STUDIES ON STATIC AND DYNAMIC BEHAVIOR OF HYBRID FIBER REINFORCED AND FUNCTIONALLY GRADED RC BEAMS

Submitted in partial fulfilment of the requirements
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DOCTOR OF PHILOSOPHY
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by

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CERTIFICATE

This is to certify that the thesis entitled "**STUDIES ON STATIC AND DYNAMIC BEHAVIOR OF HYBRID FIBER REINFORCED AND FUNCTIONALLY GRADED RC BEAMS"** being submitted by**Ms.RADHIKA KALA SRIDHAR** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Faculty of Engineering and Technology of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafideresearch work carried out by her under my supervision and it has not been submitted elsewhere for award of any degree.

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This Thesis entitled "**STUDIES ON STATIC AND DYNAMIC BEHAVIOR OF HYBRID FIBER REINFORCED AND FUNCTIONALLY GRADED RC BEAMS**" by **Ms.RADHIKA KALA SRIDHAR** is approved for the degree of Doctor of Philosophy.

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DECLARATION

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(Name of the Student: **RADHIKA KALA SRIDHAR**)

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Dedicated

To

The Almighty Lord,

My Beloved Parents, Family Members,

Teachers, Well-Wishers and Friends

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ABSTRACT

Concrete is the most frequently used building material all over the world because of its ease formability and availability. Tensile strength of the concrete is one of the most significant drawback hence the usage has become restricted in all practical applications. Further, the mechanical properties of concrete can be improved by adding randomly oriented short discrete fibers which control initiation, propagation or coalescence of cracks. In the recent years, the usage of fibers in reinforced concrete (RC) for strengthening purpose has also been increased due to its enhanced properties after cracking of the composite matrix. Besides these applications, the usage of engineered cementitious composite (ECC) material in the tension zone of RC beam which surrounds the main flexural reinforcement increases the deflection capacity of the beam. The class of ultra-ductile fiber reinforced in cementitious composite exhibits high ductility and tensile strain capacity of the beam. Hence, the incorporation of ECC ductile material in RC beams enhances the load carrying capacity of the beam which can also be referred as functionally graded reinforced concrete (FGRC) beams.

This research work has been focused with an objective to evaluate the static and dynamic behavior of RC beams strengthened with mono fibers, hybrid fibers and ECC material. Effect of mono and hybrid fibers on different grades of concrete such as M25 and M50 (Standard grade) was investigated. The effect of fiber hybridization on mechanical properties of ECC with different percentage variation of steel and polyvinyl alcohol fibers was also studied. Fibers used in the present investigation were hooked end steel (SF), polypropylene (PP) and polyvinyl alcohol (PVA). Entire experimental programme was carried out in three different phases.

First phase of investigation is carried out to determine the mechanical and dynamic properties of mono and hybrid fiber reinforced concrete. Fiber dosage of mono steel is varied from

0.5%, 0.75%, 1.0% and 1.25% of volume of concrete, fiber dosage of mono PP varied from 0.1%, 0.2%, 0.3% and 0.4% of total volume fraction. Also, three types of fiber hybrid combinations were considered to prepare HFRC i.e. SF 25% + PP 75%, SF 50% + PP 50% and SF 75% + PP 25% at a total fiber volume fraction of 0.25%, 0.5% and 0.75% to evaluate the properties of hybrid fiber reinforced concrete. Mechanical properties like compressive strength, split tensile strength and flexural strength were determined. Dynamic properties like natural frequency, damping ratio and mode shapes were also determined for the similar mixes. From the results of mechanical properties, it has been observed that there was marginal improvement in compressive strength and significant improvement in split tensile strength and flexural strength.

