5 covers discussions. It encompasses background, nominal moment and design equation modification, relationship between material properties and prototype performance and summary.

Chapter 6 covers conclusions and future work.

Bibliography is presented right after chapter 6.

Chapter 2

Literature Review

2.1 Background

Fibers have been utilized for enhancement in concrete properties, better performance and serviceability. Jute fibers are natural fibers with enhanced properties, are cheap in price and abundantly available in tropical regions. Jute fibers are natural fibers utilized to improve the toughness, crack resistance and durability of concrete. GFRP rebars are corrosion less, with high tensile strength and low cost in maintenance. GFRP rebars are used as a substitute to steel rebars in concrete structures specifically in harsh environments and marine structures. In this chapter brief literature review is performed on natural fibers, jute fibers, GFRP rebars and testing practice.

2.2 Failure in RC-Columns under Concentric Load Condition

In reinforced concrete (RC) structures columns are critical structural members as columns are required for safely transmission of gravity and external dynamic loads to the ground through foundation. Short RC-columns under concentric load condition experienced stresses. As load carrying capacity of short column depended on its cross sectional area. When subjected axial load was greater than the cross sectional area, the concrete and steel rebars approached their yield stress and ultimately resulted in failure of column due to material crushing. Each year plenty of resources are utilized for repair and rehabilitation of RC-columns. Failure of RC-columns during earthquake events were of major concerns. Seismic events caused cracks in compression members, these cracks facilitated penetration of moisture, water and rusted the steel rebars [15]. Since columns were required to provide resistance against the axial compressive loads. Therefore, strength capacity of columns are of great significance as RC-columns should have adequate design capacity to withstand large deformations for all possible load combinations. Steel corrosion was a major problem in RC structures specifically in coastal regions, buildings exposed to harsh environments and marine structures [16]. Corrosion of steel damaged the interface between steel rebar and concrete and reduced the bond strength that caused reduction in strength and serviceability of columns which ultimately resulted in failure of columns. This corrosion problem of steel rebars reduced the column strength, axial load carrying capacity and service life of steel RC-columns whereas coating solution for maintenance was an expensive option. Previously conducted researches on rectangular RC-columns concluded that reduced strength responded to the poor performance of columns [17]. Thus, it is important to enhance the toughness, crack resistance and corrosion resistance of RC-columns for better structural performance under concentric load conditions.

2.3 Use of Natural Fibers in Concrete

ACI 544 [18] defines FRC in to four groups as per material types. These include natural fiber reinforced concrete (NFRC), synthetic fiber reinforced concrete (SNFRC), steel fiber reinforced concrete (SFRC) and glass fiber reinforced concrete (GFRC). Enhancement in toughness, energy absorption, damping ratios, durability and longer service life of RC-columns can be achieved by addition of natural fibers in concrete. Some of the previous literatures on natural fiber reinforced concrete are discussed here:

Khan and Ali [19] investigated effectiveness of fly ash, coconut fibers and silica-fume on properties of concrete. The behavior of silica-fume with fly ash in plain concrete (FA-SPC) and fly ash silica-fume in coconut fiber reinforced concrete (FA-SCFRC) was determined. The dosage of silica fume is 15% by mass of cement with the incorporation of 0%, 5%, 10% and 15% fly ash content by cement mass. The length of coconut fibers was 50 mm with a dosage of 2% by mass of cement for preparation of FA-SCFRC. It was concluded that FA-SCFRC demonstrated enhancement in properties as compared to FA-SPC. Over all FA-SCFRC with 10% dosage of fly ash showed improvement in mechanical properties than other dosages. Sepe et al. [20] conducted experiments on the hemp fiber reinforced concrete to investigate mechanical properties. The conclusions drawn indicated that woven hemp fiber after saline treatment enhanced flexure and tensile properties of composites. Ali et al. [21] conducted tests on bond strength of coconut fibers. Fiber pullout tests were performed and the properties of fibers and concrete were tested. It was concluded that better bond between concrete and coconut was observed under mix design ratio of 1:3:3 with treated thick fibers of 0.30-0.35 mm diameter and 30 mm length. Increment in pullout energy, tensile strength and bond strength was also observed. Chin and Nepal [22] investigated straw fibers in plain concrete. Different volumes with same fiber length of 45 mm and 0.47 mm diameter was used. From the researched work, the conclusion drawn indicated that cube and cylinder prepared with 0.25% volume of wheat straw demonstrated increment in compressive strength and water absorption. Hari and Mani [23] experimented tests on durability of self compacting concrete with sisal-nylon fibers. Mono specimens were prepared with 0.1, 0.2 and 0.3% of total volume. Whereas hybrid specimens of sisal-nylon were prepared with 25/75%, 50/50%, and 75/25% of total volume. It was concluded that hybrid specimens demonstrated improved and better performance than mono specimens. The conclusions drawn also indicated that water absorption was controlled which resulted in reduction of fiber deterioration. Poor bonding was also observed as a hurdle for infield implementation. Momoh and Osofero [24] studied the effectiveness of oil palm broom fibers (OPBF) in concrete. For preparation of specimens, a mix proportion of 1:1.5:3 with addition of 50 mm length of short discrete fibers was used at a content of 0.5%, 1%, 1.5%, 2%, 3% and 4% of total aggregate volume. From the conducted study, it was concluded that the post yield behavior of OPBF reinforced concrete demonstrated enhancement in energy absorption between 70% and 320%. This indicated the effectiveness of fibers to be utilized in low rise seismic resistant houses. Yan and Chouw [25] investigated coir and flax fibers reinforced concrete. It was concluded that flax fiber reinforced polymer and coir fiber reinforced concrete showed improvement in ductility, mechanical properties and showed potential to be used for axial and flexural members. Ali et al. [26] conducted experimental research on coconut fiber reinforced concrete to determine their dynamic and mechanical properties. The effectiveness of fiber dosage at a content of 1%, 2%, 3% and 5% with fiber length of 2.5, 5 and 7.5 cm was determined. The conclusions drawn indicated that the damping ratio of coconut fiber reinforced concrete specimens enhanced as compared to PC. Whereas the static and dynamic moduli reduced and showed lower structural damage. Overall best performance was reported at 5% dosage with 5 cm fiber length. Wang and Chouw [27] conducted experiments to determine the effectiveness of coconut fiber reinforced concrete subjected to impact load condition. Drop height tests were performed and different impact energies were determined. The conclusions indicated that under repeated impact load, coconut fiber reinforced concrete of 25 and 50 mm demonstrated better crack resistance than that of 75 mm coconut fiber reinforced concrete.

2.4 Use of Jute Fibers in Concrete

Jute fibers are natural green vegetable fibers. These fibers are easily available in tropical regions having low cost. Some of the previous literatures on natural fibers are discussed;

Park et al. [28] reported that tensile strength of jute fibers decreased with aging conditions as fibers expanded and deteriorated. Sen et al. [29] investigated durability of jute fibers under salt water and distilled water conditions. Jute fiber composites when exposed to salt water condition, slightly compromised on the durability as compared to distilled water condition. Ramakrishna and Sundarararajan [30] found that jute fibers after immersion in saturated lime solution for 60 days possessed 65% of the original strength as compared to sisal fibers. Toledo Filho et al. [31] studied durability of coconut fibers in sodium hydroxide and calcium hydroxide solutions. Coconut fibers in calcium hydroxide solution after 210 days retained 55% of their original tensile strength. For sodium hydroxide solution, the strength retained was 62% of their original tensile strength.

Hussain and Ali [32] reported on effectiveness of jute fibers for enhancement of impact resistance in RC slabs under impact load condition. Fifty two RC steel slab panels of 430 x 280 x 75 mm with and without jute fibers were prepared with 50 mm fiber length and 5% fiber content by mass of cement. Drop weights tests at varied heights of 60 and 90 cm for impact resistance were performed while dynamic and mechanical tests of materials have been also carried out. Researchers concluded that impact resistance of slabs with jute fibers increased by 6 and 6.5 times at 90 and 60 cm drop heights, respectively. Nevertheless dynamic elastic modulus increased by 68% for jute fiber reinforced concrete slabs than steel RC slabs. Table 2.1 showed mechanical properties of jute fibers as investigated by Wrake and Dewangan [33].

From the reported properties of jute fibers, it was noted that jute fibers possessed high tensile strength. Moreover, jute fibers were cheap in price, easily and abundantly available in tropical regions.

Alam and Riyami [34] investigated shear strengthened behavior of RC beams with natural fiber reinforced polymer (NFRP) composites plates. Natural fibers involved jute fibers, jute rope and kenaf composite plates whereas a total of 8 beam specimens were prepared with steel reinforcement. The conclusion drawn indicated that beams with untreated jute fibers, jute rope and kenaf composite plates had enhanced shear capacities by 36%, 34%, and 35% as compared to the controlled specimen. While treated jute fibers, jute rope and kenaf plates showed comparable shear capacities of 31%, 23 and 10% respectively. It was concluded that beams with natural fibers showed improvement in toughness and overall strength.

