CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Use of Jute Fibre Reinforced Concrete having GFRP Rebars in Thin Shear Wall to Avoid Catastrophic Failure

by

Abaid ur Rehman

A thesis submitted in partial fulfillment for the
degree of Master of Science

in the
Faculty of Engineering
Department of Civil Engineering

May 2020

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 meet the challenges with ingenuity and boldness, and who made us what we are today.

CERTIFICATE OF APPROVAL

Use of Jute Fibre Reinforced Concrete having GFRP Rebars in Thin Shear Wall to Avoid Catastrophic Failure

by
Abaid ur Rehman
(MCE183001)

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Engr. Prof. Dr. Ayub Elahi	UET, Taxila
(b)	Internal Examiner	Engr. Dr. Shuja Safdar Gardezi	CUST, Islamabad
(c)	Supervisor	Engr. Prof. Dr. Majid Ali	CUST, Islamabad

Engr. Prof. Dr. Majid Ali
Thesis Supervisor
May 2020

Engr. Dr. Ishtiaq Hassan
Head
Dept. of Civil Engineering
May 2020

Engr. Prof. Dr. Imtiaz Ahmed Taj
Dean
Faculty of Engineering
May 2020

Author's Declaration

I, **Abaid ur Rehman** hereby state that my MS thesis titled "**Use of Jute Fibre Reinforced Concrete having GFRP Rebars in Thin Shear Wall to Avoid Catastrophic Failure**" is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my MS Degree.

(Abaid ur Rehman)

Registration No: MCE183001

Plagiarism Undertaking

I solemnly declare that research work presented in this thesis titled "**Use of Jute Fibre Reinforced Concrete having GFRP Rebars in Thin Shear Wall to Avoid Catastrophic Failure**" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

(Abaid ur Rehman)

Registration No: MCE183001

List of Publications

It is certified that following publication(s) are made out of the research work that has been carried out for this thesis:-

Conference Proceedings

1. Ur Rehman, A., and Ali, M. (2019). Behavior of thin shear concrete walls during earthquakes in last decade. *International Conference on Sustainable Development in Civil Engineering*, MUET, Pakistan Dec 5-7, Paper 217.
2. Ur Rehman, A. and Ali M. (2020). Influence of jute fibre and GFRP rebars in compressive and dynamic behavior of prototype thin shear concrete walls. *11th International Civil Engineering Conference*, NED, Karachi, Pakistan. March 13-14, Paper 95.

Abaid ur Rehman
(MCE183001)

Acknowledgements

- I would like to thank Almighty Allah for his countless blessing.
- I would like to pay special gratitude to **Engr. Prof. Dr. Majid Ali** for his guidance and supervision, without which, this was not possible.
- I am grateful to all members of structural material research group (SMaRG), especially Engr. Shehryar Ahmed and Engr. Hassan Raza for their kind help in lab work.
- I am also grateful to my family for their continuous moral support.

Abaid ur Rehman
(MCE183001)

Abstract

Failure of thin shear concrete walls was observed in many high-rise buildings during 2010 Chile and 2011 Christchurch, New Zealand earthquake. Buildings having shear walls experienced severe damage. The structural configuration of system and non-ductile behavior of thin shear walls led to damage of these buildings. A common type of damage observed was compression failure of thin shear concrete walls at lower stories of buildings. Experimental investigations on thin shear walls suggests that wall without proper confinement of longitudinal reinforcement failed abruptly under uniform compression loading. The damage in medium rise buildings was due to thin unconfined walls subjected to high axial stresses which increased due to the dynamic effect.

In current study, the compressive behavior of prototype thin shear walls having jute fibre reinforced concrete (JFRC) with glass fibre reinforced polymer (GFRP) rebars is investigated for possible mitigation of catastrophic failure. Mix design ratio for plain concrete (PC) is 1:2:3:0.6 (cement: fine aggregate: coarse aggregates: water). Jute fibres having cut length of 50 mm and fibre content of 5% by mass of cement, are used for preparing JFRC. Sixteen prototype thin shear walls having steel and GFRP rebars with PC and JFRC are prepared with simplified boundary condition for compression testing. Prototypes are kept in curing tank for 28 days. Dynamic properties are tested prior to compression testing done in servo hydraulic testing machine (STM). The compression parameters studied are strength, energy absorption, ultimate strain and toughness index.

The results show that JFRC prototypes have more damping ratio, strength, ultimate strain and toughness index as compared to plain reinforced concrete (PRC) prototypes. Compressive strength of JFRC prototype having GFRP rebars is generally more as compared to JFRC prototype having steel rebars. Spalling of concrete is more for PRC prototypes as compared to JFRC prototypes. Scanning electron microscope (SEM) analysis suggests that jute fibres are uniformly dispersed throughout the concrete matrix. Empirical results for peak axial loading are in good agreement with experimental results. Further investigation on durability of jute fibre and bond behavior of GFRP rebars need to be investigated for possible use in thin shear walls.

Contents

List of Figures

List of Tables

Abbreviations

$\mathbf{CE}_m$	Compressive Energy Absorption till Peak Load
$\mathbf{CE}_u$	Compressive Energy Absorption from Peak Load to Ultimate Load
CS	Compressive Strength
CTI	Compressive Toughness Index
$\mathbf{E}_u$	Energy Absorption from Peak Load to Ultimate Load
$\mathbf{E}_m$	Energy Absorption till Peak Load
FS	Flexural Strength
FTI	Flexural Toughness Index
$\mathbf{f}_l$	Longitudinal Frequency
$\mathbf{f}_t$	Transverse Frequency
$\mathbf{f}_{tr}$	Torsional Frequency
GFRP	Glass Fibre Reinforced Polymer
JCG	Jute Fibre Reinforced Concrete having GFRP rebars
JCS	Jute Fibre Reinforced Concrete having Steel rebars
JF	Jute Fibre
JFRC	Jute Fibre Reinforced Concrete
kN	Kilo Newton
mm	Milli Meter
MPa	Mega Pascel
PC	Plain Concrete
PCG	Plain Concrete with GFRP Rebars
PCS	Plain Concrete with Steel Rebars
PRC	Plain Reinforced Concrete
s	Seconds

STM	Servo Hydraulic Testing Machine
STS	Split Tensile Strength
STI	Split Tensile Toughness Index
TCE	Total Compressive Energy Absorption
TE	Total Energy Absorption
TI	Toughness Index

Symbols

Ø	Diameter
$\boldsymbol{\xi}$	Damping Ratio
$\mathbf{P}_{max}$	Maximum Load
$\boldsymbol{\varepsilon}$	Strain
δ	Strength

Chapter 1

Introduction

1.1 Background

Junemann et al. [1] highlights that concrete shear walls are typically used to resist lateral loading (i.e. earthquake and wind) in seismic regions, and carry vertical loads to the base simultaneously. Adebar [2] highlighted that many buildings were severely damaged during the February 2010 earthquake in Chile. A common failure in high rise buildings was the compression failure of concrete shear walls. Thickness of the walls ranged from 120 mm to 200 mm. Even though it is difficult to establish a simple definition of thin shear wall, a wall having thickness 200 mm or less can be considered as thin shear wall [2]. Sherstobitoff et al. [3] highlighted that more than 100 buildings having concrete shear walls were damaged in February 2010 earthquake in Chile. A common type of damage observed was compression failure of thin shear concrete walls at lower stories of buildings. Yathon et al. [4] highlighted that during 2010 Chile earthquake and 2011 Christchurch earthquake, buildings having shear walls experienced severe damage. The structural configuration of system and non-ductile behavior of thin shear walls led to damage of these buildings. Junemann et al. [5] highlighted that the damage in medium rise buildings was due to thin unconfined walls subjected to high axial stresses which increased due to the dynamic effect. Among these flaws, compression failure is reported to be dominant flaw in thin shear concrete walls when thickness of shear wall is reduced.

Adebar [2] reported that its a common practice in Chile to make partitions walls between rooms as shear walls. Older buildings had thicker walls while new buildings had thin walls. The walls supported the floor slab and controlled the lateral loading (i.e. earthquake and wind). Mostly, the damage observed was in thin walls. Rojas et al. [6] observed that compression in walls of buildings could cause crushing of concrete and buckling of reinforcement. Saatcioglu et al. [7] highlighted that as 1996 Chilean code did not restrict any structural irregularities. A fifteen story building had a shear wall with an offset at first story towards which it collapsed. The vertical irregularity in this slender shear wall may have caused the compressive stresses to increase at first story level resulting in crushing of unconfined concrete at the ends of wall. Adebar and Lorzadeh [8] reported that 22 story hotel Grand Chancellor in Christchurch underwent damage beyond repair when its concrete wall in lobby failed in compression. The wall was supporting a transfer girder on sixth story level of building that was cantilever past the concrete wall. Hoult et al. [9] reported that Pyne Gould building collapsed in a brittle, non-ductile and catastrophic manner during 2011 Christchurch earthquake. Hoult et al. [10] highlights that failures witnessed during Christchurch earthquake are signs of the catastrophic structural damages that would possibly transpire in low to moderate seismic regions of Australia if same magnitude earthquake occurs. Insufficient reinforcement in these reinforced concrete walls may trigger the failure.

Crushing of concrete can lead towards the abrupt failure thus, ultimately leading towards catastrophic failure of a concrete structure. Hence, to avoid this abrupt crushing of concrete, natural fibres in concrete are used. Different types of natural fibres are investigated by researchers for enhancing mechanical properties. There is a need to promote cheap and locally available materials in order to save cost without compromising on mechanical properties. Jute fibre has the ability to increase compressive parameters and dynamic properties of concrete. Hence, JFRC is a locally available fibre which is cheap in cost. Increasing cost of steel rebars and corrosion issues have promoted the use of more corrosion resistant reinforcement like GFRP rebars. Jute fibre reinforced concrete (JFRC) has the ability to create a bridging phenomenon with unstable concrete while glass fibre reinforced polymer (GFRP) rebars acts as corrosion resistant reinforcement.

To the best of author's knowledge, no study has been done to avoid thin shear wall failure using JFRC with GFRP rebars. Hence, an experimental study is planned to investigate the potential of JFRC having GFRP rebars in thin shear walls.

1.2 Research Motivation and Problem Statement

Earthquake causes severe damage like collapse of buildings, which may kill many people. Due to real estate issues high-rise buildings have become a trend and for achieving economy and more usable floor area, thickness of structural members like column and shear walls are reduced. The failure of shear walls have resulted in collapse of certain parts of buildings leading towards infrastructural and human loss. Sudden failure due to crushing of concrete does not allow appropriate evacuation time to the occupants of building. Hence, there is a need of experimental study to investigate the failure mode of thin concrete walls under axial compressive load. Thus, the problem statement is as follow:

"In thin shear wall, compressive failure was observed in brittle mode due to less ultimate compressive strain [2]. Damage observed in buildings was due to crushing of concrete. Point of concern was that crushing of concrete results in catastrophic failure without prior warning. There is a need to increase the compressive toughness of thin wall so that catastrophic failure (even failure) can be avoided."

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 fibers for improved durability and performance.

"The specific aim of this MS research work is to investigate the compressive behavior of prototype thin shear concrete walls having jute fibres and GFRP rebars for possible mitigation of catastrophic failure."

1.4 Scope of Work and Study Limitation

Cylinders of PC and JFRC are tested for compression and split tensile strength, while beamlets are tested for flexural strength. Flexural testing is done keeping in view that in case of analytical modelling, flexural strength and toughness is required. Two sets of prototype thin shear walls are tested for PRC, one having steel rebars and other having GFRP rebars. Similarly, two sets of prototype thin shear walls are tested for JFRC, one having steel rebars and other having GFRP rebars. Dynamic testing of specimens (i.e. PC and JFRC cylinders and beamlets) and prototype thin shear wall is done using resonance apparatus according to ASTM standard C215. Then prototypes are tested in servo hydraulic testing machine (STM) according to ASTM standard to get compressive strength and toughness index.

Study limitation is that simplified boundary condition (i.e. without boundary element) are being cast. To start with, only axial load is being considered in current study. However, lateral load application is recommended for future work.

1.5 Methodology

Compressive, flexural and split tensile strength for PC and JFRC specimen are tested in STM. Mix design for PC and JFRC 1:2:3:0.6 with an addition of 5% fibre of 50 mm length in JFRC. Almeida et al. [11] tested five specimens of wall at a scale which varied from 2/3 to 1/1. Similar approach is used with a scaling factor of approximately 1/6 in present study with simplified boundary condition as shown in figure 1.1. It is difficult to test full length of shear wall in lab. Hence, a prototypes having simplified boundary conditions (i.e. without boundary elements) are tested in lab having dimensions of 457 mm x 153 mm x 45 mm. All the specimens and prototypes are tested according to ASTM standards.