Later stage RC beams with the inclusion of optimum dosage of mono and hybrid fibers have been cast and assessed the static and dynamic behavior. Dynamic behavior of undamaged and damaged RC beams strengthened with mono steel and PP fibers and also hybrid fibers (steel and PP) was investigated using impact hammer technique. The envelopes of the FRF's obtained by the experimental modal analysis and the variation in natural frequency and damping values are determined from the curve fitted FRF's using modal analysis software and the results are correlated with the damage level. From the static behavior of beams with hybrid steel and PP fibers, load carrying capacity increasedcompared to RC beams with mono fiber and control RC beams. It is also observed that reduction in natural frequency values is less due to damage induced for the beams with hybrid fibers compared to that of control RC beamsand beams strengthened with mono fibers.

Second phase of investigation is carried out to develop engineered cementitious composite (ECC) with different percentage variation of mono steel, mono polyvinyl alcohol (PVA) and hybrid fibers. ECC is developed using mono steel and PVA fibers at 2% fiber volume fraction with different combinations i.e. SF 1% + PVA 1%, SF 0.5% + PVA 1.5% and SF 1.5% + PVA 0.5% and the results are compared with the ECC without fibers. For these mixes compressive strength, flexural strength and uni-axial tensile strength were obtained. From the mechanical properties results it has been observed that the optimum hybrid fiber combination of ECC achieved at SF 0.5% + PVA 1.5%. It was also observed that the ECC reinforced with SF and PVA fibers in combination enhances the flexural strength and uni-axial tensile strength of the composite compared with mono ECC for the same fiber volume fraction. Later stage FGRC beams with the optimum dosage layered ECC material is prepared and placed in the tension zone of the RC beamto assess its static and dynamic behavior. Static behavior of FGRC beams is obtained by testing the beam in flexure under four point monotonic loading and dynamic behavior at undamaged and different damage levels is carried out using impact hammer technique under free-free condition. From the static behavior of FGRC beams, load carrying capacity increases with the increase of ECC layers in the tension zone of the beam. From the dynamic tests, it is observed that reduction in natural frequency values is very less for FGRC beams with three layered ECC material compared to that of control RC and FGRC beams with one and two layers of ECC material.

In the third phase of investigation, modeling of RC beams strengthened with mono steel and PP fibers by FEM is done for the undamaged condition of the beams; further modeling is done for RC beamsstrengthened with hybrid fibers and FGRC beams with different layers of ECC in tension zone. The results obtained from the FEM modeling are compared with the experimental values, which are in good agreement. The variation between experimental results and values obtained by FEM model is within 15%.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

FRC	:	Fiber reinforced concrete
ACI	:	American concrete institute
SFRC	:	Steel fiber reinforced concrete
PPFRC	:	Polypropylene fiber reinforced concrete
HFRC	:	Hybrid fiber reinforced concrete
ECC	:	Engineered cementitious composites
HFRECC	:	Hybrid fiber reinforced engineered cementitious composites
UHPFRCC	:	Ultra-high performance fiber reinforced engineered cementitious composites
FGM	:	Functionally graded material
FGRC	:	Functionally graded reinforced concrete
RC	:	Reinforced concrete
OPC	:	Ordinary Portland cement
HRWRA	:	High range water reducing admixture
HPMC	:	Hydroxypropyl methyl cellulose
SF	:	Steel fiber
PP	:	Polypropylene fiber
PVA	:	Polyvinyl alcohol fiber
FRF	:	Frequency response function
FFT	:	Fast fourier transform
ASTM	:	American society for testing and materials
IS	:	Indian standard code

NOTATIONS

f_{ck} : Compressive strength

P : Ultimate load

Pu : Ultimate load of RC beam

A : Cross-sectional area of the specimen

f_{st} : Split tensile strength

f_{ft} : Flexural strength

f : Natural frequency

ζ : Damping ratio

V_f : Fiber volume fraction

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a widely used construction material all over the world, because of numerous advantages like high compressive strength, easy mouldability and lower life-cycle cost makes the concrete as more promising construction material. With the superior advantages compared to other construction materials concrete also has some serious limitations to utilizeas a construction material in civil engineering structures. Concrete is brittle in nature and almost have no ductility and toughness especially under tensile loading. With the low tensile strength and toughness of concrete, cracks can develop and propagate rapidly which leads to failure of the members at a low ultimate strain without any warning of impending failure.