TABLE 2.1: Mechanical properties of jute fibers

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
Stiffness (kN/mm^2)	10-30

Kundu et al. [35] reported on utilization of jute fibers in concrete paver blocks. Test matrix involved 5 mm jute fibers with 1% weight by cement. It was found that paver blocks with jute fibers depicted improvement in mechanical properties. The flexural strength and toughness improved up to 49% and 166% while strength in compression was enhanced by 30% than that of controlled specimen block. Furthermore, it also indicated that utilization of jute fibers in concrete blocks led to longer service life and low repair costs. Razmi et al. [36] investigated the fracture resistance of jute fiber reinforced concrete. Jute fibers of 20 mm length with various percentages of 0%, 1%, 3% and 5% by weight of mixture were incorporated for the preparation of specimens. Conclusions indicated that fracture resistance of jute fiber reinforced concrete was enhanced by 45% as compared to plain concrete specimens. Furthermore, crack resistance was enhanced as the fiber ratios increased but no significance improvement was shown on 5% ratio. Parameters such as flexure strength, compressive strength, tensile strength and fracture toughness of jute fiber reinforced concrete were higher than that of plain concrete specimens. Zakaria et al. [37] conducted experiments on mechanical properties of jute fibers with various mix design ratios of 1:2:4: and 1:1.5:3 (cement: sand: brick chips) having different jute fiber lengths of 10, 15 20 and 25mm 25 mm, and different dosages of 0, 0.1, 0.25, 0.50 and 0.75% by volume, respectively. Brief analysis of results indicated that the fiber content and length greatly influenced the effectiveness of concrete. The maximum compressive strength achieved was 15% for 15 mm fiber length with 0.10% fiber content and 1:2:4 mix design ratio. The maximum compressive strength was 10% with same fiber length and content for 1:2:4 mix design ratio as compared to the plain concrete. The flexure strength enhanced by 22% for 15 mm fiber length with 0.10% fiber content and 1:1.5:3 mix design ratio whereas for 1:2:4 mix design ratio with same fiber length and fiber content 14% enhancement was achieved.

2.5 Fibre Reinforced Polymer Rebars

Fiber reinforced polymer (FRP) rebars are composed of high strength glass fibers and vinyl ester resin matrix. In last few decades, FRP rebars have emerged as an alternative to conventional steel rebars in harsh environment conditions. FRP rebars possessed many advantages over conventional steel rebars such as high tensile strength, corrosion resistance, lighter weight, low maintenance cost, electrically non-conductive and transparent to magnetic fields (hospital MRI) as compared to steel rebars [38]. Occurrence of micro buckling in FRP rebars caused complications in compression test due to antistrophic and non-homogeneous nature of FRP material. Moreover, ACI 440.1R-15 [8] do not suggest utilization of FRP rebars in compression members. However, the use of FRP rebars specifically in corrosive environment can be advantageous to reduce the issues in severe weather conditions [39].

2.6 Use of GFRP Rebars in Concrete Columns

In last few decades, huge demand in utilization of GFRP rebars has been witnessed. Even though ACI prohibits GFRP rebars for the real design in compression members, but previous researches has shown better performance of GFRP rebars in compression and recommends for further research purposes. Dietz et al. [40] reported that the GFRP reinforcement bars possessed 50% lesser compressive strength as compared to their flexural strength.

According to previous studies, GFRP rebars possessed low elastic modulus. Deformed GFRP rebars were used for better bonding with concrete. Berrocal et al [41] reported that deterioration of the bond greatly reduced safety and durability of the structural members. According to Zemour et al. [42], columns cast with normal concrete indicated better bond strength than columns cast with self consolidated concrete. GFRP rebars in self consolidated concrete showed an average of 5% lesser bond strength as compared to normal concrete. Rosa et al. [43] concluded that the bond between GFRP rebars and concrete significantly reduced in elevated temperatures of 150 °c and 300 °c respectively. Kim et al. [44] investigated bond-slip behavior by direct pull-out test. GFRP rebars due to sand coating showed higher bond performance as compared to carbon-S series and ARA-S series of FRP rebars.

Prachasaree et al. [45] explored behavior of RC columns reinforced with GFRP rebars. It was concluded that the effect of longitudinal GFRP rebars on the strength of column is lesser as compared to the effectiveness of lateral ties. Ahmad Hassan et al. [46] investigated structural behavior of eccentrically loaded circular concrete columns with GFRP rebars and steel rebars as main longitudinal reinforcement. The main conclusions drawn from this study indicated that concrete columns having GFRP rebars as main longitudinal reinforcement reduced load carrying capacity as compared to steel RC columns. Previous researchers also reported that increment in slenderness ratio reduced the compressive strength and ductility of both GFRP-RC column and their counterpart columns. Luca et al. [47] conducted laboratorial experiments on concentric concrete columns with GFRP and steel rebars as longitudinal reinforcement. Five full scale columns of square cross section 610 x 3000 mm were tested under axial load. The conclusions indicated that GFRP as longitudinal reinforcement possessed higher strains due to lower load carrying capacity than that of traditional steel reinforced concrete columns. Buckling of the longitudinal rebar was dominantly influenced by confinement of lateral ties. Axial deformation behavior of GFRP RC column was similar to steel RC-column at 1% reinforcement ratio. GFRP longitudinal rebars contributed less than 5% load carrying capacity and hence it can be ignored in load capacity determination.

Many studies reported that GFRP bars possessed low elastic modulus due to which they were susceptible to the buckling failure as compare to steel rebars. Therefore, it was important to restraint longitudinal GFRP rebars by transverse reinforcement. Alsayed et al. [48] reported on rectangular RC columns with dimensions of 450 x 250 x 1200 mm at reinforcement ratio of 1.07%. It was found that substitution of longitudinal steel rebars with equal amount of GFRP rebars decreased the load carrying capacities by 13% excluding of lateral reinforcement type (whether steel or GFRP). The conclusions drawn also indicated that the load capacity was reduced by 10% with the addition of GFRP ties as a substitute to steel ties. The behavior of load-deformation was unchanged till 80% ultimate capacity. Pantelides et al. [49] studied load carrying capacity of reinforced concrete columns with GFRP rebars. It was revealed that columns with GFRP longitudinal bars and GFRP helices showed 84% load carrying capacity as compared to steel RC columns. Studies conducted on GFRP rebars as transverse reinforcement included different parameters such as effect due to spacing between transverse rebars, effect due to volumetric ratios and shapes. GFRP transverse rebars provided high level of confinement to the concrete core with greater deformation capacity because of greater strains at ultimate levels [50] and [51]. Afifi et al. [52] reported that GFRP transverse reinforcement indicated more effectiveness on the ductile behavior and confinement effectiveness than load carrying capacities of GFRP RC-columns. Improvement of 3% to 7% in axial compressive strength while 57% to 208% and 21% to 43% enhancement was observed in ductility and confinement efficiency, respectively. Hales et al. [53] drawn the conclusions and reasons for such requirement that it is due to lower modulus of elasticity of GFRP rebars than that of higher modulus of elasticity of steel rebars. Hasan et al. [54] investigated high strength concrete (HSC) columns with steel and GFRP rebars under concentric loading. It was informed that equivalent amount of GFRP rebars as a replacement to conventional steel bars resulted in 30% reduction of load capacity as compared to steel reinforced HSC columns.

2.7 Testing Practice

The structural behavior of any structure can be predicated by four methods as given below

1. full scaled structures with realistic field scenarios [55].
2. full scaled elements of a structure with exact boundary conditions [56].
3. to scale the structure or members of the structure, which involves proper gradient of raw materials, size, load scenarios and end-conditions [57].
4. small scaled prototype structural members for comparison purposes to find efficacy of one variable while rest of the limits are same [58, 59].

In present study method four is selected, the structural behavior of plain concrete and jute fiber concrete reinforced with steel and GFRP longitudinal rebars are investigated for relative comparisons.

2.8 Summary

Brief literature review showed that fibers can be used to enhance the mechanical properties of concrete. Jute fibers possessed enhanced properties and effectively influenced the hardened properties of concrete. For corrosion resistance and better structural performance, GFRP rebars demonstrated enhanced mechanical properties and can be used as a substitute to steel rebars in harsh environments.

To the best of author's knowledge based on the conducted literature review no research work has been performed on the suitability of jute fibers along with GFRP rebars in concrete structures. In this research work, 8 prototype rectangular columns with GFRP rebars as a replacement to steel rebars in jute fiber reinforced concrete is experimentally tested. The clear cover of 12.5 mm is provided on top and bottom sides whereas 12.5 mm on each side. Various properties are determined such as resonance frequencies, damping ratios, mechanical properties for PC, PRC, JC and JFC specimens. Concentric axial behavior was also determined for PRC and JFRC prototypes.

Chapter 3

Experimental Program

3.1 Background

Since last two decades huge demand for utilization of GFRP rebars in natural fiber reinforced concrete has been witnessed for better performance. Enhancement in mechanical properties, energy absorption and toughness index are the chief outcomes of natural fibers. Behavior of GFRP rebars in jute fiber reinforced concrete is investigated through experimental work. In this chapter selection of raw materials, mix design ratios and casting, mechanical properties and dynamic properties of PC and JFC, testing procedure, prototype detailing and effectiveness of jute fibers in concrete is discussed in details.