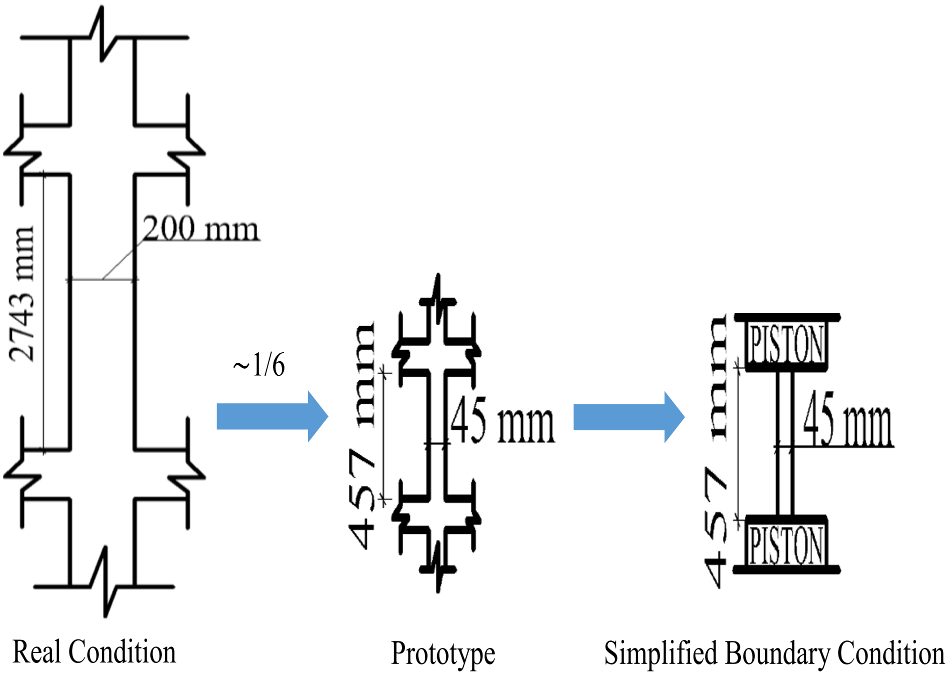


Figure 1.1: Scaling down of thin shear concrete wall

1.6 Thesis Outline

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

Chapter 1 consists of introduction section. Concept and flaws of thin shear wall is presented in this chapter. It also consists of research motivation and problem statement, overall objective, specific aim, scope of work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background, flaw identification in thin shear concrete walls, governing mechanical property in dominant flaw, alternate approach to improve governing properties, additives in concrete and summary.

Chapter 3 covers experimental work. It contains background, raw materials, mix design, casting procedure and mechanical properties, specimens, testing procedure and summary.

Chapter 4 encompasses experimental results. It contains background, behavior of prototype thin shear wall under compressive loading, SEM analysis and summary.

Chapter 5 includes of discussion. It contains background, relation between material properties and behavior of prototype, empirical modelling and summary.

Chapter 6 encompasses conclusion and recommendations.

References are presented right after chapter 6.

Annexure is given at the end.

Chapter 2

Literature Review

2.1 Background

Many researchers have reported numerous thin shear concrete walls failures. The literature presents the performance of thin shear concrete walls during past earthquakes of last decade. There are four aspects with the help of which behavior is being evaluated; (i) flaw identification in thin shear concrete walls, (ii) governing mechanical property in dominant flaw, (iii) alternate approach to improve governing properties, and (iv) additives in concrete. Various researchers explored different non-conventional materials to change the post cracking behavior of concrete. The output of using non-conventional materials to enhance mechanical properties of concrete are also reported. There is a need to explore behavior of thin shear walls with non-conventional materials is also emphasized.

2.2 Flaw Identification in Thin Shear Concrete Walls

More than 70% of population was affected during 2010 Chile earthquake. Thin shear walls were constructed to support floor slabs and also control lateral forces i.e. wind and earthquakes. Latin American countries build thin walls with single reinforcement mesh in buildings. A common failure mode for these thin walls is out of plane failure [12]. Large unsupported length of web near the critical portion at base of wall are prone to out of plane buckling under cyclic loading [13]. In Chile, its a common practice to make the partition wall between rooms a shear wall in high-rise buildings. Walls having a thickness of 200 mm or less can be considered as thin shear concrete walls [2]. Most of these thin shear walls were of thickness 120 mm to 200 mm. When the length of shear wall decreases while going down the structure, there is a sudden increase in demand of compressive strain. This in turn leads to crushing of concrete leading to a catastrophic failure [2]. More than 100 buildings were damaged in 2010 Chile earthquake which had a magnitude of 8.8 on richter scale [3]. Old frame structures are very rare in western Canada. Majority of pre 1980s buildings have shear walls for resisting lateral loads (i.e. earthquake and wind loadings). Shear walls are expected to perform better than the frame structure but at the same time they are susceptible to brittle failure mode. In 2010 Chile earthquake and 2011 Christchurch earthquake, buildings having shear wall faced severe damage due to structural configurations and brittle mode of failure of thin shear walls [4]. Crushing and spalling of concrete along with buckling of longitudinal reinforcement was observed over the length of the wall in 2010 Chile earthquake [14].

Chilean Seismic code 1996 did not restrict any structural irregularities thus number of buildings were built with horizontal irregularities. A 15 story Alto Rio Condominium building in Concepcion shown in figure 2.1 (a) prior to earthquake and figure 2.1 (b) shows the collapsed building after the earthquake. This building was designed in 2008 and had shear walls which had an offset at the first story towards which it collapsed as shown in figure 2.1 (c). Figure 2.1 (d) shows the plan at ground floor of the building having setback. This vertical irregularity resulted in an increase of compressive stress which led to crushing of unconfined concrete at first story level. These shear walls were slender walls without confinement reinforcement at boundaries of the wall. It was observed that crushing of concrete along with tensile failure of reinforcement within wall triggered total collapse of building [7].

FIGURE 2.1: Alto Rio Condominium building in Concepcion; (a) building prior to earthquake, (b) building post-earthquake, (c) failure of shear wall, and (d) approximate plan of building [7]

2.3 Governing Mechanical Property in Dominant Flaw

A common type of failure observed in high rise buildings was compression failure of thin shear walls as shown in figure 2.2. Figure 2.2 (a) shows buckling of reinforcement due to opening of cross ties subsequently leading to spalling of concrete. Lack of boundary elements and rebar buckling is evident in figure 2.2 (b). Pyne Gould Building in Christchurch, New Zealand collapsed as east core wall failed abruptly in compression. The wall had single mesh of reinforcement and had a thickness of about 200 mm. It was observed that most of thin shear walls in Chile did not have confinement reinforcement. Transverse reinforcement had a 90 degree hook around the two longitudinal rebars at the end of the shear wall [2]. Sattcioglu et al. [7] highlighted that number of mid and high rise buildings in Santiago faced shear wall failure in lower stories due to compression failure of slender thin shear walls.

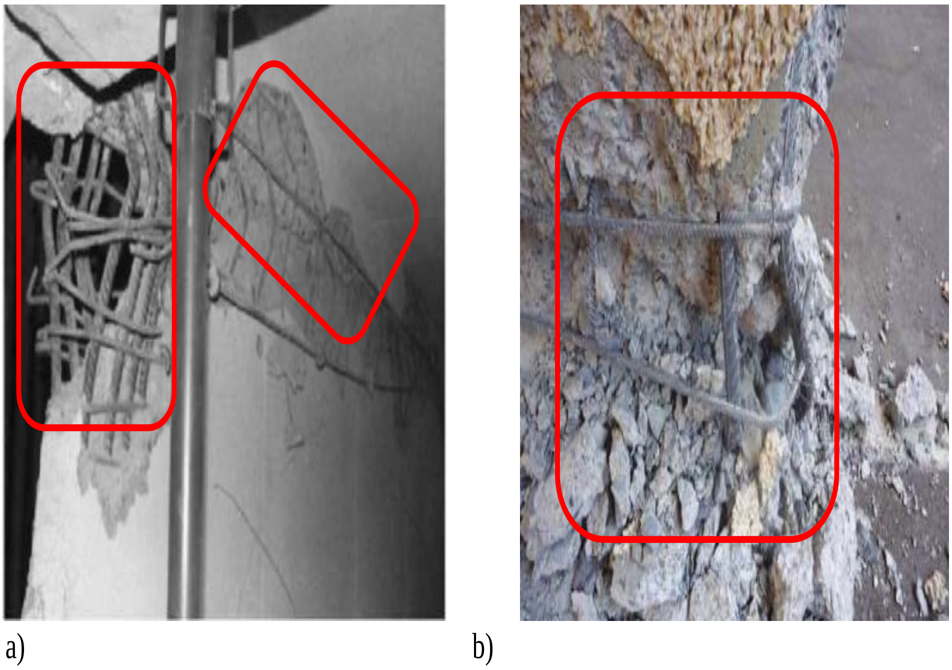


FIGURE 2.2: Thin shear wall failure, (a) flexural compression failure, and (b) buckling of vertical bar due to lack of boundary elements

During the 2010 earthquake in Chile, compressive failure in thin shear wall was observed in several high rise buildings. Experiments conducted showed that thin shear concrete walls with two layers of transverse reinforcements failed in compression due to low strain as thin concrete layer between the horizontal reinforcement became unstable [3]. Observation of buildings showed that the compression in walls can trigger crushing of concrete along with buckling of longitudinal reinforcement at ground level of wall in tall buildings. Reinforcement buckling and tension could result in breaking and pullout of longitudinal of rebars due to tension in case of inadequate development lengths [6]. The building code of Chile (NCh 433.96) allowed the construction of slender shear walls in multistory buildings. A small wall thickness of 150 mm was permitted with ties to prevent buckling of reinforcement. There was no requirement for boundary zones in these thin walls. This resulted in shear walls were damage as there was crushing of concrete and buckling of longitudinal reinforcement throughout the length of wall [7]. An experimental investigation was carried out by Adebar [2] in which multiple wall samples were subjected to axial compression. The parameters considered were thickness of wall, transverse reinforcement (i.e. no horizontal rebars, single and double layer), clear cover of transverse reinforcement and height. It was observed that walls without any ties failed at a strain of 0.001. The crushing of concrete occurs without any warning (i.e. without prior warning). Thinner walls with single reinforcement mesh failed in a brittle way but at a higher compressive strain as compared to walls having double reinforcement mesh. It was due to large volume of undamaged concrete in walls with single layer of reinforcement. The observations from nonlinear finite element modeling for a wall step-back irregularity showed an increase in demand of compressive strain at the compression edge of short length concrete wall supporting the overhanging concrete shear wall above. Adebar and Lorzadeh [8] reported that a twenty-two story Grand Chancellor hotel faced severe damage due compression failure of concrete wall in lobby. The wall supported a cantilever transfer girder at sixth floor. Segura and Wallace [15] tested two thin wall specimens under combined axial loading and increasing cyclic shear and moment. The wall specimens represented lower part of a cantilever wall of eight story building. The varying parameters in specimens were depth of compression zone and arrangement of vertical and horizontal rebars. The results showed a brittle compressive failure as the thin compressive zone was not able to distribute compressive strain over a considerable length leading to crushing of concrete. Arteta et al. [16] conducted an experimental investigation by casting seven boundary elements of concrete shear walls subjected to compression. The horizontal reinforcement for specimens was such that either it matched or exceeded the code requirement. A brittle axial failure was observed in wall specimens after being subjected to monotonic loading.

2.4 Alternate Approach to Improve Governing Properties

To avoid brittle compression failure in walls, increasing the thickness of wall and changes in detailing provisions (i.e. confinement of boundary zones) have been suggested in studies. The experimental investigation showed that wall specimens having ties with 90 degree hooks never opened. Hence, buckling of reinforcement can be avoided which triggers crushing of concrete. It is suggested that there should be a limit on the compressive strain depth to a certain portion of wall which will depend on the drift demand [2]. Shear walls without sufficient boundary confinement fail in a brittle manner in compression zone. As the compressive strain capacity of wall maybe less than what was assumed. In order to avoid brittle mode of failure and buckling of web, the compression stress block of the walls must be limited to ensure a tension controlled failure in concrete walls [17].

Wallace [18] suggested to design the walls for ductile compression yielding by limiting the slenderness and minimum thickness of wall. Changes to the displacement design of shear wall were also recommended for ACI 318-11. Lu et al. [19] recommended that design standards must adopt requirements for providing a greater portion of the steel reinforcement at the boundary elements (i.e. wall ends) of reinforced walls to improve the ductility and cracking behavior of walls. Junemann et al. [5] suggested to increase the wall thickness or reduce the wall stresses to improve in plane bending and compression of wall as confining the boundary does not have a great amount of impact on ductility of wall.