In order to overcome these drawbacks, researchers have been focusing on various necessary techniques such as adding of short discrete fibers into concrete matrix to improve the properties which is called fiber reinforced concrete (FRC).And also adding different types of fibers together to arrest the multi-scale cracks forming at various stress-levels.If two or more number of fibers are rationally combined to produce a cement concrete composite that derives the benefits from each of the individual fibers and exhibits a synergic response, the composite thus obtained is called as hybrid fiber reinforce concrete (HFRC). Amongst these, addition of fibers like steel, polypropylene, polyvinyl alcohol, natural and synthetic fibers into concrete has been accepted widely because of improved mechanical properties of concrete such as compressive strength, split tensile strength, flexural strength and flexural toughness. The provision of fibrous materials in concrete enhances the structural integrity of a brittle matrix in hardened state and also to control cracking due to plastic shrinkage and drying shrinkage of fresh concrete.

The recent advances in material science and engineering, the associated technology have facilitated the development of hybrid fiber reinforced engineered cementitious composites (HFRECC) with superior strength, ductility and toughness. The class of ultra-ductile fiber which is reinforced with cementitious composites ably known as engineered cementitious composite (ECC) is another alternative to improve the tensile strength of concrete composite, *Victor Li (2003)*. It is apparent that, fiber reinforced engineered cementitious composites (FRECC) is produced to have superior properties compared to normal concrete and it will depend on the micromechanical design principles which exhibits a remarkable tensile strain capacity with the addition of total fiber volume fraction typically around 2% to 3%. The striking characteristic feature of ECC is its tensile ductility, with strain capacity varying from 3-7%when compared with normal concrete.

1.2 Necessity of Hybrid Fiber Reinforced Concrete and its Assessment

Effect of different fibers on concrete mainly depends on the fiber properties like fiber volume fraction, aspect-ratio, geometry and Young’s modulus. Fibers which are having low Young's modulus such as polypropylene, polyester and nylon, etc., having low density and high aspect-ratio can effectively controls the plastic shrinkage and micro-cracks forming at low-stress levels. With the use of low modulus fibers load carrying capacity at high stress-levels is not good, *Hsie et al. (2008)*. High Young’s modulus fiber like steel which can control the propagation of macro-cracks at higher stress levels and improves the load carrying capacity and toughness of concrete thus catastrophic failures can be avoided. Therefore if these two metallic and non-metallic fibers are rationally combined to produce a composite that derives the benefits from each of the individual fibers and exhibits a synergic response at all stress levels.

1.3 Importance of Engineered Cementitious Composites

During the past 10 years, with the development of micromechanical models, matrix and fiber/matrix interface have been tailored to develop a new cementitious composites which exhibits a better strain hardening behavior.These composites are called Engineered Cementitious Composites (ECC) with effective crack bridging provided by the numerous short discontinuous fibers. The ultimate tensile strain capacity of ECC can reach a value as high as 2–6%, which is 200 to 600 times greater thanthat of concrete.Failure of ECC occurs with the formation of multiplecracks.

These materials have very low water-binder ratio and high contents of silica fume, fibers and super-plasticizers. In spite of possessing high cost, ultra-high performance fiber reinforced cementitious composites (UHPFRCC) can tolerate high impact loading with least repair cost, *Zhou et al. (2010)*. Providing the ECC tension face of reinforced concrete members have been improved the performance under flexure and also it can delay the reinforcement yielding due to the crack bridging action of fibers. The aim of using hybrid combinations is to generate synergetic interaction between fibers that may invigorate the advantages those cannot be achieved by mono-fibers.