3.2 Raw Materials

In current research work, the ingredients utilized for the preparation of plain reinforced concrete (PRC) and jute fiber reinforced concrete (JFRC) are locally available ordinary Portland cement, Lawrencepur sand, coarse aggregate of Margallah, fresh tap water, jute fibers, steel rebars and glass fiber reinforced polymer (GFRP) rebars. Coarse aggregates have a maximum size of 10 mm. Fig.3.1 displays utilized jute fibers which are initially in raw form and then cut to a uniform length of 50 mm with scissor. Scanning electron microscope (SEM) analysis has been also performed for jute fibers. It can be seen that narrow thread like structure is present on its top surface.

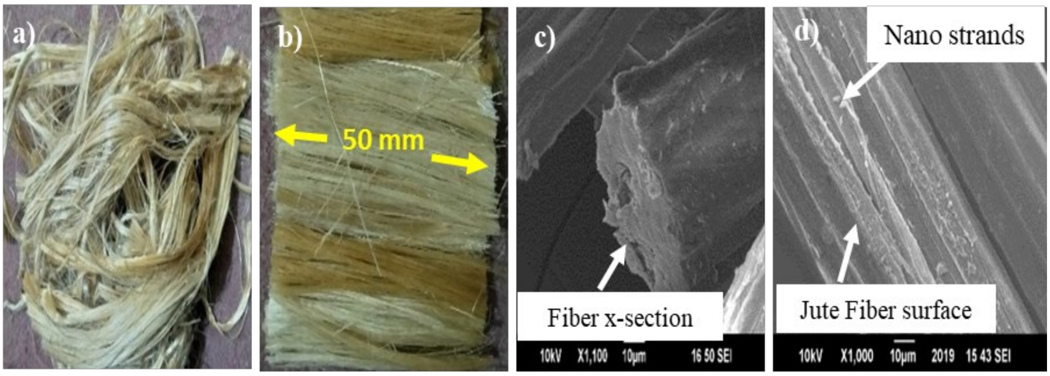


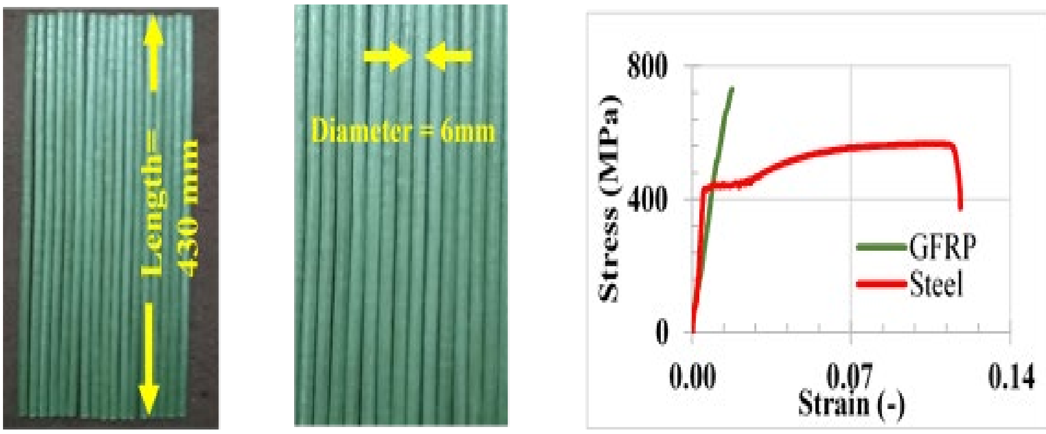
FIGURE 3.1: Jute fibers; a) Raw fibers, b) Prepared fibers, c) 10um SEM view and d) Top surface

Mechanical properties of jute fibers have been investigated experimentally in the laboratory as reported in Table 3.1. It has been noted that jute fibers possessed high tensile strength while low extensibility. The tensile strength ranged from 393-773 MPa. The density and water absorption property of jute fibers are 1460 kg/m3 and 13%, respectively.

TABLE 3.1: Mechanical properties of rebars

Properties	**GFRP rebar**	**Steel rebar**
Diameter (mm)	6	6
Cross Sectional Area (mm^2)	28.27	28.27
Density (kg/m^3)	2200	7850
Weight (kg/m)	0.051	0.22
Tensile Strength(MPa)	729.74	505.75
Elastic Modulus (GPa)	44	200
Ultimate Shear Strain (%)	1.8-3.1	6-12

Steel and GFRP rebars have same size of 6 mm diameter and 430 mm longitudinal length. Steel rebars of 6 mm have been used as transverse shear reinforcement for all prototype columns. The length, diameter and stress-strain curve of GFRP rebars are presented in Fig 3.2. The mechanical properties of GFRP rebars are determined experimentally as presented in Table 3.1. Tensile properties of GFRP rebars have been determined as per ASTM D7205 [60]. It is noticed that GFRP rebars possessed high tensile strength, low density and modulus of elasticity as compared to steel rebars.



a) b) c)

FIGURE 3.2: GFRP rebars; a) Cut length of rebars, b) Diameter of rebars and c) Relative strength of steel and GFRP rebar

3.3 Mix Design, Casting Procedure and Mechanical Properties

In this research work single mix design ratio of 1:2:3:0.6 (cement: sand: aggregate: water) is used for preparation of all the specimens. The target strength of PC is 15 MPa. The reason for using this rich mix ratio is non SSD condition due to utilization of local sand, aggregates and fibers. Local sand and aggregates from same source are used for JFRC as well. The main purpose is to check the effectiveness of jute fibers in concrete mixtures on relative comparison basis. Jute fibers of 50 mm length at a content of 5% by mass of cement are used for JFRC. PC and JFC specimens are prepared by the utilization of non-tilting rotary type drum. For the preparation of PC specimens, all constituents are put in the concrete mixer with water and then concrete mixer has been rotated for three minutes to have better homogenous mix. For preparation of JFRC specimens, a new method has been encompassed to avoid balling effect as reported by [61]. All constituents are poured in layer by layer form (cement, sand, aggregate) for better mixing. One third part of the total material is placed in the mixer in layer by layer form (cement. Sand, aggregate, jute fibers) then 33% of the water is spread over all the material. Rest of the 67% water is utilized for remaining two parts. The mixer is rotated for a total of 6 minutes (2 minute each water addition). Slump cone test is performed as per ASTM standard C143/C143M -15a [62] for determination of workability of PC and JFC specimens. Slump of PC is more as compared to the JFC specimens. This reduced slump of JFC may be due to the water absorption property of jute fibers. The value of slump for PC is 40% more than JFC. Moulds are filled in three layers and tamped twenty five blows with rod to compress the concrete to avoid air voids. Similar procedure is adopted for all the specimens. Moulds are air dried for 48 hours then specimens are removed from the moulds and all the specimens are labelled. After labelling, specimens are retained in the water tank for curing period of 28 days as per ASTM C192/C192M [63].

Table 3.2: Mix design ratios for PC and JFC

Property	**Fibre (%)**	**Cement (kg/m^3)**	**Fibre (kg/m3)**	**Fine Aggregate (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	**Water ($liter/m^3$)**	**w/c**
PC	0%	333.33	0.00	666.66	1000	200.00	0.6
JFC	5%	330.81	16.67	661.61	992.42	198.48	0.6

A total of 18 specimens have been cast and tested for determination of mechanical properties of PC and JFC. For compression and split-tensile testing 12 cylinders whereas for flexural testing 6 beams have been cast and tested. The dimensions of tested cylinders and beams are 100 x 200 mm and 100 x 100 x 450 mm, respectively. The loading rates for compression, spit-tensile and flexure tests are 0.15 MPa/s, 0.78 MPa/min and 0.86 MPa/min as per ASTM standard C39/C39M-18 [14], C496/C496M-17 [64] and C78/C78M-15b [65], respectively. Non-destructive dynamic testing is also executed as per ASTM standard C215-02 [66]. Various parameters are determined and compared such as cracking behavior, strength

(S), energy absorption (E), corresponding curves and toughness index. Cracking propagation behavior and failure modes have been observed with naked eye. Furthermore, SEM analysis is performed to investigate the failure behavior under compression, splitting and flexural loading.

Resonance frequencies and damping ratios are determined for cylinder and beam specimens of PC and JFC which are presented in Table 3.3. An average of three and six readings have been taken for beam and cylinder specimens, respectively. It is noted that resonance frequencies for PC specimens are greater which are encountered by deployment of jute fibers in concrete. Enhancement in damping and energy dissipation of JFC specimens are caused due to incorporation of jute fibers. The results for resonance frequencies and damping ratios of cylinders and beams for PC and JFC are presented here:

Table 3.3: Resonance frequencies and damping ratios for beam and cylinder specimens.

Specimen		**No.**	**Resonance Frequency**			**Damping Ratio**
			f_l	**ft**	**f_r**	
Beam	PC	3	1753 ± 215	1977± 101	1698 ± 255	3.12 ± 0.25
	JFC	3	1319 ± 113	1495 ± 150	1273 ± 163	5.11 ± 0.95
Cylinders	PC	6	2825 ± 351	1895 ± 167	1385 ± 112	2.08 ± 0.45
	JFC	6	1974 ± 238	1365 ± 264	1279 ± 150	4.73± 0.64

f_l = *Longitudinal frequency,* ft = *Transverse frequency*, f_r = *Torsional frequency*

Fig. 3.3 depicts corresponding curves of mechanical properties, crack propagation and failure modes under different load conditions. The failure modes are shown schematically for more precise visuals of the cracks. Fig. 3.3(a) portrays that cracks in PC specimen are greater in length, width and number as compared to minor cracks in JFC specimen under compression loading. Some of the concrete fragments in PC have broken and fallen down. The crushing and spalling of concrete is shown in schematic diagram via red color and brown color. Brittle behavior is observed for PC whereas bridging effect is observed for JFC specimens.