The Chilean code does not limit the use of structural irregularities (i.e. setbacks and discontinuous shear walls) which in turn increases the deformation demand leading to global failures [7]. A limit on these irregularities can limit the failure of thin shear concrete walls. Shear walls are protected against shear failure by design capacity approach but at the same time number of flexural compression failure occurred in Christchurch. To avoid such type of failure, modification of shear wall design provisions will help in improving the ductility of walls. Sufficient boundary confinement will change the brittle mode of failure to ductile failure [3].

2.5 Additives in Concrete

Experimental studies showed that properly confined boundary elements do not show a complete ductile behavior when subjected to pure compression by conforming to ACI 318-11 detailing requirements only [16]. Hence, there is a need to explore non-conventional material to change the brittle mode of failure to ductile mode of failure. Natural fibres are cheap and locally available material with a potential to change the post cracking behavior of concrete without compromising the mechanical properties of concrete. Izquierdo et al. [20] used sisal fibre in hollow concrete blocks, wallette and walls. It was observed that sisal fibre increased the ductility of the blocks as the fibre bridged the opening cracks and prevented further discontinuity of the material. Due to low elastic modulus of sisal fibre, they become effective after cracking of concrete hence, there is an increased energy absorption due to which wallettes can withstand increase in loading even after cracking. Madandoust et al. [21] investigated the effect to rice husk ash on properties of concrete and its durability. The durability was assessed by placing the specimen in extreme environment for 11 months. It was observed that partial replacement of cement by rice husk ash increased the durability of concrete and there was an increase in compressive strength of concrete at later ages. Ali et al. [22] investigated the mechanical and dynamic properties of concrete. The varying parameters were fibre content (i.e. 1% - 5%) and length of fibre. The testing result showed an increase in damping of coconut fibre reinforced concrete beams while a decrease of fundamental frequency of beam was observed due to damage. Further test results revealed that 5% fibre content and 50 mm length of fibre increases the compressive toughness unto 21% as compared to PC. Islam and Ahmed [23] highlighted the influence of jute fibre on the properties of concrete. The results showed a positive impact on compressive strength of concrete with low percentage of fibre content (i.e. 0.25%). Compressive strength of jute fibre reinforced concrete increases with the increase of curing age.

The failure pattern of specimen during compressive testing showed that jute fibre decreases the width of the cracks hence, altering the cracking pattern of concrete. Zakaria et al. [24] concluded from his experimental investigation of jute fibre in concrete that there is an increase in mechanical properties by keeping the fibre content of 0.1% and 0.25% with the fibre length of 10 mm and 15 mm. Malai and Datta [25] conducted an experimental investigation on bamboo reinforced slabs. An enhancement in load carrying capacity and deformation ability was observed by using bamboo strip as reinforcement as compared to plain concrete and reinforced cement concrete (RCC). Lima et al. [26] conducted an experiment to evaluate the durability of bamboo fibre. Specimens were exposed to wetting and drying cycles. Samples with concrete were kept in water and samples without concrete were kept in calcium hydroxide. The results of the tests showed no noticeable change in mechanical properties of bamboo fibre proving the durability of bamboo fibres. Zia and Ali [27] studied the behavior of fibres in concrete to control the rate of cracking in canal lining. It was observed that fibres are effective in controlling the rate of cracking. There was a decrease of 35% in compressive strength of JFRC as compared to PC, while an increase of 124% in compressive toughness of JFRC is reported as compared to PC. There is no limit of compromised strength reported as the experimental studies conducted are based on relative comparison. Mozzali et al. [28] concluded that fibres like macro polypropylene and polyethylene are effective in controlling the width of cracks and a delay in crack initiation. Fibres also have the ability to enhance the dynamic properties of concrete. Table 2.1 summarizes the dynamic properties of fibres.

John et al. [32] investigated the durability of coconut fibre. The fibres were 12 years old and were taken from internal and external walls of houses. SEM analysis showed that fibres were undamaged even after being exposed to 12 years of natural environmental conditions. Lignin content in fibre was same for internal and external wall. Shivaraj et al. [33] highlighted the durability of coconut fibre. The mechanism of testing was 2 years of wetting and drying cycles of specimens and it was concluded that there was no decrease in mechanical properties of coconut fibre reinforced concrete.

Table 2.1: Dynamic properties of fibre reinforced composites

Sr #	**Reference**	**Fibre**	**Conclusion**
1	Ali et al. [22]	Coconut	Increase of fibre content increases the damping ratio and reduces the fundamental frequency especially after cracking of specimen. Fibre length of 5 cm and 5% fibre content has the best dynamic properties.
2	Hussain and Ali [29]	Jute	Addition of jute fibre in concrete increases the damping ratio and dynamic elastic modulus by 100% and 68%, respectively.
3	Yan and Chouw [30]	Coir	Fibre decreases the fundamental frequency, dynamic Poisson's ratio and modulus of elasticity but significantly increases the damping ratio. It was observed that jute fibre reinforced composite showed a better dynamic behavior.
4	Omar et al. [31]	Jute and kenaf	Jute fibre had more compressive modulus, flow stress and compressive strength increased upon dynamic loading compared to kenaf fibre.

Prasannan et al. [34] investigated the compressive, flexural and split tensile strength of banana fibre. Amount of fibre content used was 1% and 1.5%. It was observed that flexural and split tensile strength increased while compressive strength remained same after 28 days of curing. The increase was directly proportional to the amount of fibre. It was observed that banana fibre has small elongation and is light in weight. Banana fibre improves the post cracking behavior of concrete due to its effective bridging property. Farooqi and Ali [35] investigated the compressive behavior of wheat straw reinforced concrete(WSRC). It was observed that the compressive toughness of natural wheat straw reinforced concrete increased by 14% as compared to plain concrete. There was a bridging effect in case of WSRC whereas brittle failure was observed for PC.

As mentioned in table 2.1, Omar et al. [31] investigated the dynamic properties of jute and kenaf fibre. It was observed that under dynamic loading, jute fibre reinforced composite had higher dynamic response than kenaf fibre composites in terms of flow modulus, compression strength and compression modulus. Hussain and Ali [29] reported that addition of jute fibre in concrete decreased the compressive strength by 6% and increased the compressive toughness of concrete by 4 times of plain concrete. Damping ratio and elastic modulus of JFRC increased by 100% and 68%, respectively, in comparison to plain concrete. There is a need to promote cheap and locally available materials in order to save cost without compromising on mechanical properties. Hence JFRC fulfills these standards.

2.5.1 Use of GFRP Rebars for Vertical Members

Corrosion of steel affects its mechanical properties especially ultimate stress and strain prompting the use of glass fibre reinforced polymer (GFRP) rebars. Reduction in ultimate elongation is also a major issue due to corrosion of steel [36]. Arfa et al. [37] conducted an experimental investigation on GFRP reinforced squat walls. It was observed that GFRP reinforced walls can undergo high deformation if designed and detailed properly without compromising on its strength. Due to the elastic nature of GFRP rebars, cracks were realigned and then closed which helped in proper distribution of shear deformations along the height of squat wall. Smaller diameter and closer spacing of GFRP rebars in column showed more ductility resulting in a gradual failure pattern. Afifi et al. [38] highlighted that an effective confinement and ductility can be achieved by using close spaced GFRP transverse reinforcement with a small diameter as compared to large diameter with more spacing.

Mohamed et al. [39] conducted an experimental study on GFRP reinforced shear wall under lateral cyclic loading. The results showed that if GFRP reinforced shear walls are properly designed, they can reach their flexural capacities with no decrease in strength. Based on limited test results Deitz et al. [40] concluded that compressive Youngs modulus of GFRP rebar is approximately equal to Youngs modulus in tension. Chaallal and Benmokrane [41] concluded from limited fatigue tests on GFRP that fatigue performance is satisfactory for GFRP reinforcement. The mechanical characteristic described indicate that an engineer can design structural elements like column and bridges with GFRP rebars. Zang et al. [42] highlighted that GFRP in shear wall shows same load carrying capacity and deformation ability as compared to same reinforcement ratio of steel in shear wall.

2.6 Summary

From literature review, it is concluded that crushing of concrete leads towards failure of thin concrete walls. Natural fibres like jute fibre which is locally available has the ability of increasing the toughness index, ultimate strain and dynamic properties of concrete. It alters the cracking pattern of concrete thus, changing brittle modes of failure into ductile mode of failure. Steel has a tendency of undergoing corrosion over the years which weakens its bond with the concrete matrix resulting in loss of load carrying ability. GFRP rebars are a solution to corrosion free reinforcement. Thus, addition of jute fibre and GFRP rebars in concrete is supported by the literature based on their properties.

Chapter 3

Experimental Program

3.1 Background

Use of jute fibres in concrete is discussed in previous chapter. The literature suggest that jute fibres increases the compressive toughness of concrete. Fibres have the tendency of changing the brittle failure mode of concrete into ductile failure. GFRP is a corrosion resistant reinforcement. It has same load carrying capacity as that of steel rebars. In this chapter the methodology for casting of prototypes and testing of specimens is discussed.

3.2 Methodology

3.2.1 Raw Materials

Ordinary Portland cement, water, locally available sand, 1/2" down aggregates, GFRP rebars, steel rebars and jute fibres are used in preparation of PC and JFRC specimen and prototypes. Jute fibre is locally available in raw form and are prepared manually by hand to a length 50 mm as shown in Figure 3.1 along with SEM image of fibre. Table 3.1 shows the mechanical properties of jute fibres.

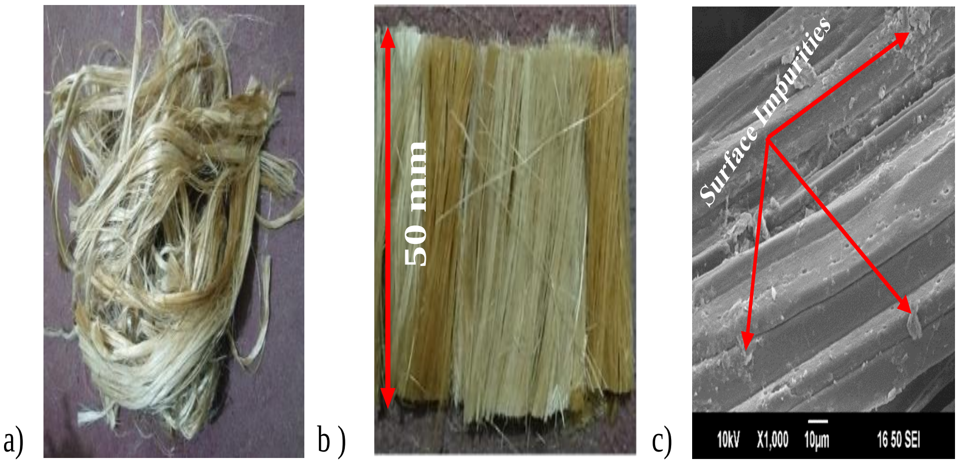


FIGURE 3.1: Jute fibres, a) raw jute fibres, b) cut length of jute fibre, and c) SEM of jute fibre

TABLE 3.1: Mechanical properties of jute fibre [43]

Properties	**Values**
Fibre Diameter	0.04mm - 0.35mm
Tensile Strength	29 – 312 MPa
Elongation	19%

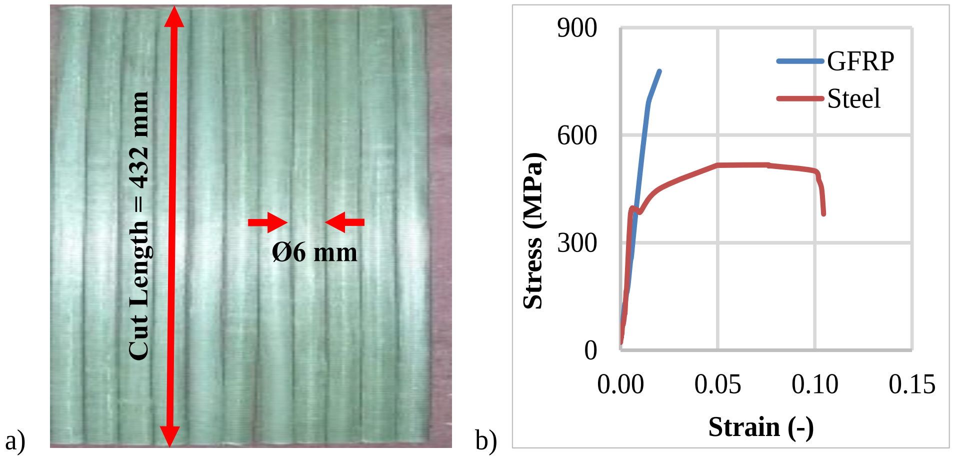


FIGURE 3.2: Glass Fibre Reinforced Polymer Rebars, a) GFRP rebars cut length, and b) stress-strain graph of steel and GFRP rebars

The length and diameter of GFRP rebars is 432 mm and 6 mm, respectively. Figure 3.2 (a) and (b) shows the GFRP rebars and the comparison of stress strain curve between steel rebar and GFRP rebars, respectively.