1.4 Functionally Graded Reinforced Concrete and its Assessment

Advance in material amalgamation technologies have invigorated the development of a new class of materials called functionally graded material (FGM) with promising applications in aerospace, civil infra-structure, energy, electronics and bio-medical engineering.Functionally graded reinforced concrete (FGRC) is a continuously graded material that has different properties in certain directions either in the top or in the bottom portion of the beam, *Maalej et al. (2003)*. Predominantly, strong fiber matrix as well as dense concrete matrix will be achieved with the help of properly designed FGRC and it may offer enhanced mechanical behavior such as compressive strength, flexural strength, splitting tensile strength, uni-axial tensile strength and higher toughness index. The major issue associated with the practical use of FGM or FGRC structure, is often the material cost and mostly fiber would be dominated the entire cost, *Mastali et al. (2015)*. In recent days, use of ECC materials in FGRC structures in the tension zone will provide enhanced strength and prevents ingress of aggressive substances into the concrete and thus avoid spalling and delamination problems. Schematic view of functionally graded concrete beam is shown in Figure 1.1.

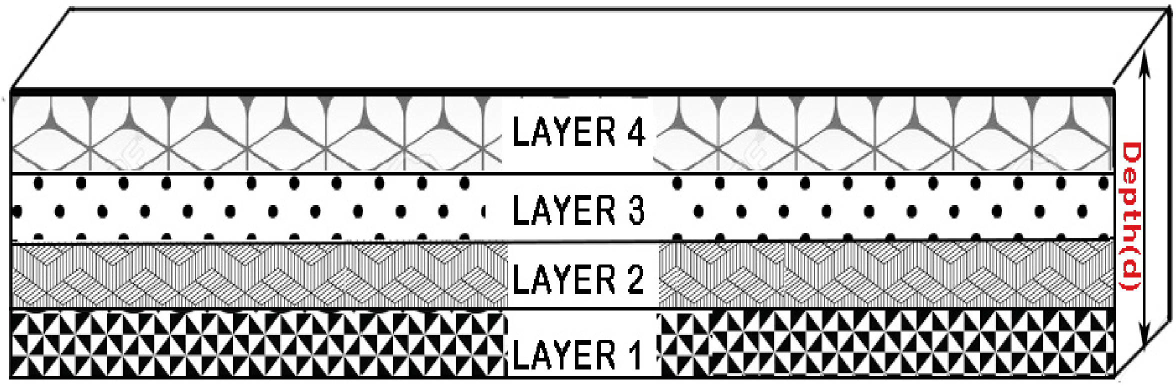


Figure 1.1 Schematic view of functionally graded concrete beam

1.5 Motivation of Research Work

Repairing and strengthening of reinforced concrete structures are becoming paramount important in civil engineering in recent times. With the development in material science, the use of new cement composite materials is a extensively common technique for improving the behavior of RC beams and frames under various service load conditions. The internal flaws and occurrence of damage under service loads which may significantly reduce the structural integrity and performance.

Damage assessment plays an important role in the evaluation of the stability and strength of structure, which is significant for both the existing ones and those under construction. Reinforced concrete structures may also be subjected to damage as a result of insufficient reinforcement, large deflection and poor quality of concrete, corrosion of steel reinforcement or insufficient capacity. In the last decades, condition assessment through vibration monitoring has gained popularity and its applications in civil constructions such as bridges, towers, frames and beams, *Capozzuca (2013)*. The flexibility to assess any concrete structure and detect damage in its earliest state could be easily done or achieved only through vibration monitoring. The essential concept concealed with vibration monitoring technique for any reinforced concrete structure is based on dynamic characteristics due to damage induced in the structures; as a result, changes will occur in the dynamic behavior of structures.Vibration based monitoring technique is one of the best methods which is used to assess the damage behavior of reinforced concrete beams and it could be correlated to the damagelevels*Capozzuca et al. (2015)*.