However, in JFC specimen with increment in load only the crack size enlarged which is restrained by jute fibers from further propagation. Fig. 3.3(b) displays failure mode under split-tensile loading. It can be noted that the PC specimen broke in to two parts suddenly without any indication whereas bridging effect is seen in JFC specimen. Fig. 3.3(c) portrays failure mode under flexure loading. It is visible from the actual and schematic diagram that PC beam break in to two parts suddenly. However, bridging effect is seen for JFC beam specimen. Addition of jute fibers restrained the cracks and changed crushing failure mode to bridging failure mode. All the calculated properties for mechanical specimens such as peak load (P.m), strength (S), energy absorption at peak load (E1), energy absorption from peak to ultimate load (Ecr) and total energy absorption (T.E) and toughness index (T.I) are presented in Table 3.4. It can be noted that the compressive strength of JFC specimen has reduced whereas E1, Ecr, E and T.I has been increased.

Fig. 3.3 depicts comparison of material properties under various loading. Significant enhancement can be noted from the experimental calculations in total energy absorption in compression (T.E.C), total energy absorption in splitting (T.E.S) and total energy absorption in flexure (T.E.F) and their corresponding toughness (T.I). For JFC specimens under compressive, splitting tensile loading the (E1), (T.E) and (T.I) has increased up to 8.69%, 63%, 276%, 304%, 124%, and 200% respectively than PC specimens. Although load carrying capacities and compressive strengths have reduced in JFC than PC specimens but properties such energy and toughness index have significantly increased in JFC specimen.

Furthermore, fracture surfaces have been studied at micro level through SEM analysis for compression, splitting and flexural specimens as shown in Fig. 3.3. From Fig. 3.3(a) fiber pullout is observable in matrix which resulted in failure. Few small voids near fiber indicates improper concrete mixing. In Fig. 3.3(b) small pore signifies better bonding between concrete matrix and jute fiber. Small pore exhibits the entrapped air near fiber toe. In-depth examination reveals that the pore is not deep. The fractured slice of fiber is evitable as well. Fig. 3.3(c) exposes fiber de-bonding as a consequence of failure. Fiber breakage is visible which means splitting of fiber is caused by the flexural load. It can be concluded that jute fibers depicted bridging effect which has been weakened due to the applied load.

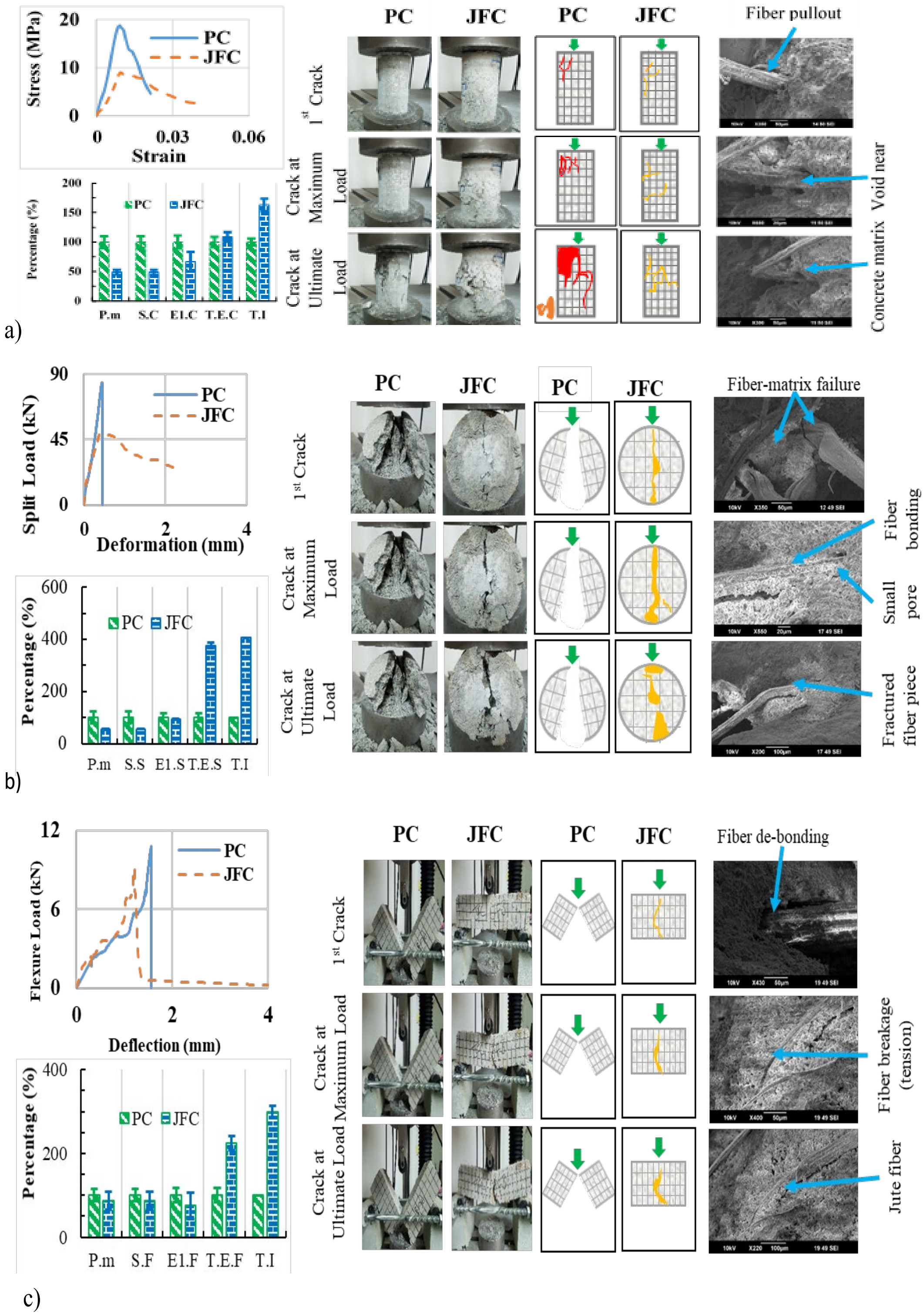


FIGURE 3.3: Mechanical properties under; a) Compression loading, b) Splitting loading and c) Flexural loading

Table 3.4: Mechanical properties of PC and JFC

Property	Compressive		Splitting-tensile		Flexural	
	PC	**JFC**	**PC**	**JFC**	**PC**	**JFC**
P.m (kN)	139.13± 14.24	67.87± 2.84	83.84± 19.66	47.10± 1.40	9.28± 1.40	8.05± 1.70
Strength (MPa)	17.70± 1.81 MJ/m^3	8.63± 0.36 MJ/m^3	2.66± 0.62	1.49± 0.04	4.18± 0.63	3.62± 0.76
E1	0.09± 0.01 MJ/m^3	0.06± 0.01 MJ/m^3	23.30± 3.64 J	21.54± 2.31 J	6.16± 1.05 J	4.61± 1.46 J
Ecr.	0.14± 0.01 MJ/m^3	0.19± 0.01 MJ/m^3	0 J	66.15± 8.76 J	0 J	9.22± 0.75 J
T.E	0.23± 0.02	0.25± 0.02	23.30± 3.64 J	87.69± 11.08 J	6.16± 1.05 J	13.83± 2.21 J
T.I	2.55± 0.15	4.16± 0.44	1	4.07± 0.09	1	3± 0.40

3.4 Specimens

A total of 8 prototype rectangular columns of 100 x 150 x 450 mm (width x depth x height) have been prepared for investigation of structural behavior and performance under concentric load conditions. Prototypes have been divided in to two groups in order of 4 prototypes for plain reinforced concrete (PRC) and 4 prototypes for jute fiber reinforced concrete (JFRC) columns as presented in Table 3.5. Furthermore, from 4 PRC prototypes 2 columns have been reinforced with longitudinal steel rebars and 2 columns with longitudinal GFRP rebars. Similarly from 4 JFRC prototypes 2 columns have been reinforced with longitudinal steel rebars and 2 columns have been reinforced with longitudinal GFRP rebars. Selection of dimensions for prototype rectangular columns are based on the favorable condition and capacity of the servo-hydro testing machine (STM) apparatus in the laboratory. The prototype specimens are identified by variation in the longitudinal reinforcement type i.e. GFRP rebars and steel rebars. Longitudinal reinforcement has been provided by steel and GFRP rebars of 6 mm diameter in PRC and JFRC prototypes, respectively. Steel rebars of 6 mm diameter have been utilized for shear reinforcement in both PRC and JFRC prototypes. Reinforcement detailing of all the prototype columns are demonstrated in Fig. 3.4. Two different loading rates of 0.19 and 0.27 MPa/s have been used according to ASTM C39M-18 [14] and average of two prototypes have been taken. Non-destructive dynamic testing has been performed before concentric testing for prototype columns.