3.2.2 Mix Design, Casting Procedure and Mechanical Properties

For PC, the mix design ratio for cement, sand and aggregates is 1, 2 and 3 respectively, with a water-cement ratio of 0.6. The mix design of JFRC is similar to PC except that 50 mm long jute fibres of 5% by cement mass are added. The electronic drum type concrete mixer is used in preparing PC and JFRC. For preparing JFRC, all materials are added in the mixer in layers. One third proportion of aggregate followed by one third jute fibre (JF) is placed in electronic mixer. Then one third part of sand and one third cement is laid in the mixer. After spreading all the material layer-wise in the same sequence, an addition of water (one third) is done. Then the drum mixer is rotated for two minutes, after which the remaining water is added and further mixed for three minutes. The layer wise addition of raw material is done to avoid balling effect in JFRC mix. A slump test for PC and JFRC is done before pouring it in molds. Slump values of PC and JFRC are 40 mm and 20 mm, respectively. The test is carried out as per specifications of ASTM C143/C143M15a [44]. Molds and beamlets are filled with PC and JFRC in three layers, and for proper compaction, tamping of each layer is done 25 times with tamping rod.

Cylinders of dimension 100 mm x 200 mm are prepared for compression and split tensile testing, and beamlets of dimensions 100 mm x 100 mm x 450 mm are prepared for flexural testing of PC and JFRC. Cylinders are cast for compressive strength as per ASTM standard C39-16a. Table 3.2 shows the resonance frequencies and damping ratios of cylinders for compression and split tensile testing and beamlets for flexural testing. There is an increase of 21% and 17% in damping ratios of JFRC cylinders and beamlets, respectively, as compared to PC specimens. Six PC cylinders and six JFRC cylinders are considered for dynamic testing whereas six beamlets (i.e. three for PC and three for JFRC) are considered for dynamic testing.

Table 3.2: Dynamic parameters of cylinders and beamlets

Specimens		**No. of Specimens Considered**	**Resonance Frequency (Hz)**			**Damping Ratio (%)**
			f$_l$	**f**$_t$	**f**$_{tr}$	**(ξ)**
Cylinders	PC	6	2952± 800	1420± 450	2750± 800	4.4± 0.02
	JFRC	6	1783± 275	1413± 475	858± 25	5.3± 0.01
Beams	PC	3	2263± 750	1600± 125	2412± 800	3.6± 0.02
	JFRC	3	2249± 775	1257± 75	1242± 50	4.2± 0.02

The loading rate considered for compression testing, split tension and flexure are 0.25 MPa /s, 1.05 MPa / min and 1.035 MPa / min according to ASTM standards C39 [45], C496 [46] and C293 [47], respectively. Figure 3.3 shows the crack propagation, stress-strain curves, energy absorption and toughness index of specimens under compression, split tesnsile and flexural loading.

There is a decrease in strength of JFRC specimens of all three tests performed as compared to PC specimens. Figure 3.3 (a) shows the stress-strain curve, energy absorption, SEM image and crack propagation. There is a reduction of strength for JFRC specimen as compared to PC which is evident in stress-strain graph. The cracking pattern in PC is brittle as spalling of concrete is observed at ultimate loading whereas in case of JFRC, bridging effect did not allow spalling of concrete. Bulging of concrete is observed at peak and ultimate loading conditions in JFRC cylinders. Although, the cracks are wide but there is no chipping or crushing of concrete which is evident in the case of PC cylinders. Bonding of jute fibre with rest of concrete matrix is studied with the help of SEM images. Image shows breakage of fibres in region where there is formation of cavity. The cavity formation suggests improper bonding of fibre with concrete.

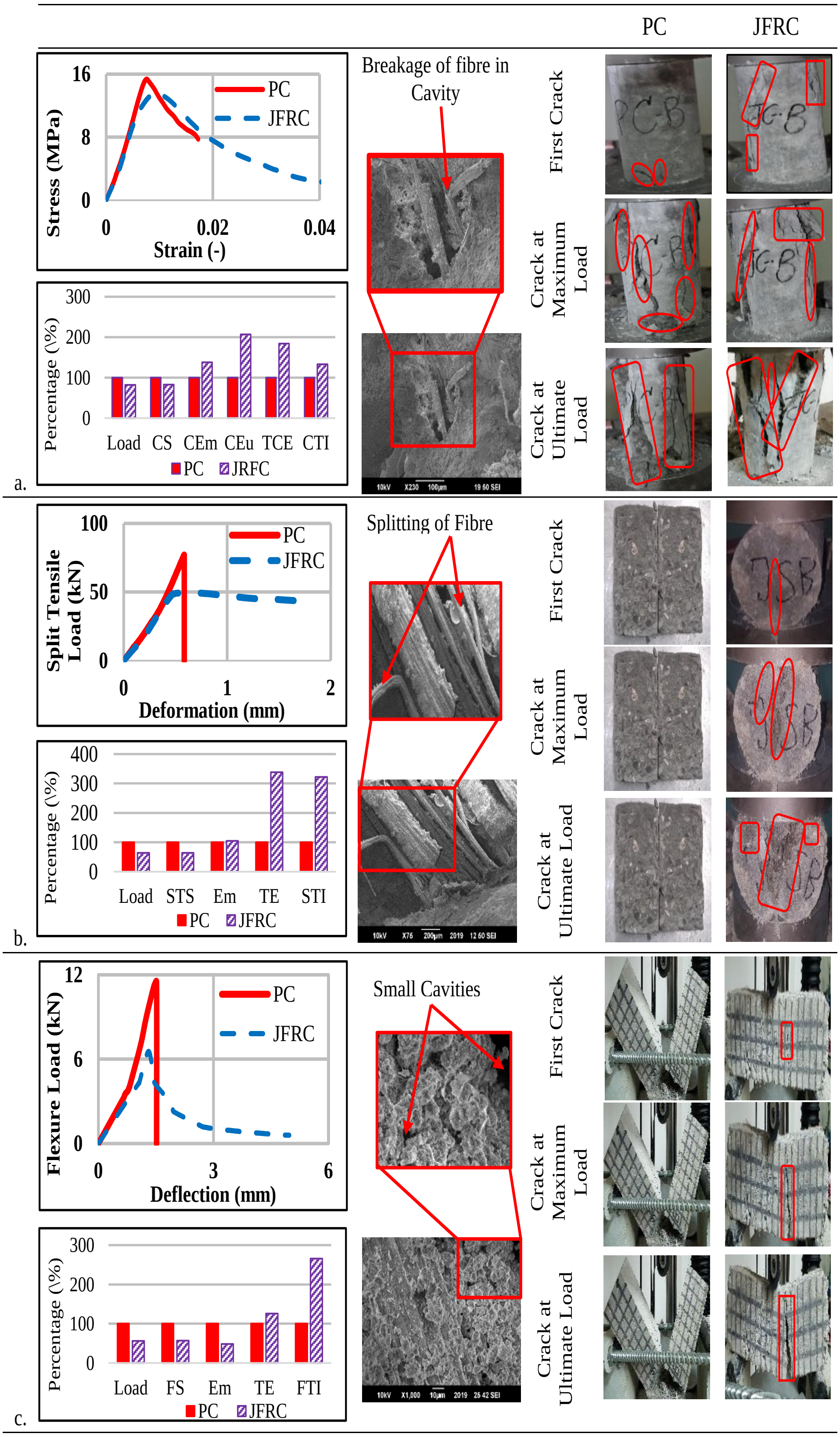


FIGURE 3.3: Mechanical properties of PC and JFRC specimens, a) under compression loading, b) under split tensile loading and, c) under flexural loading

Figure 3.3 (b) shows load-deformation curve, energy absorption, SEM image and crack propagation for split tensile loading. There is a decrease in strength of JFRC as compared to PC specimens. PC specimen shows a brittle behavior as the graph drops to zero after attaining peak load whereas JFRC specimens undergo further deformation after attaining peak load showing a ductile behavior. SEM image shows that the cause of failure is splitting of fibre. The crack propagation shows a brittle failure for PC specimens as it breaks into half at peak load. JFRC specimen did not split into two halves due to bridging effect of jute fibres. Figure 3.3 (c) shows load-deflection curve, energy absorption and crack propagation for flexural loading. PC specimens shows more strength as compared to JFRC specimen which is evident from the graph. The PC specimen breaks into half at peak load whereas JFRC specimen undergoes deflection even after attaining peak load due to jute fibres. The failure mode of PC beamlet is brittle due to the sudden deflection resulting in breakage into two halves without any prior warning. The bridging phenomena of jute fibre did not allow the JFRC beamlet to break into two halves like PC beamlet. SEM image shows small cavity formation. These cavities are not too deep which suggests that the jute fibres are well dispersed with the rest of the concrete matrix.

Table 3.3 shows the maximum load (Pmax), strength, energy absorption till peak load (Em), energy absorption from peak load to ultimate load (Eu), total energy absorption (TE) and toughness index (TI). There is a decrease in compressive, split tensile and flexural strength of JFRC specimens by 17%, 36% and 43%, respectively as compared to PC specimens. Similar trend is observed for peak axial loading. For compression cylinders, there is a decrease of 18% in peak axial load for JFRC as compared to PC. There is a decrease of 36% and 44% in peak axial load for split tensile loading and flexural loading, respectively. There is an increase in compressive, split tensile and flexural total energy absorption of JFRC specimens by 183%, 239% and 126%, respectively as compared to PC specimens. Similar trend of increase is observed in toughness index of JFRC. Compressive, split tensile and flexural toughness index of JFRC specimens increases by 33%, 222% and 166%, respectively in comparison with PC specimens.

Table 3.3: Compressive, split tensile and flexural properties of PC and JFRC specimens

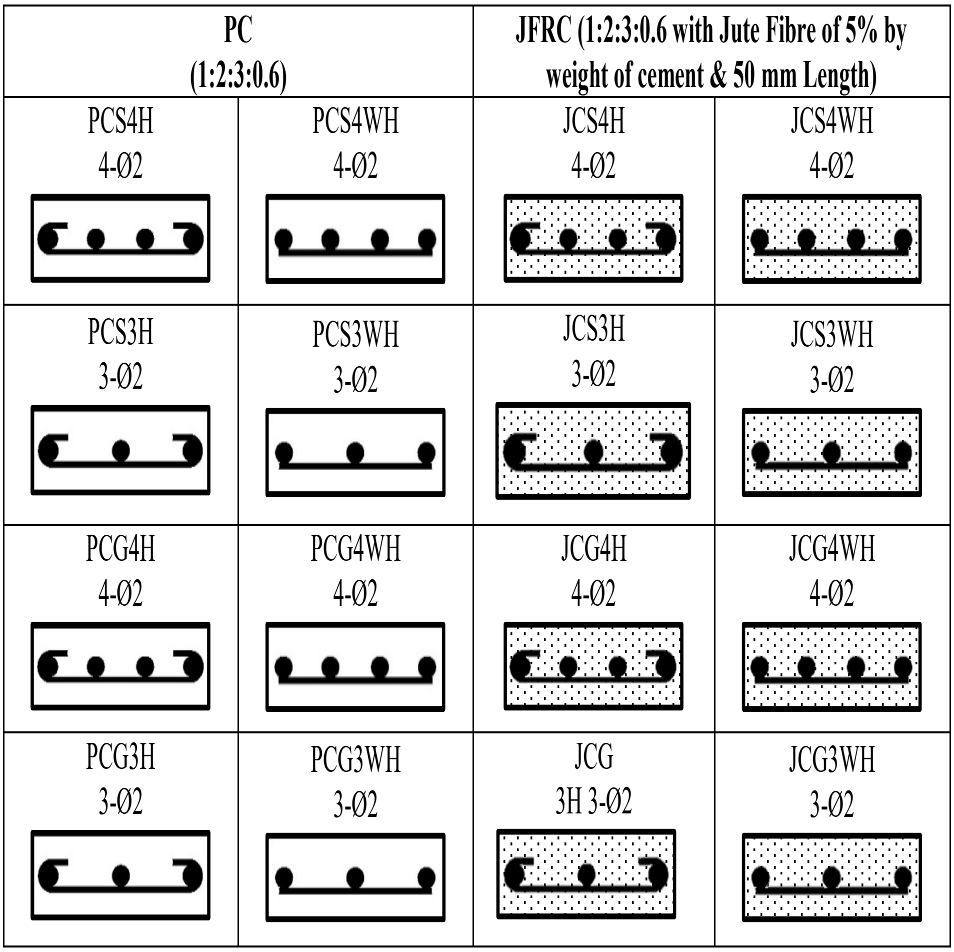
Property	**Specimen**	$\mathbf{P}_{max}$	δ	$\mathbf{E}_m$	$\mathbf{E}_u$	**TE**	**TI**
		(kN)	(MPa)	(-)	(-)	(-)	(-)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Compression	PC	115.5±9.5	14.24±1.14	0.0574±0.008 MJ/m^3	0.1087±0.001 MJ/m^3	0.1661±0.02 MJ/m^3	2.89±0.16
	JFRC	94.5±13.5	11.8±1.8	0.0792±0.007 MJ/m^3	0.225±0.02 MJ/m^3	0.305±0.027 MJ/m^3	3.85±0.16
Splitting-tension	PC	77±6	9.5±0.6	19.3±5.15 J	0 J	19.63±5.15 J	1
	JFRC	49.5±5.5	6.1±0.7	20.62±0.97 J	45.83±7.76 J	66.45±7.9 J	3.22±0.19
Flexure	PC	11.5±0.5	3.95±0.14	7.1±0.37 J	0 J	7.1±0.37 J	1
	JFRC	6.5±0.5	2.25±0.18	3.37±0.58 J	5.59±1.8 J	8.96±1.5 J	2.66±0.3