The aim of the present investigation is first to develop mono fiber reinforced concrete with steel and polypropylene fibers (SFRC & PPFRC), hybrid fiber reinforced concrete using steel and PP fibers and functionally graded reinforced concrete (FGRC) beams using engineered cementitious composites (ECC), and then to characterize and quantify the benefits obtained in mechanical and dynamic properties from the concept of fiber hybridization.

The present investigation also focused on the static and dynamic assessment of reinforced concrete beams strengthened with steel fibers, polypropylene fibers, hybrid fibers and also functionally graded concrete beams using ECC. Combined static and free vibration analyses carried out permitted to assess the actual behavior of strengthened beams at different damage states.

1.6 Organization of the Thesis

The present thesis organized in the following way

Chapter 1 starts with a brief introduction about concrete, fiber reinforced concrete and its advantages, necessity of hybrid fiber reinforced concrete and functionally graded reinforced concrete. Problem statement as well as the aim of research work has also been discussed.

Chapter 2consists a critical review of the state of art. An overview of literature survey on mono fiber reinforced concrete, hybrid fiber reinforced concrete, engineered cementitious composites, functionally graded concrete and damage assessment of reinforced concrete beams have also been presented.

Chapter 3 represents the scope and objectives of the research work.

Chapter 4 provides detailed information on the experimental program such as determination of material properties, concrete mix proportions. Casting and testing of specimens are also discussed.

Chapter 5 presents the results of mechanical behavior of mono and hybrid fiber reinforced concrete and also consist the assessment of static and dynamic behavior of RC beams strengthened with mono and hybrid fibers.

Chapter 6 presents the detailed discussion of results on static and dynamic behavior of functionally graded reinforced concrete beams using engineered cementitious composites.

Chapter 7 includes the validation of results obtained experimentally with the values through modeling of RC beam specimens using FEM software (ABAQUS).

Chapter 8 presents the overall conclusions drawn from the present research work. The scope for further research and references are also presented.

1.7Outline of the Thesis

Effect of fibers on static and dynamic assessment of HFRC and FGRC beams

Phase 1: Mechanical and dynamic properties of mono-FRC and HFRC.

Static and dynamic assessment of mono-FRC and HFRC beams.

Variables of mono-FRC:M25 and M50 grade of concrete with mono steel fiber dosage varied from 0.5%, 0.75%, 1.0% and 1.25%.

Mono PP fiber dosage varied from 0.1%, 0.2%, 0.3% and 0.4%.

Variables of HFRC:M25 and M50 grade of concrete with steel and PP at a total fiber dosage varied from 0.25%, 0.5%, and 0.75%.

Hybrid combinations: 1) 25% SF + 75% PP 2) 50% SF + 50% PP 3) 75% SF + 25% PP

Phase 2: Mechanical behaviorof ECC. Static and dynamic assessment of FGRC

Variables:steel and PVA at a total fiber dosage of 2%.

Mono and Hybrid combinations: 1) 2% SF + 0% PVA 2) 0% SF + 2% PVA 3) 1% SF + 1% PVA 4)0.5% SF + 1.5% PVA 5) 1.5% SF + 0.5% PVA

Phase 3: Modeling of HFRC and FGRC beams.

Modeling by FEM software (ABAQUS) and the results are validated for mono FRC, HFRC and FGRC.

Outcome from all phases:
Phase 1: Development of HFRC using steel and PP fiber. Effect of mono and hybrid fibers on damage assessment of RC beams.
Phase 2: Development of ECC using steel and PVA fiber. Also, development of FGRC beams using ECC and its behavior under static and dynamic loading.
Phase 3: Modeling of mono FRC, HFRC and FGRC with ECC using FEM software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

An extensive review of literature relevant to the research work has been presented in this chapter. The literature review mainly focuses on fiber reinforced concrete which includes steel and polypropylene fibers and hybrid fiber reinforced concrete; fiber reinforced engineered cementitious composites, functionally graded reinforced beams and damage assessment of reinforced concrete beams.