Table 3.5: Test matrix with labelling for prototype specimens.

S. No	**Longitudinal Rebars**	**Steel Ties**	**GFRP ratio**	**Labels**	
			(ρ)	**PRC**	**JFRC**
1	10-Ø6	Ø6-64mm	0.018	10SPC-A/B*	10SJC-A/B*
2	10-Ø6	Ø6-64mm	0.018	10GPC-A/B*	10GJC-A/B*

***Note**: *A and B represents different load rates (0.19 MPa/sec and 0.27 MPa/sec) applied on prototype specimen A and B respectively.*

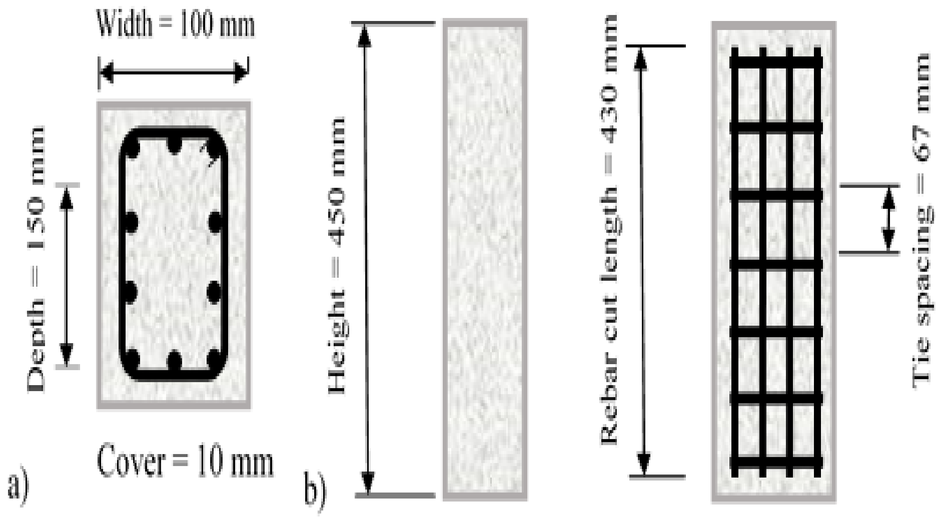


Figure 3.4: Reinforcement detailing and dimensions for Steel-RC and GFRP-RC prototype columns; a) Top view and b) Side view

3.5 Testing Procedure for Prototype Rectangular Columns

3.5.1 Dynamic Testing

In current research work, non-destructive dynamic testing has been performed for prototype rectangular columns of PRC and JFRC. Properties such as damping ratios, torsional frequency, transverse frequency and longitudinal frequency have been determined as per ASTM standard C215-02 [66].

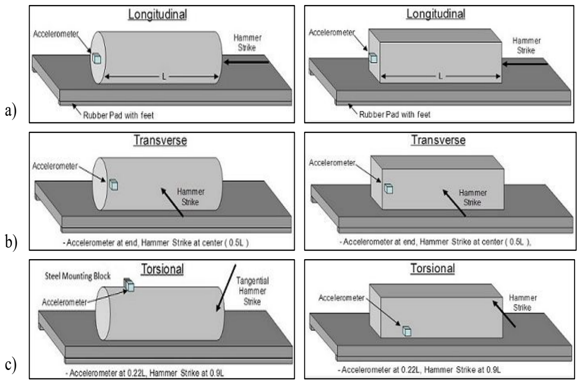


FIGURE 3.5: Resonance apparatus for dynamic testing as per ASTM C215 [67] for; a) Longitudinal frequency, b) Transverse frequency and c) Torsional frequency.

3.5.2 Concentric Load Testing

ASTM standard C39/C39M-18 [14] has been followed for determination of compressive strength, energy absorption and compressive toughness index of PRC and JFRC prototype columns. For uniformly distribution of load on the cross sectional area, prototype rectangular columns are capped with plaster of paris. Servo-hydro testing machine (STM) has been utilized for concentric load testing. Fig. 3.6 depicts load mechanism for concentric testing as displayed through schematic diagram while experimental test set up with actual scaled down prototype to be placed for testing has also been shown.

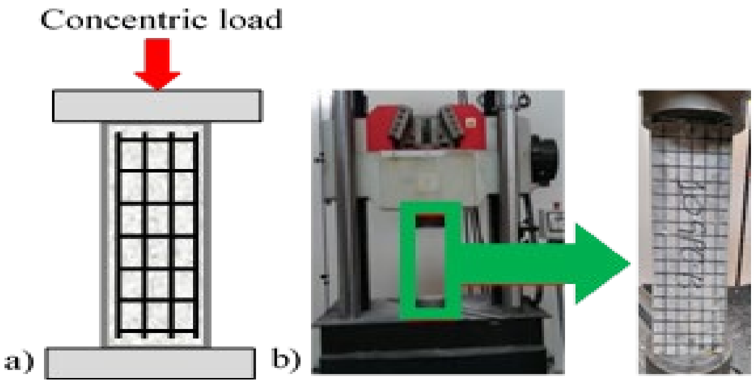


FIGURE 3.6: Concentric Load Mechanism; a) Schematic diagram and b) Experimental test set up with actual prototype to be placed.

3.6 Summary

Non-destructive dynamic properties such as resonance frequencies and damping ratios of PC and JFC specimens are determined. Post dynamic testing the mechanical properties of PC and JFC specimens are determined. Specimens with jute fibers demonstrated greater damping ratios and better performance as compared to PC specimens. Mechanical properties are investigated to explore the behavior and crack restraining phenomena for PC and JFC specimens. Enhancement in all properties are observed except for compressive strength. Over all better performance is depicted by the JFC specimens as compared to PC specimens.

Chapter 4

Experimental Evaluation

4.1 Background

The mix design proportion of 1:2:3:0.6 (cement: sand: aggregate: water/cement) is utilized for the preparation of plain reinforced concrete (PRC) prototypes. For the preparation of jute fiber reinforced concrete (JFRC) prototypes same mix proportion is utilized with the addition of 5% jute fibers by mass of cement. Jute fibers of 50 mm length are utilized throughout the work. In this chapter, the outcome of dynamic testing for prototypes, structural performance and behavior of prototype rectangular columns are discussed in details. Furthermore, bond mechanism between jute fibers and concrete matrix is examined through SEM analysis.

4.2 Frequencies and Damping Ratios of Prototype Rectangular Columns

The damping ratios and energy dissipation capacity of RC-columns during seismic events are of major significance as resonance might produce and cause catastrophic failures in regions of high seismicity. Chopra [67] reported that increment in damping ratio reduced the response of the structure to external dynamic load. The reason for determination of the damping ratio is to investigate the effectiveness of jute fibers in prototype rectangular columns. Table 4.1 shows outcomes of the resonance frequencies such as longitudinal frequency *(fl)*, transverse frequency *(ft)*, torsional frequency *(fr)* and damping ratios (ξ) for all prototype columns. Damping ratios are determined by utilization of the formula given by Chopra [28] as ξ = (fb-fa)/fn, whereas fn = maximum frequency, fa and fb are frequencies related with $\gamma/\sqrt{2}$. Amplitude is denoted by γ and is related with fn. For each reported prototype column an average of two readings are taken for both PRC and JFRC prototypes respectively. The methodology adopted for investigation of JFRC prototypes are similar to that of PRC prototypes due to non-availability of standards for FRC in the code. It can be noted that longitudinal frequency *fl*, transverse frequency *ft* and torsional/rotational frequency *fr* for prototype column 10SJC reduced up to 222 hz, 444 hz and 182 hz as compared to their counterpart prototype column 10SPC, respectively. Similar trend is observed for prototype column 10GJC as longitudinal frequency *(fl)*, transverse frequency *(ft)* and torsional/rotational frequency *(fr)* decreased by 221 hz, 578 hz and 79 hz than prototype column 10GPC, respectively. The decrement in resonance depicts effectiveness of employment of jute fibers in JFRC-columns to restrict the structural response to resonance failure. Moreover, damping ratios of prototype column 10SJC and 10GJC increased up to 2.48% and 3.4%, as compared to their counterpart 10SPC and 10GPC prototype column, respectively. Increment in damping ratio is one step more forward towards the safety and serviceability of building as energy absorption is increased. Thus, catastrophic failure can be prohibited in active seismic zones by enhancement in material properties. The outcomes for resonance frequencies and damping ratios of prototype rectangular columns of PRC and JFRC are presented.

Fig. 4.1 depicts comparison of dynamic properties for prototype columns of PRC and JFRC. Prototype 10SPC is taken as reference prototype for comparison purpose. It can be noted that longitudinal frequency *(fl)*, transverse frequency *(ft)* and torsional frequency *(fr)* reduced up to 13%, 20%, and 10% for prototype 10SJC as compared to 10SPC prototype column, respectively. Similarly *(fl)*,*(ft)* and *(fr)* for prototype 10GJC portrayed reduction up to 18%, 42% and 10% as compared to 10SPC prototype column, respectively. Prototype 10GPC demonstrated reduction in *(fl)*, *(ft)* and *(fr)* up to 4.8%, 3% and 5.1% than 10SPC prototype column, respectively.

TABLE 4.1: Resonance frequencies and damping ratios for prototypes specimens.