3.2.3 Specimens

Sixteen prototype thin shear walls having dimensions of 457 mm x 153 mm x 45 mm with simplified boundary conditions are cast for PC and JFRC having steel rebars and GFRP rebars. Eight prototype thin shear walls have JFRC and eight prototypes are of PRC. All prototypes prepared are cured for 28 days prior to dynamic and compression testing. Table 3.4 shows the labelling scheme of prototypes prepared. Figure 3.4 shows the structural details of prototype thin shear walls. GFRP rebars are used as longitudinal reinforcement whereas steel rebars are used as transverse reinforcement. The diameter used for longitudinal and transverse reinforcement is 6 mm. Out of sixteen prototypes, eight prototypes have 180 degree transverse hooks while eight prototypes are without 180 degree transverse hooks. Varying longitudinal reinforcement ratios are used (i.e. four longitudinal rebars and three longitudinal rebars) in prototypes. Eight prototypes have four longitudinal rebars while eight prototypes have three longitudinal rebars. Number of transverse rebars are same in all sixteen prototype thin shear walls (i.e. five).

Table 3.4: Labelling scheme of prototypes

PRC		**JFRC**		**Longitudional Rebars**	**Transverse Rebars**
Hooks	Without Hooks	Hooks	Without Hooks	-	-
(1)	(2)	(3)	(4)	(5)	(6)
PCS4H	PCS4WH	JCS4H	JCS4WH	4-Ø2	5-Ø2
PCS3H	PCS3WH	JCS3H	JCS3WH	3-Ø2	5-Ø2
PCG4H	PCG4WH	JCG4H	JCG4WH	4-Ø2	5-Ø2
PCG3H	PCG3WH	JCG3H	JCG3WH	3-Ø2	5-Ø2



PC (1:2:3:0.6)		JFRC (1:2:3:0.6 with Jute Fibre of 5% by weight of cement & 50 mm Length)	
PCS4H 4-Ø2	PCS4WH 4-Ø2	JCS4H 4-Ø2	JCS4WH 4-Ø2
PCS3H 3-Ø2	PCS3WH 3-Ø2	JCS3H 3-Ø2	JCS3WH 3-Ø2
PCG4H 4-Ø2	PCG4WH 4-Ø2	JCG4H 4-Ø2	JCG4WH 4-Ø2
PCG3H 3-Ø2	PCG3WH 3-Ø2	JCG 3H 3-Ø2	JCG3WH 3-Ø2

FIGURE 3.4: Structural details of thin shear walls

3.2.4 Testing Procedure

Thin shear wall with steel and GFRP rebars are tested in servo hydraulic testing machine (STM) for the determination of compressive strength, energy absorption and toughness index. The compressive testing is done as per specifications given in ASTM C39 [46]. The loading rate for compression testing is 0.25 MPa /s. The prototypes are capped with plaster of Paris for uniform distribution of load. The testing of prototype shear walls is done under concentric compression loading. Figure 3.5 shows the test setup for compression testing. Figure 3.5 (a) shows the load application in schematic diagram. The load application is concentric axial load. Figure 3 (b) shows the prototype thin shear placed in STM. The prototype is placed in the center of the two pistons of STM in order to ensure that the axial load applied is concentric.

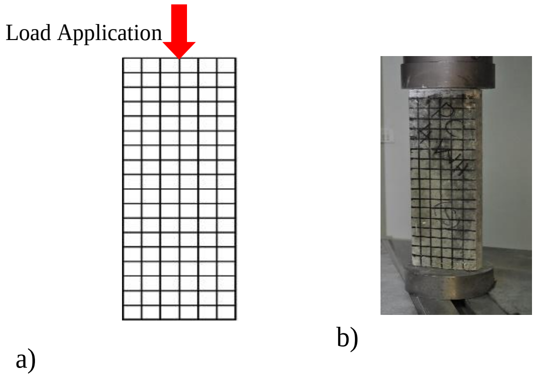


Figure 3.5: Testing of prototype, a) schematic diagram of load application and, b) prototype in STM

3.3 Summary

The mix design for PC and JFRC is 1:2:3:0.6. The only difference between JFRC and PC mix design is the addition of 5% fibre content by mass of cement of 50 mm cut length. 16 specimens are prepared for mechanical properties and 16 prototypes are prepared for compression testing. Dynamic testing of specimens is done before testing them in STM under compression, split tensile and flexural loading. An increase in damping ratio and compressive toughness is observed for JFRC specimen as compared to PC specimens with a compromise in strength.

Chapter 4

Experimental Evaluation

4.1 Background

Mix design, casting procedure, dynamic testing results and mechanical properties are discussed in previous chapter. Results of prototype testing (i.e. dynamic testing parameters and compression testing of prototype thin shear walls in STM), cracking patterns at different stages of load application along with SEM analysis are being discussed this this chapter.

4.2 Dynamic Parameters of Prototypes

Resonance frequencies and damping ratios (ξ) of PRC and JFRC are shown in Table 4.1 for prototype thin shear walls. Resonance frequencies shown are longitudinal frequency (f_l), transverse frequency (f_t) and torsional frequency (f_{tr}). Eight prototypes are considered for PRC and eight prototypes are considered for JFRC to know the dynamic parameters. An increase of 32% in damping ratio is observed for JFRC prototype as compared PRC prototype.

Table 4.1: Dynamic parameters of prototype thin shear wall

Prototypes		**No. of Specimens Considered**	**Resonance Frequency (Hz)**			**Damping Ratio (%)**
			$\mathbf{f}_l$	$\mathbf{f}_t$	$\mathbf{f}_{tr}$	$(\boldsymbol{\xi})$
Thin Shear Walls	PRC	8	2243± 725	2060± 550	2222± 175	3.1± 0.01
	JFRC	8	2125± 600	1810± 300	1990± 650	4.1± 0.03

4.3 Behavior of Prototype Thin Shear Wall under Compressive Loading

Figure 4.1 shows the compressive behavior of prototype thin shear walls. It shows the strain-strain curve of prototypes with and without 180 degree hooks of transverse rebars and having three and four longitudinal rebars. The graph shows a decrease in compressive strength and strain of PRC prototypes as compared to JFRC prototypes. Prototypes having GFRP rebars with jute fibre have more compressive strength as compared to prototypes having steel rebars with jute fibre. The bar graph shows decrease in peak loading and strength of JFRC prototypes as compared to PRC prototypes whereas an increase of total compressive energy absorption and compressive toughness index of JFRC prototypes as compared to PRC prototypes is shown.

The cracking behavior of PRC and JFRC prototype thin shear walls without 180 degree transverse rebar hooks is observed at first crack, cracks at peak load and cracks at ultimate load. Spalling of concrete was observed in case of PRC prototypes at peak and ultimate loading as compared to JFRC prototype walls. A bridging effect was observed in JFRC prototype due to presence of fibre with widening of cracks which held the concrete matrix together. The crack propagation in PRC prototype with steel rebars (PCS) was more as compared to PRC prototypes having GFRP rebars (PCG). More spalling of concrete is observed in schematic diagram of PCS prototypes as compared to PCG prototypes. Similar trend is observed in case of JFRC prototypes. Thinner and shallow cracks are observed in JFRC prototypes having GFRP rebars (JCG) as compared to JFRC prototype having steel rebars (JCS). No significant change in cracking pattern is observed between three (i.e. 3WH) and four vertical rebars prototypes of PRC and JFRC.

The stress-strain curve of PRC and JFRC prototype thin shear walls with 180 degree transverse rebar hooks show a decrease in compressive strength of JFRC prototypes as compared to PRC prototypes. Strength of JCG-4H prototype decreases as compared to JCS-4H whereas strength of JCG-3H increases as compared to JCS-3H. Compressive strength of PCG decreases as compared to PCS prototypes. The bar graph shows decrease in load carrying capacity for JFRC specimens as compared to PRC prototypes while an increase in total energy absorption and toughness index of JFRC prototypes as compared to PRC prototypes. The strength of JFRC prototypes having four longitudinal rebars is more as compared to prototypes having three longitudinal rebars

Cracking pattern of PRC and JFRC prototype thin shear walls with 180 degree transverse rebar hooks is also observed at first crack, cracks at peak load and cracks at ultimate load. Spalling of concrete is observed at peak and ultimate loading in case of PRC prototypes whereas in JFRC prototypes, fibres created a bridging phenomenon due to which spalling of concrete is avoided to a great extent. It is observed that spalling of concrete and depth of crack in PCG prototypes is less compared to PCS prototypes. Same trend is observed in JFRC prototypes. The schematic diagram of JCG shows less deep and thin cracks as compared to JCS prototypes. Schematic diagrams in figure 4.1 shows that complete failure is avoided in case of JFRC prototypes, while PRC prototypes faced irreversible damage. Thus, use of JFRC is likely to avoid the abrupt failure in thin walls, thus, leading towards avoiding the catastrophic failure of structures.

Table 4.2 shows the peak load (Pmax), compressive strength, compressive energy absorption till peak load (CE$_m$), strain at peak load (ε), compressive energy