Specimen	**Avg**	**Resonance Frequency**			**Damping Ratio ξ**
		f_l	f_t	f_r	
10SPC	2	1708 ± 21	2152 ± 31	1977 ± 56	4.35 ± 0.21
10SJC	2	1486 ± 79	1708 ± 282	1795 ± 94	6.83 ± 0.37
10GPC	2	1625 ± 106	2086 ± 0.05	1876 ± 108	4.1 ± 0.36
10GJC	2	1404 ± 147	1508 ± 62	1797 ± 408	7.5 ± 0.79

f_l = *Longitudinal frequency,* ft = *Transverse frequency,* f_r = *Rotational/ Torsional frequency*

It is indicated that energy dissipation is greater in JFRC prototype rectangular columns as compared to their counterpart PRC prototypes respectively. The damping ratio (ξ) for prototype column 10SJC and 10GJC enhanced up to 57% and 72% as compared to 10SPC respectively. Prototype 10GPC depicted reduction in damping ratio (ξ) up to 5% than 10SPC prototype. Such improvement in damping ratio signifies the worth of jute fibers employment for greater energy absorption. The calculated results clearly validated greater damping ratios for JFRC prototype rectangular columns as compared to PRC prototype rectangular columns. Yan and Chouw reported enhancement in damping ratios for coconut fiber reinforced concrete [68].

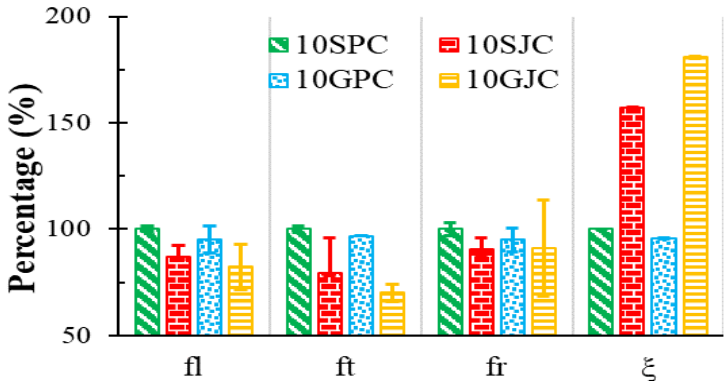


FIGURE 4.1: Comparison of dynamic results for prototypes

In current research work, longitudinal steel rebars were varied with GFRP rebars. For transverse shear reinforcement steel rebars are employed in both cases with the addition of jute fibers in scaled down prototype rectangular RC-columns. All prototype rectangular columns have been compared, and the effectiveness of jute fibers with GFRP rebars in compression members have been explored.

4.3 Structural Behavior of Prototype Rectangular Columns

Table 4.2 summarizes the experimental outcomes of the tested prototype rectangular columns of PRC and JFRC. Properties such as maximum load taken (P.m), strength in compression (S.C), compressive energy absorption from the initial to the maximum load (E1.C), energy absorption from maximum to ultimate load (Ecr.C), total energy absorption (T.E.C), toughness index (T.T.I) and failure modes are explained for PRC and JFRC prototype rectangular columns. PRC prototype rectangular columns 10SPC and 10GPC showed more load carrying capacity of 109.95 kN and 109.92 kN as compared to JFRC prototype rectangular columns 10SJC and 10GJC respectively. Prototype column 10SPC showed 65.16 kN more load carrying capacity than prototype 10GPC. Prototype 10GPC demonstrated 44.79 kN more load carrying capacity than prototype 10SJC. Similarly prototype 10SJC showed 65.13 kN more load carrying capacity than prototype column 10GJC. The compressive strength (S.C) is determined as the maximum stress from the stress-strain curve. It can be noted that the compressive strength reduced up to 7 kN for JFRC prototype columns as compared to PRC prototype columns. The total energy absorption of 10SJC and 10GJC has increased up to 0.38 MJ/m^3 and 0.19MJ/m^3 as compared to prototype columns of 10SPC and 10GPC. The toughness index of prototype 10SJC and 10GJC has increased up to 2.85 and 2.11 than prototype 10SPC and 10GPC. The failure mode for 10SPC and 10GPC is crushing mode, whereas for 10SJC and 10GJC bridging effect occurred due to presence of jute fibers. Fig. 4.2 portrays compressive behavior of PRC and JFRC prototype columns under concentric loading. Fig. 4.2(a) depicts stress-strain relationship for 10SPC, 10SJC, 10GPC and 10GJC prototype rectangular columns. It can be noted that the strain increased for 10SJC and 10GJC prototypes however decrement in strain is observed for 10SPC and 10GPC prototypes. Furthermore, prototype 10SPC demonstrated maximum compressive strength followed by prototype 10GPC, 10 SJC and 10 GJC, respectively. It is evitable from the graph that the prototype 10SPC carries more strength as compared to 10SJC but shows less ductile behavior as the curve drops immediately after reaching a certain point and strain stops at a certain point. However 10JSC carries low strength but demonstrates more ductile behavior than 10SPC as curve falls gradually and the strain is increased after a certain point. Similar incremental trend in strain is seen for 10GJC prototype as compared to 10GPC prototype. Addition of jute fibers in 10SJC and 10GJC prototypes are the reason for increment in strain and more gradual drop of the curve. Therefore, it can be stated that bridging effect between jute fibers and concrete in JFRC prototypes can be the reason for greater strain, ductility and improved performance.

Table 4.2: Experimental results of tested prototypes.

Specimen	**P.m** (kN)	**S.C** (MPa)	**E1.C** (MJ/m^3)	**Ecr.C** (MJ/m^3)	**T.E.C** (MJ/m^3)	**T.T.I** (-)	**Failure Mode**
10SPC	360.79±8.04	24.05±0.54	0.08±0.02	0.10±0.01	0.18±0.03	2.25±0.25	Crushing
10SJC	250.84±4.35	16.72±0.30	0.11±0.02	0.45±0.02	0.56±0.04	5.10±0.72	Bridging
10GPC	295.63±5.72	19.70±0.38	0.07±0.01	0.08±0.01	0.15±0.02	2.14±0.17	Crushing
10GJC	185.71±3.45	12.38±0.23	0.08±0.01	0.26±0.02	0.34±0.03	4.25±0.18	Bridging

Note: n average of two reading is taken. As per ASTM standard C39/C39M-18 loading rates are 0.19 MPa/sec and 0.27 MPa/sec for compressive strength test.

Fig. 4.2(b) depicts crack propagation with actual scenario and schematic diagrams at initial, maximum and ultimate load for prototype rectangular column of 10SPC, 10SJC, 10GPC and 10GJC. Applied concentric load is clearly evident from the actual scenario and schematic diagram. For prototype 10SPC, small cracks at initial stage occurred. However cracks width and length are smaller in size and lesser number of cracks are observed but at the maximum load more visible and larger cracks in width, length and numbers appeared. Furthermore, at ultimate load prototype 10SPC demonstrated spalling and crushing failure and some of the fragments have broken and fallen down. Similar behavior is observed for prototype 10GPC at initial loading but at maximum loading the cracks are much larger than 10SPC and some of the fragments have fallen down as a result of crushing failure. Prototype column 10SJC demonstrated hair line cracks at initial loading and with the increased loading only cracks width, length and number increased. Moreover, the mode of failure has changed from crushing to bridging effect. This bridging effect of jute fibers have restraint the cracks propagation to grow much larger due to which more load is taken and more strain is produced in 10SJC and 10GJC prototype columns. For 10SPC and 10GPC prototype, the first crack occurred at 92% of the peak load. For 10SJC and 10GJC prototypes first crack occurred at 87% of the peak load. Durability of 10SJC and 10GJC prototype enhanced due to better bond mechanism of jute fibers. Furthermore to explore the failure mechanism of jute fibers some of the JFRC prototypes have been intentionally broken. It can be noticed that 60% of jute fibers have broken while rest of 40% have pulled out of the matrix. The effectiveness of jute fibers in concrete is clearly evident by crack restraining mechanism, increased toughness and better structural performance of JFRC prototypes. It is concluded that compressive strength of JFRC is reduced than PRC specimen but properties such energy absorption and toughness index have significantly increased in JFRC specimens.

Fig. 4.3 displays comparison of compressive properties of prototype columns. The comparison of S.C, E.C, E1.C, Ecr.C, T.E.C and T.T.I has been performed by taking 10SPC as a reference prototype. It is evident from the graph that prototype 10SPC demonstrated increment in load carrying capacities up to 30%, 18% and

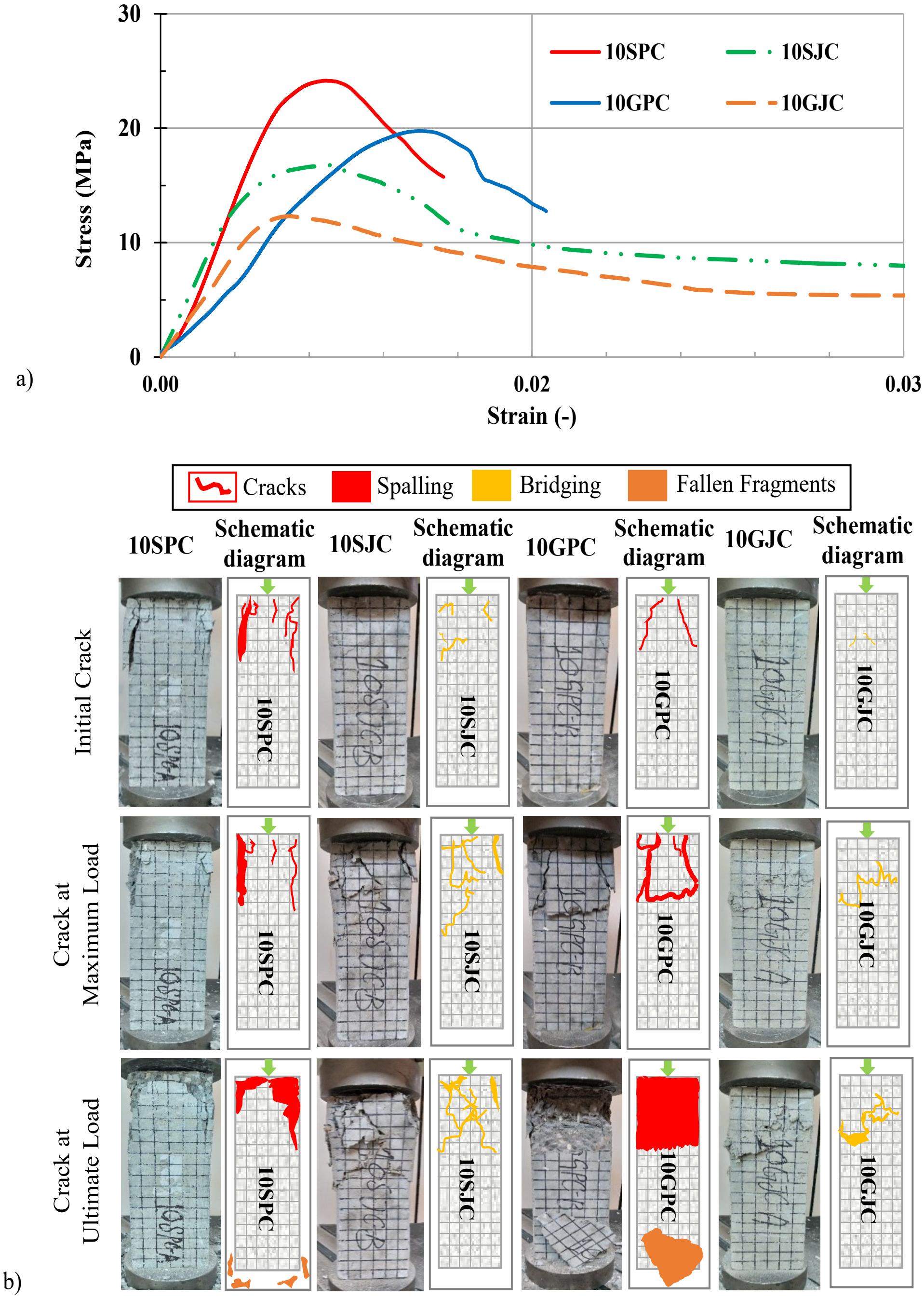


FIGURE 4.2: Compressive behavior of prototype rectangular columns; a) Stress-strain relationship and b) Cracking behavior

48% as compared to prototype 10SJC, 10GPC and 10GJC, respectively. The compressive strength is increased up to 43%, 22% and 94% for prototype 10SJC, 10GPC and 10GJC as compared to 10SPC. It is noted that the compressive strength reduced up to 40% for prototype 10GJC as compared to prototype 10GPC. Lower column capacity can be enhanced by increasing the column cross section in JFRC. With addition of jute fibers, enhanced amount of concrete volume can be achieved due to low density of fibers which do not effect the overall cost. The post cracked energy absorption (Ecr.C) for 10SJC and 10GJC increased up to 350% and 160%, respectively, as compared to 10SPC. The total energy absorption increased for 10SJC and 10GJC up to 211% and 88% whereas for 10GPC T.E.C reduced up to 16.6% as compared to prototype 10SPC. Enhancement in energy absorption is observed for all JFRC prototypes as compared to PRC prototypes. The T.T.I for prototype 10SJC and 10GJC increased up to 126% and 88% as compared to 10SPC prototype column, respectively.

Overall JFRC prototype rectangular columns demonstrated enhancement in mechanical properties except only for compressive strength as compared to PRC prototypes. Moreover JFRC prototypes revealed better behavior due to employment of jute fibers as compared to PRC prototypes.

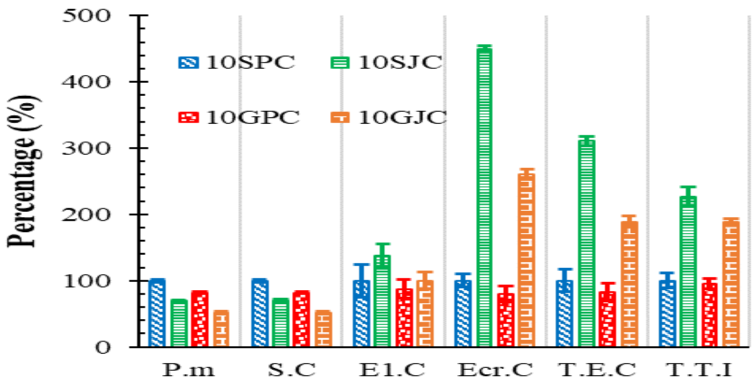


FIGURE 4.3: Comparison of various properties of prototype RC-column

4.4 SEM Analysis for Rectangular Prototype JFRC-Column

Fig. 4.4 depicts scanning electron microscope (SEM) analysis at failure surfaces of concentrically tested prototype rectangular column. SEM is performed to explore interfacial bonding between jute fibers and concrete matrix at micro level. Fig. 4.4(a) reveals presence of hairline cracks in the concrete matrix at post failure phase of concentric test. Tiny crack post peak load is also witnessed from the SEM image. Fig .4.4(b) portrays bridging effect between jute fiber and surrounding matrix to restrain further propagation of cracks. Absence of voids in concrete matrix shows better mixing of concrete and jute fibers. Fig. 4.4(c) visualizes existence of small cavities near the fiber. These voids may have remained due to entrapped air during casting. It is clearly visible that the number and size of these cavities are smaller with low depth which signifies better bonding phenomena. Poor adhesion between jute fiber and matrix is also observable from SEM image. Fig. 4.4(d) indicates fiber pullout due to concentric loading, better bonding between jute fiber and concrete at the toe of fiber pullout is clearly visible. SEM image also witnessed the breakage of jute fibers due to compression load as slices of jute fibers have broken and pulled out. Fig. 4.4(e) exhibits de-bonding failure of jute fibers as some of the fibers have split from the matrix. From clear examination of SEM image, interfacial de-bonding is evident. Fig. 4.5(f) demonstrates fiber failure which may have occurred due to shearing of fiber as a result of concentric loading. Fractured jute fiber surfaces are also noticeably visible through SEM images.

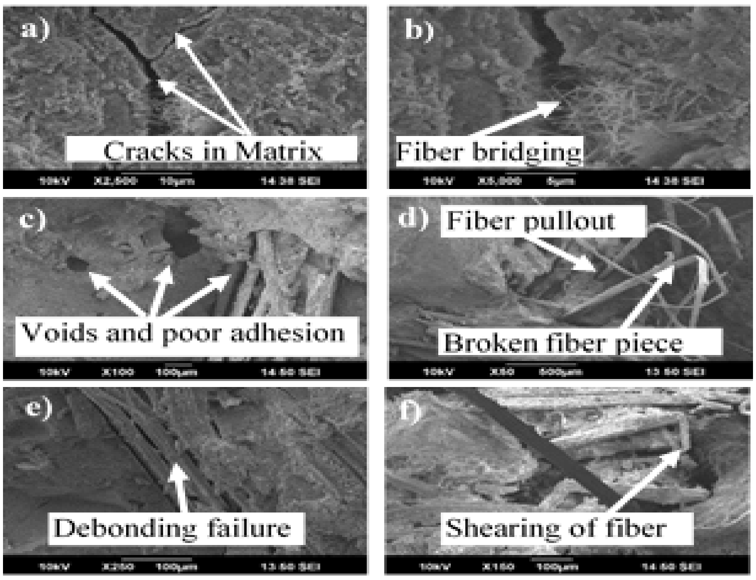


FIGURE 4.4: SEM images for tested prototype rectangular column under concentric load showing; a) Concrete matrix, b) Bridging effect, c) Presence of voids, d) Fiber breakage, e) Fiber de-bonding and f) Fractured fiber

Based on brief analysis of SEM images, it can be concluded that better bonding between jute fibers and concrete matrix existed. This better bonding shows greater bridging capacity to restrain crack formation due to concentric loading. However at maximum loading bridging effect of jute fibers weakened and failure occurred. Furthermore pullout of jute fibers, presence of cavities and pores in concrete matrix and fiber interfacial de-bonding were the key flaws as a consequence of concentric loading.