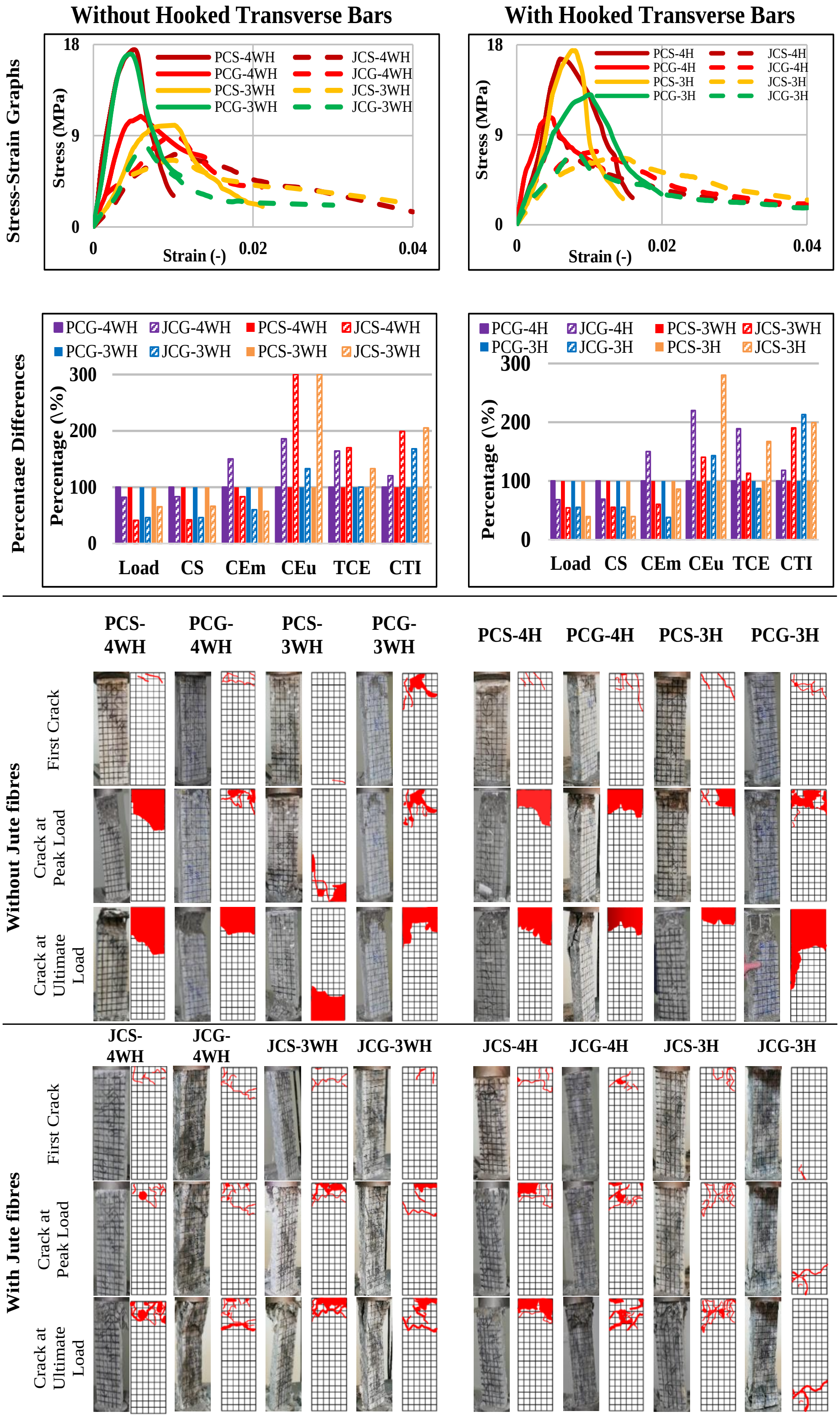


FIGURE 4.1: Compressive behavior of Prototype

absorption from peak load to ultimate load (CE_u), total compressive energy absorption (TCE) and compressive toughness index (CTI) for sixteen prototypes. There is a decrease of 59% in strength of JCS-4WH as compared to PCS-4WH whereas an increase of 70% and 100% in TCE and CTI, respectively, for JCS-4WH as compared PCS-4WH prototype. There is a decrease of 18% in strength of JCG-4WH as compared to PCG-4WH whereas an increase of 64% and 20% in TCE and CTI, respectively, for JCG-4WH as compared PCG-4WH prototype. Strength reduction of 34% is observed for JCS-3WH prototype as compared to PCS-3WH whereas an increase of 33% and 103% is observed in TCE and CTI, respectively for JCS-3WH as compared to PCS-3WH. Similar trend is observed for PCG-3WH and JCG-3WH as there is a decrease of 54% in strength of JCG-3WH prototype as compared to PCG-3WH prototype. An increase of 68% is observed in CTI of JCG-3WH as compared to PCG-3WH while the TCE is same for both prototypes.

In case of rebars with hooks, similar trend is observed. A decrease of 45%, 47%, 62% and 45% in compressive strength of PCS-4H, PCG-4H, PCS-3H and PCG-3H is observed as compared to JCS-4H, JCG-4H, JCS-3H and JCG-3H prototype, respectively. An increase of 13%, 89%, and 67% in TCE is observed for PCS-4H, PCG-4H and PCS-3H as compared to JCS-4H, JCG-4H, and JCS-3H, respectively. A decrease of 13% in TCE is observed for JCG-3H as compared to PCG-3H. An increase of 90%, 18%, 99% and 113% in TCE is observed for JCS-4H, JCG-4H, JCS-3H and JCG-3H is observed as compared to PCS-4H, PCG-4H, PCS-3H and PCG-3H prototype, respectively.

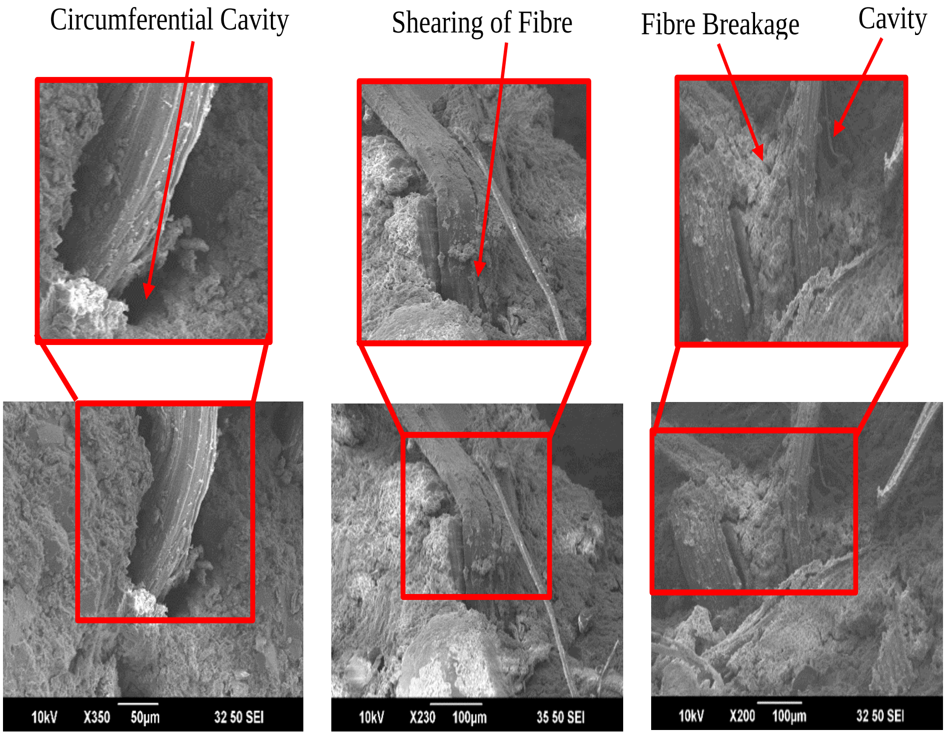
An increase in strength of 25% and 20% is observed for JCG-4WH and JCG-3WH as compared to JCS-4WH and JCS-3WH, respectively. CTE of PCG-4WH and PCG-3WH increases by 56% and 25% as compared to PCS-4WH and PCS-3WH, respectively. In case of 180 degree transverse hooks, there is an increase in CTE of 8% and 15% for PCG-3H and JCG-3H as compared to PCS-3H and JCS-3H, respectively.

Table 4.2: Experimental results of prototype thin shear wall

Specimens	Load	Strain	Strength	CE$_m$	CEu	TCE	TI
	(kN)	(-)	(MPa)	MJ/m^3	MJ/m^3	MJ/m^3	(-)
PCS-4WH	122	0.008	17.5	0.06	0.04	0.10	1.76
JCS-4WH	50	0.012	7.2	0.05	0.12	0.17	3.51
PCG-4WH	76	0.006	10.9	0.04	0.07	0.11	2.74
JCG-4WH	62	0.01	9.0	0.06	0.13	0.18	3.29
PCS-3WH	70	0.01	10.0	0.07	0.05	0.12	1.8
JCS-3WH	46	0.01	6.6	0.04	0.12	0.16	3.65
PCG-3WH	119	0.005	17.2	0.05	0.06	0.11	2.25
JCG-3WH	55	0.007	7.90	0.03	0.08	0.11	3.77
PCS-4H	116	0.006	16.6	0.05	0.1	0.15	3.18
JCS-4H	63	0.006	9.1	0.03	0.14	0.17	6.04
PCG-4H	75	0.005	10.7	0.04	0.05	0.09	2.55
JCG-4H	51	0.01	7.4	0.06	0.11	0.17	3.01
PCS-3H	121	0.008	17.4	0.07	0.05	0.12	1.70
JCS-3H	47	0.01	6.7	0.06	0.14	0.20	3.39
PCG-3H	91	0.01	13.0	0.08	0.07	0.15	1.83
JCG-3H	50	0.008	7.1	0.03	0.10	0.13	3.89

4.4 SEM Analysis

Figure 4.2 shows the SEM image of prototype under compressive loading. Figure 4.2 (a) shows circumferential cavity formation. The formation of cavity is due to compressive loading. The image shows efficient bonding of jute fibre with rest of concrete. Figure 4.2 (b) shows shearing of fibre. Shearing of fibre also causes splitting of threads of fibres. Figure 4.2 (c) shows breakage of fibre and cavity on failure surface. The SEM analysis shows that the cavity formation is the main flaw in JFRC prototype after load application. It is evident from the images that there is a cavity formation due to debonding of fibre from concrete matrix, shearing, splitting of fibre and fibre breakage. All three images show adequate dispersion of fibre in the concrete matrix.



a) b) c)

FIGURE 4.2: SEM images of prototype, a) circumferential cavity formation, b) shearing of jute fibre, and c) breakage of fibre and cavity formation

4.5 Summary

The dynamic and compressive parameters are determined. There is an increase in damping ratio of JFRC prototypes as compared to PRC prototypes. Decrease in compressive strength whereas an increase in toughness index is observed in JFRC prototypes as compared to PRC prototypes. Strength of JFRC specimens Having GFRP rebars showed more compressive strength as compared to JFRC specimens having steel rebars. Both sets of prototype were without hooked transverse rebars. Hence, use of JFRC with GFRP rebars showed positive results in mitigation of catastrophic failure of thin shear wall.

Chapter 5

Discussion

5.1 Background

The experimental results for prototype thin shear wall are discussed in previous chapter. It is observed that there is significant increase in compressive toughness index for prototypes having JFRC as compared to PRC. Spalling of concrete is evident in PRC prototypes while bridging of cracks by fibres in JFRC prototypes did not allow spalling of concrete. SEM analysis showed cavity formation that were not too deep. Overall fibres were well dispersed with the rest of concrete matrix.

5.2 Relation between Material Properties and Behavior of Prototype

Mechanical properties for cylinders and beamlets (i.e. compression, split tension and flexure) are determined with the mix design ratio for cement, sand and aggregates 1, 2 and 3 respectively, with a water-cement ratio of 0.6. The mix design of JFRC is similar to PC except that 50 mm long jute fibres of 5% in content by cement mass is added. Same mix design is kept for prototypes. The results show an overall decrease of compressive strength for JFRC prototypes as compared to PRC prototypes with both types of reinforcements (i.e. Steel and GFRP rebars). A maximum increase of 105% in toughness index is reported for JCS-3WH as compared to PCS-3WH. Generally prototypes having GFRP rebars in JFRC prototypes showed higher strength as compared to JFRC prototypes having steel rebars. This shows a strong bond between GFRP rebars and jute fibre as compared to the combination of jute fibre and steel rebars. The strength of JFRC prototypes having four longitudinal rebars is more as compared to prototypes having three longitudinal rebars. The crack propagation of prototypes having greater compressive toughness undergoes a gradual failure as compared to the prototypes with less compressive toughness. Increase in total energy absorption and toughness index changes the brittle mode of failure to ductile mode of failure. Prototypes having vertical rebars without hooked transverse rebars showed better performance as compared to prototypes having hooked transverse rebars. The spalling of concrete is avoided due to bulging phenomena. An increase in damping ratio of JFRC prototypes as compared to PRC prototypes suggests that jute fibre absorbs a certain amount of force. Chopra [48] reported that increase in damping could reduce the response of structure to any type of dynamic loading. Hussain and Ali [29] reported that there is an increase in damping due to energy absorption. This suggests that an increase in damping ratio means that some extend of dynamic loading is catered by the increased damping ratio phenomenon in case of JFRC prototypes.

The trend in compression testing of prototypes is coherent with the specimens tested for mechanical properties (i.e. compression testing). There is an increase in toughness index and total energy absorption of JFRC specimens as compared to PC specimens under compression, split tensile and flexural loading. There is a compromise in strength of PC as compared to JFRC specimens. Same trend is observed for prototypes, as there is a compromise in strength for JFRC prototypes as compared to PRC prototypes.

Adebar [2] reported that thin walls without cross ties faced crushing of concrete which occurred abruptly with no prior warning. The compressive properties and failure pattern of JFRC prototypes suggests that addition of jute fibre increases its toughness. Hence, increase in toughness, ultimate strain and bridging phenomenon of jute fibre in JFRC prototypes ensures a ductile failure. JFRC is likely to avoid abrupt failure in thin walls thus, leading towards avoiding catastrophic failure of the structure. Addition of GFRP as longitudinal rebars in thin shear wall is step towards corrosion free reinforcement without compromising of load capacity and deformation ability.

5.3 Empirical Modelling

Shaikh and Hosan [49] proposed new empirical equations to predict compressive and indirect tensile strengths. Qamar et al. [50] and Ali [51] calculated the percentage difference between experimental results and proposed empirical equations. In current study, similar approach is used to make an empirical relation for numerically studying the trend of peak axial load. Percentage difference is calculated between the experimental results and empirical equations. The proposed emperical equation for peak axial load is based on simple empirical modelling.

Figure 5.1 shows the trend for peak axial load for prototypes having four longitudinal reinforcing bars with and without transverse hooks (i.e. 4WH and 4H). The trend for 4H and 4WH reveals that 180 transverse hooks have no effect at peak axial load. The coefficients of equations are simplified in order to have one empirical equation for both reinforcement arrangement (i.e. 4WH and 4H). The peak axial loads from empirical equation and experimental work are compared. Table 5.1 shows the percentage difference in peak axial load from empirical equation and experimental load. Simplified empirical equation applicable for both reinforcing ratio is given below:

$\mathrm{P}_{emp}=\mathrm{RA}* \mathrm{c}^{-0.6}$.......................(5.1)

Where reinforcement arrangement (RA) is 115 for 4WH and 4H. 115 is the base score given on the basis of best fit curve for both RA's. Value of "c" is 1, 2, 3 and 4 for PCS, PCG, JCS and JCG, respectively.

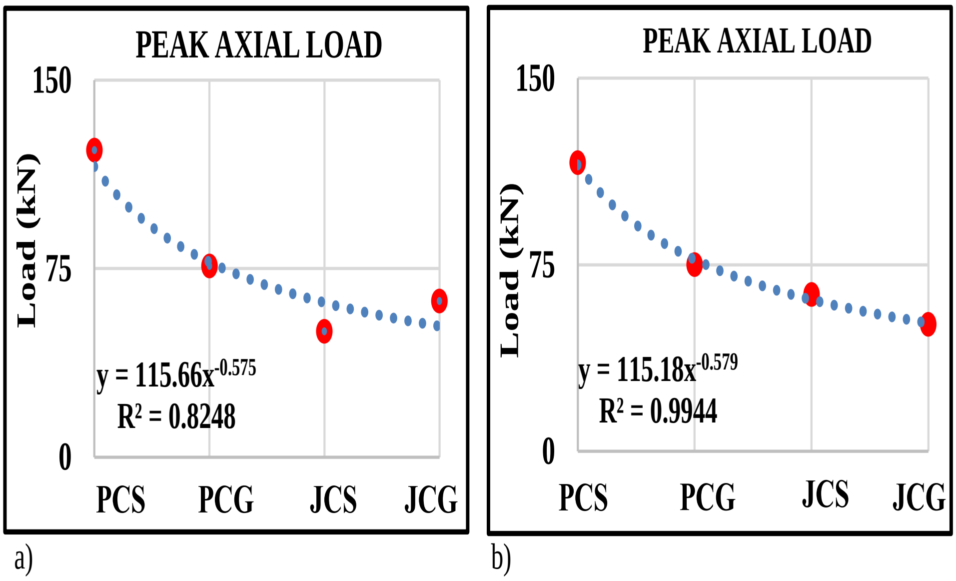


FIGURE 5.1: Peak axial load trend for reinforcement arrangement, a) 4WH, and b) 4H

TABLE 5.1: Comparison of experimental and empirical results

Peak Axial Load				
c	**Prototype**	**Empirical Values**	**Experimental Values**	**Percentage Difference**
1	PCS-4WH	115	122	5.7
2	PCG-4WH	75.9	76	0.2
3	JCS-4WH	59.5	50	-19.0
4	JCG-4WH	50.1	62	19.3
1	PCS-4H	115	116	0.9
2	PCG-4H	75.9	75	-1.2
3	JJCS-4H	59.5	63	5.6
4	JJCG-4H	50.1	51	1.8

Note: c = 1, 2, 3 and 4 for PCS, PCG, JCS and JCG, respectively

It can be seen in table 5.1 that the empirical results are close to the experimental results. The percentage difference in empirical results for prototypes of 4WH and 4H is -19% to +19% and -1% to 6%, respectively, as compared to experimental results.

5.4 Summary

In this chapter the effect of increase in toughness index of JFRC prototypes as compared to PRC prototypes is discussed. A reduction in compressive strength of JFRC prototypes is observed as compared to PRC prototypes. An increase in damping ratio of JFRC prototypes is observed as compared to PRC prototypes. There is a compromise in strength for JFRC specimens (i.e. cylinders and beamlets) as compared to PC specimens. Whereas, increase of compressive toughness and damping ratio is observed in case of JFRC specimens as compared to PC specimens. Use of GFRP rebar is a step towards corrosion free reinforcement without compromising the load carrying capacity with respect to steel rebars. The empirical results are in good agreement with experimental results.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The effectiveness of jute fibre is studied by conducting an experimental investigation on thin shear wall with jute fibres and GFRP rebars. For preparation of plain concrete, mix design ratio of 1:2:3:0.6 (Cement: Sand: Aggregates: Water) is kept. Jute fibres having length of 50 mm and fibre content of 5%, by mass of cement are used for preparing jute fibre reinforced concrete (JFRC).

- Compressive strength of JFRC is less than PC but there is an increase of 21%, 56% and 33% in damping, total compressive energy absorption and compressive toughness, respectively, for JFRC as compared to PC.
  - SEM analysis show cavities that are not too deep, hence, uniformity of microstructure is present due to uniformly dispersed fibres.
- There is an increase in damping of 32% for JFRC prototypes as compared to PRC prototypes.
- There is an increase in energy absorption and toughness index with a compromised compressive strength for JFRC prototypes as compared to PRC prototypes.

- Cracking behavior of prototypes with hook is better as compared to prototypes without hooks.
- Compressive strength of JFRC prototype having GFRP rebars is generally more as compared to JFRC prototype having steel rebars.
    - Ultimate strain of JFRC prototypes is more as compared to PRC prototypes.
    - The strength of JFRC prototypes having four longitudinal rebars is more as compared to prototypes having three longitudinal rebars.
    - Spalling of concrete and depth of crack in PCG prototypes is less compared to PCS prototypes. Same trend is observed in JFRC prototypes.
    - The depth of cracks in JCG prototypes is less as compared to JCS prototypes.
- SEM analysis shows only small pockets of cavity hence, there is strong bonding of jute fibre with rest of the concrete matrix.
- Empirical results are coherent with the experimental results.

The results of current research shows that JFRC prototypes having GFRP rebars behaved better under compressive loading as compared to prototypes having JFRC with steel rebars in terms failure pattern (i.e. ductile failure in JFRC prototypes having GFRP rebars). There is an increase in compressive toughness of JFRC prototypes as compared to PRC prototypes. Hence, JFRC with GFRP rebars can be used in thin shear wall to avoid catastrophic failure of structure.

6.2 Future Work

Being a pilot study, simplified boundary conditions under compression loading is studied. Following recommendations are made for future work:

- Full scale testing with complete instrumentation (i.e. lateral loading) needs to be done.
- Behavior of JFRC prototypes with addition of chemical admixtures needs to be studied for better bonding of fibre with concrete matrix.
- Durability of jute fibre and bond behavior of GFRP rebars need to be investigated for possible use in thin shear walls.

Bibliography

[1] R. Junemann, J. C. de la Llera, M. A. Hube, J. A. Vasquez, and M. F. Chacon, "Study of the damage of reinforced concrete shear walls during the 2010 Chile earthquake," *Earthquake Engineering & Structural Dynamics*, vol. 45, no. 10, pp. 1621-1641, Aug. 2016.

[2] P. Adebar, "Compression failure of thin concrete walls during 2010 Chile earthquake: lessons for Canadian design practice," *Canadian Journal of Civil Engineering*, vol. 40, no. 8, pp. 711-721, Mar. 2013.

[3] J. Sherstobitoff, P. Cajiao, and P. Adebar, "Repair of an 18-story shear wall building damaged in the 2010 Chile earthquake," *Earthquake Spectra*, vol. 28, no. S1, pp. S335-S348, Jun. 2012.

[4] J. Yathon, P. Adebar, and K. J. Elwood, "A detailed inventory of non-ductile concrete shear wall buildings," *Earthquake Spectra*, vol. 33, no. 2, pp. 605-622, May 2017.

[5] R. Jünemann, J.C. de la Llera, M.A. Hube, L.A. Cifuentes, and E. Kau, "A statistical analysis of reinforced concrete wall buildings damaged during the 2010, Chile earthquake," *Engineering Structures*, vol. 82, pp. 168-185, Jan. 2015.

[6] F. Rojas, F. Naeim, M. Lew, L. D. Carpenter, Nabih F. Youssef, G. R. Saragoni, and M. S. Adaros, "Performance of tall buildings in Concepción during the 27 February 2010 moment magnitude 8.8 offshore Maule, Chile earthquake," *The Structural Design of Tall and Special Buildings*, vol. 20, no. 1, pp. 37-64, Feb. 2011.

[7] M. Saatcioglu, D. Palermo, A. Ghobarah, D. Mitchell, R. Simpson, P. Adebar, R. Tremblay, C. Ventura, and H. Hong, “Performance of reinforced concrete buildings during the 27 February 2010 Maule (Chile) earthquake,” *Canadian Journal of Civil Engineering*, vol. 40, no. 8, pp. 693-710, July 2013.

[8] P. Adebar, and A. Lorzadeh, “Compression failure of thin concrete walls,” *In th world conference on earthquake engineering*, Sept. 2012.

[9] R. D. Hoult, H. M. Goldsworthy and E. Lumantarna, “Plastic hinge length for lightly reinforced C-shaped concrete walls, *Journal of Earthquake Engineering*, pp. 1-32, Mar. 2018.

[10] R. D. Hoult, H. M. Goldsworthy and E. Lumantarna, “Plastic hinge analysis for lightly reinforced and unconfined concrete structural walls, *Bulletin of Earthquake Engineering*, vol. 16, no. 10, pp. 4825-4860, Oct. 2018.

[11] J. Almeida, O. Prodan, A. Rosso, and K. Beyer, “Tests on thin reinforced concrete walls subjected to in-plane and out-of-plane cyclic loading, *Earthquake Spectra*, vol.33. no. 1, pp. 323-345, Feb. 2017.

[12] A. Rosso, R. L. A. Jimnez-Roa, J. P. De Almeida, A. P. G. Zuniga, C. A. Blandn, R. L. Bonett, and K. Beyer, “Cyclic tensile-compressive tests on thin concrete boundary elements with a single layer of reinforcement prone to out-of-plane instability, *Bulletin of Earthquake Engineering*, vol. 16, no. 2, pp. 859-887, Feb. 2018.

[13] C. A. Arteta, J. Snchez, R. Daza, C. Blandon, R. Bonett, J. Carrillo, J. and Vlez, “Global and local demand limits of thin reinforced concrete structural wall building systems, *In 16th world conference on earthquake engineering*, Santiago, Chile, 2017.

[14] J. W. Wallace, L. M. Massone, P. Bonelli, J. Dragovich, R. Lagos, C. Lders, and J. Moehle, “Damage and implications for seismic design of RC structural wall buildings, *Earthquake Spectra*, vol. 28, no. S1, pp. S281-S299, Jun. 2012.

[15] C. L. Segura, and J. W. Wallace. “Brittle Compression Failures in SCI 318-14 Compliant RC Structural Walls with Well-detailed Boundary Zones, In *16th World Conference on Earthquake Engineering*, Santiago, vol. 13, Jan. 2017.

[16] P C. A. Arteta, D. V. To, and J. P. Moehle, “Experimental response of boundary elements of code-compliant reinforced concrete shear walls, *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, vol. 10, Jul. 2014.

[17] W. Y. Kam, S. Pampanin, and K. Elwood, “Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttleton) earthquake, *Bulletin of The New Zealand Society for Earthquake Engineering*, vol. 44, no. 4, pp. 239-278, Dec. 2011.

[18] J. W. Wallace, “Reassessing ACI 318 Shear Wall Provisions Based on Recent Earthquake and Test Observations, *In Performance-Based Seismic Engineering: Vision for an Earthquake Resilient Society*, pp. 449-467, 2014.

[19] Y. Lu, R. J. Gultom, Q. Q. Ma, and R. S. Henry, “Experimental validation of minimum vertical reinforcement requirements for ductile concrete walls, *ACI Structural Journal*, vol. 115, no. 4, pp. 1115-1130, Jul. 2018.

[20] I. S. Izquierdo, O. S. Izquierdo, M. A. Ramalho, and A. Taliercio, “Sisal fiber reinforced hollow concrete blocks for structural applications: Testing and modeling, *Construction and Building Materials*, vol. 151, pp. 98-112, Oct. 2017.

[21] R. Madandoust, M. M. Ranjbar, H. A. Moghadam, and S. Y. Mousavi, “Mechanical properties and durability assessment of rice husk ash concrete, *Biosystems Engineering*, vol. 110, no. 2, pp. 144-152, Oct. 2011.

[22] M. Ali, A. Liu, H. Sou, and N. Chouw, “Mechanical and dynamic properties of coconut fibre reinforced concrete *Construction and Building Materials*, vol. 30, pp. 814-825, May 2012.

[23] M. S. Islam, and S. J. Ahmed, “Influence of jute fiber on concrete properties, *Construction and Building Materials*, vol. 189, pp. 768-776, Nov. 2018.

[24] M. Zakaria, M. Ahmed, M. M. Hoque, and S. Islam, "Scope of using jute fiber for the reinforcement of concrete material, *Textiles and Clothing Sustainability*, vol. 2, no. 1, pp. 1-11, Jan. 2017.

[25] P. R. Mali, and D. Datta, "Experimental evaluation of bamboo reinforced concrete slab panels, *Construction and Building Materials*, vol. 188, pp. 1092-1100, Nov. 2018.