4.5 Summary

Non-destructive dynamic properties such as resonance frequencies and damping ratios of PRC and JFRC prototype rectangular columns have been determined. Post dynamic testing the compressive properties of PRC and JFRC prototype rectangular columns have been determined. JFRC prototype rectangular columns demonstrated greater damping ratios and better structural performance as compared to PRC prototype rectangular columns. Structural behavior and crack restraining phenomena for PRC and JFRC prototypes have been explored. Enhancement in all properties have been witnessed except for compressive strength. Over all better structural performance has been witnessed by JFRC prototype rectangular columns as compared to PRC prototype rectangular columns.

Chapter 5

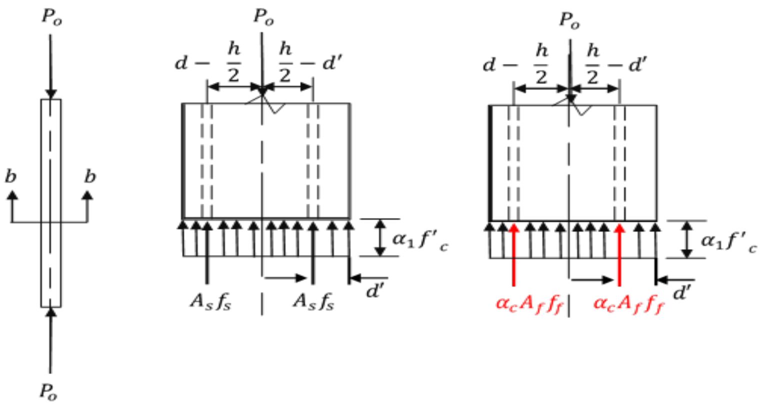
Discussion

5.1 Background

The results of the experimental work is explained in chapter 4. JFRC prototypes demonstrated enhancement in damping ratios, better crack restraining phenomena and overall better structural performance. In this chapter nominal capacity equation has been modified and relationship has been developed between material properties and prototype performance.

5.2 Nominal Capacity and Design Equation

Fig. 5.1 depicts modification of nominal strength equation for GFRP rebars under concentric load case. Fig. 5.1(a) shows the concentric loading due to compressive load P_o. Fig. 5.1(b) indicates the stress distribution for steel reinforced concrete. According to ACI440.1R-15 code, the contribution of steel longitudinal rebars in load carrying capacity is considered for RC-columns. However it prohibits the use of FRP rebars in compression members. Fig. 5.1(c) shows stresses for GFRP reinforced concrete. It is evident from the experimental work that GFRP could contribute 35% to the column capacity.



a) b) c)

FIGURE 5.1: Concentric load behavior; a) Loaded column, b) Stress distribution for steel-RC section and b) Stress distribution for GFRP-RC section

CSA S806-12 [10] allows utilization of FRP rebars as longitudinal reinforcement in RC-columns under concentric load without considering its contribution in the ultimate capacity of column. The equations proposed by ACI 440.1R-15 [9] and CSA S806-12 [10] were as follows:

$$P_o = 0.85\ f_c^{'}(A_g - A_f)\text{.......................................}(5.1)$$

$$P_o = \alpha_1\ f_c^{'}(A_g - A_f)\text{...}(5.2)$$

The equation proposed by Tobbi et al. [1] and Afifi et al. [69] on contribution of GFRP rebars in the ultimate capacity of RC-columns was as follows:

$$P_{pred} = \alpha_1\ \ f_c^{'}\,(A_g - A_f) + \alpha_f f_{fu} A_f\text{...............}(5.3)$$

whereas $\alpha_1 = 0.85;\ \alpha_f = 0.35$

In current research work, from the outcomes of experimental work and predicted theoretical calculations, the contribution of longitudinal GFRP rebars is 35% in load carrying capacity of rectangular RC-column. Table 5.1 portrays outcomes of experimental research work and predicted theoretical calculations in terms of experimental peak load and predicted nominal capacity. Based on the calculations a new reduction factor ($\propto_c$) is presented for GFRP rebars to reduce its compressive strength by taking GFRP rebar tensile strength as its function. The value of this reduction factor is equal to 0.35 as per validation of calculations. The difference between experimental maximum load and predicated theoretical nominal capacity of GFRP RC-column is reported in Table 5.1. Furthermore, for more safety concerns this new reduction factor of *($\propto_c = 0.35$)* is further reduced and a factor of *($\propto_c = 0.30$)* is assumed.

$$P_{pred} = \alpha_1 \;\; f_c^{'} \left(A_g - A_f\right) + \alpha_f f_{fu} A_f \text{..............(5.4)}$$

whereas $\alpha_1 = 0.85$; $\alpha_f = 0.35$

Thus, a modified equation with a reduction factor *($\propto_c = 0.30$)* is proposed to be considered for load carrying capacity of GFRP RC-columns.

TABLE 5.1: Experimental and theoretical results comparisons

Sr. No	**Specimens**	**Axial load**		**% Difference**
		Experimental (kN)	**Theoretical (kN)**	
1	10SPC	360.79	345.17	4.52
2	10SJC	250.84	231.33	8.43
3	10GPC	295.63	283.57	4.25
4	10GJC	185.71	169.33	9.67

5.3 Relation Between Materials Properties and Prototypes Performance

Structural performance of RC-columns under concentric loading is related to the properties of material. The brittle failure response of the concrete prominently impacts the performance of prototypes. Enhancement in structural performance of prototype corresponds to the toughness index, energy absorption and dampness. Steel deployment for bending strength enhancement may be an optimistic option but under concentric load scenarios sudden crushing of concrete predicts essentials of fiber reinforcement. Deployment of fiber encountered the issues by developing bridging effect and ultimately changed the concrete crushing behavior to bridging behavior. Material properties signifies damping ratios under concentric loading. Fiber incorporation also resulted in decrement of crack number and size. Energy absorption greatly influenced the post peak cracking behavior of concrete. Fibers deployment acts to maximize energy absorption and ultimately improved post cracking of concrete. Energy absorption increased the damping ratios and ultimately reduced the response of structure against external dynamic loading. The outcomes depicted that JFRC prototypes absorbed more energy and enhancement in damping. The basis for establishment of relationship between material properties and prototype testing is that in forthcoming prospects complex scenario could be catered for the actual in field concrete structures.

JFC specimens indicated significant enhancement in damping, energy absorption and toughness as compared to PC specimens. Similar trend has been noticed for JFRC prototypes due to deployment of jute fibers which validated improved material properties. PC prototypes demonstrated crushing failure as some of the concrete fragments degraded and dropped down. The JFC specimens demonstrated bridging effect and restraint the crack propagation through the specimen. Prototype testing validated the effectiveness of jute fibers in RC-column. JFRC prototypes demonstrated bridging effect and better structural performance.

5.4 Summary

Nominal capacity of GFRP RC-column is modified through an equation validated by experimental outcomes of the researched work. The predicted theoretical and experimental outcomes demonstrated less variance in load carrying capacities of prototype columns. The relationship between material properties and performance of prototypes are explored. Damping of JFRC prototype rectangular columns showed significant enhancement as compared to PRC prototypes. Better structural performance, crack resistance and enhanced properties are observed for JFRC prototype rectangular columns as compared to PRC prototype rectangular columns.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This research work is part of an ongoing research program at Capital university of Science and Technology Islamabad that aims to investigate the effectiveness of jute fibers and GFRP rebars in prototype rectangular RC-columns. The mix design ratio of 1:2:3:0.60 (C:S:A:W) with 50 mm fiber length at 5% content of jute fibers by mass of cement has been utilized for the preparation of JFRC prototypes. Experimental work has been performed, results are analyzed and outcomes drawn are presented.

- Deployment of jute fibers in concrete enhanced damping ratios, energy absorption and toughness index up to 127%, 8.7% and 63%, respectively as compared to PC specimens under compression loading.
  - Furthermore, significant enhancement has been observed for specimens under flexure and splitting testing.
  - Enhancement in crack resistance has been also observed due to jute fibers incorporation.

- The damping ratios for prototype column 10SJC and 10GJC enhanced up to 57% and 72% as compared to 10SPC, respectively. Whereas prototype 10GPC depicted reduction up to 5% in damping ratio.
- The post cracked energy absorption and total energy absorption for 10SJC and 10GJC increased up to 350%, 160% and 211%, 88%, respectively.
  - Post cracked energy absorption for 10GPC reduced up to 20% and 16.6%, respectively as compared to prototype 10SPC.
  - The toughness index for prototype 10SJC and 10GJC increased up to 126% and 88% as compared to 10SPC prototype column.
- SEM images depicted better bonding and bridging effect between jute fibers and concrete matrix.
- Experimental work and predicted theoretical calculations validated the contribution of GFRP rebars up to 30 % in load carrying capacity of columns. Thus, a new reduction factor ($\propto c$ =0.30) is proposed in nominal capacity equation for GFRP RC-column.
- Material properties effectively influenced the performance of prototype columns. The relative toughness, energy absorption and damping ratios significantly dominated the structural behavior under concentric load condition.

Thus, jute fibers with GFRP rebars can be an effective combination to be utilized for concentric column application in important structures for better structural performance. It is recommend for international design codes to review the aspect of load contribution for compression members.

6.2 Future Work

Following recommendations are drawn for future research work:

- Jute fibers and GFRP rebars should be investigated for long term durability and bonding with concrete.
- Experimental outcomes may be validated by simulation with Abacus software.
- Further investigations should be carried out on full scale testing for practical implementation in the construction industry.

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