[26] H. C. Lima, F. L. Willrich, N. P. Barbosa, M. A. Rosa, and B. S. Cunha, "Durability analysis of bamboo as concrete reinforcement, *Materials and Structures*, vol. 41, no. 5, pp. 981-989, Jun. 2008.

[27] A. Zia, and M. Ali, "Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining, *Construction and Building Materials*, vol. 155, pp. 726-739, Nov. 2017.

[28] A. Mazzoli, S. Monosi, and E. S. Plescia, "Evaluation of the early-age-shrinkage of Fiber Reinforced Concrete (FRC) using image analysis methods, *Construction and Building Materials*, vol. 101, pp. 596-601, Dec. 2015.

[29] T. Hussain, and M. Ali, "Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of FRC, *Construction and Building Materials*, vol. 213, pp. 592-607, July 2019.

[30] L. Yan, and N. Chouw, "Dynamic and static properties of flax fibre reinforced polymer tube confined coir fibre reinforced concrete, *Journal of Composite Materials*, vol. 48, no. 13, pp. 1595-1610, Jun. 2014.

[31] M. F. Omar, H.M. Akil, Z. A. Ahmad, A. A. M. Mazuki, and T. Yokoyama, "Dynamic properties of pultruded natural fibre reinforced composites using Split Hopkinson Pressure Bar technique *Materials and Design*, vol. 31, no. 9, pp. 4209-4218, Oct. 2010.

[32] V. M. John, M. A. Cincotto, C. Sjstrm, V. Agopyan, and C. T. A. Oliveira, "Durability of slag mortar reinforced with coconut fibre, *Cement and Concrete Composites*, vol. 27, no. 5, pp. 565-574, May 2005.

[33] M. Sivaraja, N. Velmani, and M. S. Pillai, “Study on durability of natural fibre concrete composites using mechanical strength and microstructural properties, *Bulletin of Materials Science*, vol. 33, no. 6, pp. 719-729, Dec. 2010.

[34] D. Prasannan, S. Nivin, R. R. Kumar, S. Giridharan, and M. Elavivekan, “Comparative study of Banana and Sisal Fiber reinforced Concrete with Conventional Concrete, *International Journal of Pure and Applied Mathematics*, vol. 118, no. 20, pp. 1757-1765, 2018.

[35] M. U. Farooqi, and M. Ali, “Compressive behavior of wheat straw reinforced concrete for pavement applications, *Fourth International Conference on Sustainable Construction Materials and Technologies*, Las Vegas, Aug. 2016.

[36] R. Franois, I. Khan, and V. H. Dang, “Impact of corrosion on mechanical properties of steel embedded in 27-year-old corroded reinforced concrete beams, *Materials and structures*, vol. 46, no. 6, pp. 899-910, Jun. 2013.

[37] A. Arafa, A. S. Farghaly, and B. Benmokrane, “Experimental behavior of GFRP-reinforced concrete squat walls subjected to simulated earthquake load, *Journal of Composites for Construction*, vol. 22, no. 2, pp. 04018003, Feb. 2018.

[38] M. Z. Afifi, H. M. Mohamed, and B. Benmokrane, “Axial capacity of circular concrete columns reinforced with GFRP bars and spirals, *Journal of Composites for Construction*, vol. 18, no. 1, pp.04013017, Sept. 2013.

[39] N. Mohamed, A. S. Farghaly, B. Benmokrane, and K. W. Neale, “Experimental investigation of concrete shear walls reinforced with glass fiberreinforced bars under lateral cyclic loading. *Journal of Composites for Construction*, vol. 18, no. 3, p.A4014001, May 2013.

[40] D. H. Deitz, I. E. Harik, and H. Gesund, “Physical properties of glass fiber reinforced polymer rebars in compression *Journal of Composites for Construction*, vol. 7 no. 4, pp. 363-366, Nov. 2003.

[41] O. Chaallal, and B. Benmokrane, “Physical and mechanical performance of an innovative glass-fiber-reinforced plastic rod for concrete and grouted anchorages, *Canadian Journal of Civil Engineering*, vol. 20, no. 2, pp. 254-268, Apr. 1993.

[42] Q. Zhang, J. Xiao, Q. Liao, and Z. Duan, “Structural behavior of seawater sea-sand concrete shear wall reinforced with GFRP bars, *Engineering Structures*, vol. 189, pp. 458-470, Jun. 2019.

[43] G. Ramakrishna, and T. Sundararajan, “Studies on the durability of natural fibres and the effect of corroded fibres on the strength of mortar, *Cement and Concrete Composites*, vol. 27, no. 5, pp. 575-582, May 2005.

[44] ASTM C143/C143M, “Standard Test Method for Slump of Hydraulic-Cement Concrete, *ASTM International*, West Conshohocken, PA, 2015. http://www.astm.org.

[45] ASTM C39/C39M, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, *ASTM International, West Conshohocken*, PA, 2015. http://www.astm.org.

[46] ASTM C496/C496M, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, *ASTM International*, West Conshohocken, PA, 2011. http://www.astm.org.

[47] ASTM C293/C293M, “Standard Test Method for Flexural Strength of Concrete (using Simple Beam with Center-Point Loading), *ASTM International*, West Conshohocken, PA, 2016. www.astm.org.

[48] A.K. Chopra, “Dynamics of Structures, *Theory and Applications to Earthquake Engineering*, 2017.

[49] F. U. A. Shaikh, and A. Hosan, “Mechanical properties of steel fibre reinforced geopolymer concretes at elevated temperatures, *Construction and building materials*, vol. 114, pp.15-28, Jul. 2016.

[50] F. Qamar, T. Thomas, and M. Ali, “Assessment of mechanical properties of fibrous mortar and interlocking soil stabilised block (ISSB) for low-cost masonry housing, *Materiales de Construccin*, vol. 69, no. 336, pp. 1-18, Dec. 2019.

[51] M. Ali, “Role of post-tensioned coconut-fibre ropes in mortar-free interlocking concrete construction during seismic loadings, *KSCE Journal of Civil Engineering*, vol. 22, no. 4, pp. 1336-1343, Apr. 2018.

Annexure A

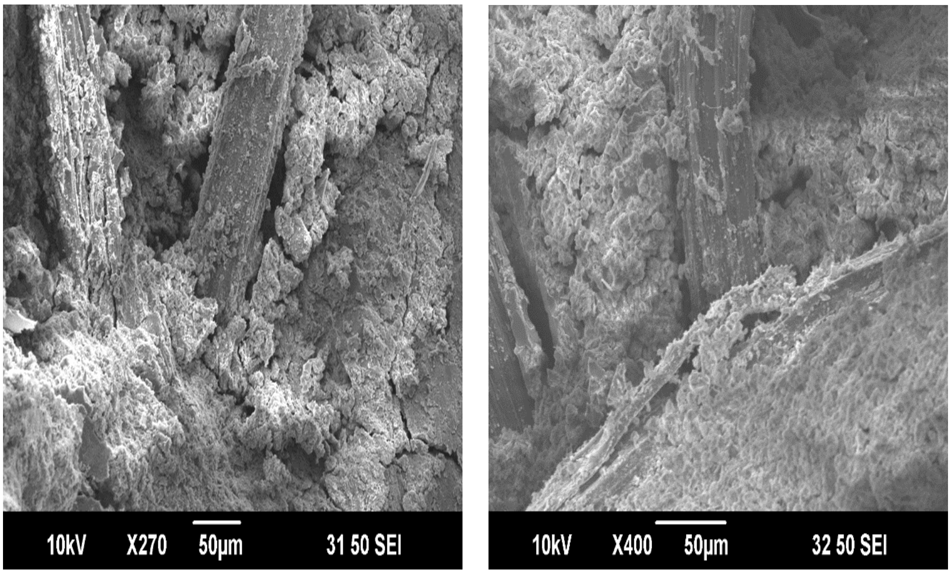


Figure A.1: SEM of failure surface of JFRC prototypes

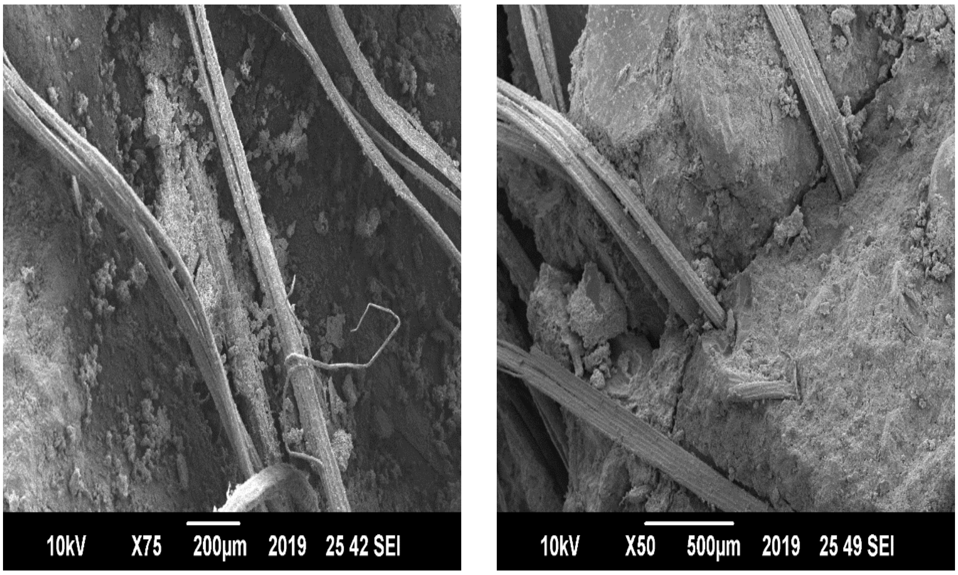


Figure A.2: SEM of failure surface of JFRC beamlets

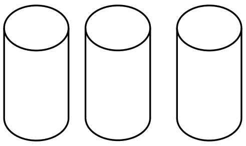
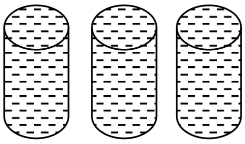
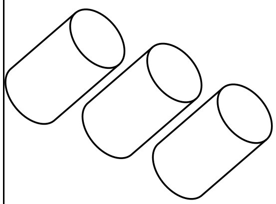
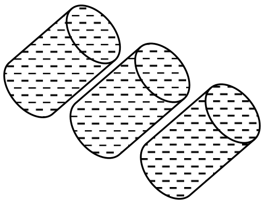
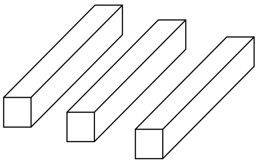
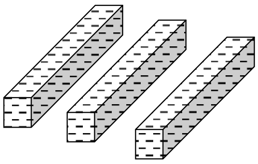
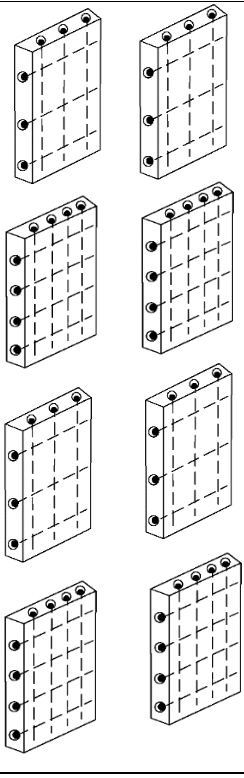
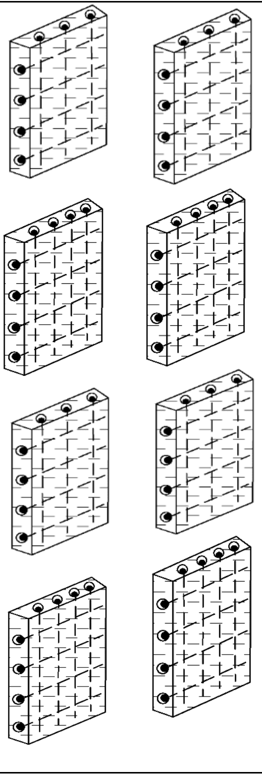
Specimens	**PC (1:2:3:0.6)**	**JFRC (1:2:3:0.6) with 5% fibre content and 50 mm fibre length**	**Specimen Dimensions**	**Parameters**
Compression specimen			100x200 mm cylinders	Dynamic properties, Compressive strength, CE_{max}, CE_{total} and CTI
Split tensile specimen			100x200 mm cylinders	Dynamic properties, Load-deformation curve, STS, SE_{max}, SE_{total} and STI
Flexure specimen			100x100x450 mm beamlets	Dynamic properties, Load-deflection curve, MoR, FE_{max}, FE_{total} and FTI
Prototype testing of thin shear wall			457x153x45 mm shear wall	Dynamic properties, Compressive strength, CE_{max}, CE_{total}, CTI, damping and cracking pattern

FIGURE A.3: Specimens and prototypes tested