2.2 Literature Review on Steel Fiber Reinforced Concrete

Guneyisi et al. (2014), mechanical properties of steel fiber reinforced concrete incorporated with metakaoline have been investigated. The combined effect of 10% addition of metakaoline with water-to-binder ratios of 0.35 and 0.50 were designed and considered as parameters. Hooked end steel fibers with different aspect ratios of 80 and 40 have used to produce steel fiber reinforced concrete combined with metakaoline to the total fiber volume fraction of 0.25% and 0.75%. Mechanical properties such as compressive, flexural, splitting tensile and bonding strengths were investigated to evaluate the effectiveness of metakaoline and steel fibers with different aspect ratios in concrete. This paper has been concluded that the mechanical properties of concrete enhanced with the addition of metakaoline at 10% when compared to that of plain ones for both water-to-binder ratios. And also it has been concluded that there was a remarkable improvement in bond strength and tensile strength capacities of the concrete with the inclusion of steel fibers.

Aylie et al. (2015), influence of steel fibers in combination with the confinement in the compression zone of a flexural member has been investigated experimentally. This study has analyzed the effect of confinement on load carrying capacity and cracking moment capacity of a simply supported beam in pure bending. Five steel fiber reinforced beams were cast and tested with a variation in confining reinforcement configurations. The experimental results emphasized that the addition of steel fibers to concrete mixture and confined reinforcement in the compression zone plays an important role and had major impact on the ultimate moment and cracking moment of the RC beams. Also, the addition of steel fibers increases the first cracking and ultimate moment for both confined and unconfined beams.

Iqbal et al. (2015),investigated the mechanical properties of high strength light-weight self-compacting concrete with the addition of hooked end steel fibers at 0.5%, 1% and 1.25% total fiber volume fraction. Mechanical properties have been determined by conducting compressive strength, splitting tensile strength, modulus of elasticity and flexural strength tests on SFRC specimens. The results indicated that there was around 12% reduction in compressive strength and 37% and 110% increase in splitting tensile and flexural strength respectively with the addition of steel fiber content at 1.25%.

Afroughsabet et al. (2017),determined the properties of sustainable high performance double hooked-end steel fiber reinforced concrete with recycled coarse aggregate. Mechanical and durability properties have been obtained for steel fiber reinforced concrete at 50% and 100% replacement of coarse aggregate with recycled aggregates. Durability properties like water absorption, electrical resistivity and shrinkage of the concrete mixes were determined. This research work has concluded that the addition of steel fibers at 1% fiber volume fraction significantly improves the mechanical properties of recycled aggregate concretes.

Abbass et al. (2018), investigated the mechanical properties of steel fiber reinforced concrete with different concrete strengths. In this experimental study, the effect of addition of hooked end steel fibers with two different aspect ratios of 65 and 80 have been considered as parameters. Total thirty mixes were cast with three different fiber volume fractions 0.5%, 1% and 1.5% to examine the mechanical properties such as compressive, tensile and flexural strengths of steel fiber reinforced concrete. This research work has concluded that the addition of steel fibers with different aspect ratios was significantly improved the mechanical properties. The maximum improvement in compressive, tensile and flexural strength of steel fiber reinforced concrete was about 27%, 28% and 128% respectively with the addition of 1% total fiber volume fraction.

Jin et al. (2018), studied static and dynamic mechanical properties of steel fiber reinforced ultra-high strength concretes. In this investigation mechanical properties have been obtained with total fiber volume fractions 1%, 2% and 3% of concrete. Compressive strength was increased by about 12% and 15% for cube and prism specimensrespectively, with the addition of total fiber volume fraction of 3%, whereas the splitting tensile and flexural strengths were increased by 140% and 94% for the same volume fraction of fibers.

Li et al. (2018), investigated the effectiveness of fiber type, volume fraction and aspect ratio on the flexural behavior of steel fiber reinforced concrete under four-point bending test. Three types of steel fibers such as straight, hooked-end and corrugated fibers with four different volume fraction of fibers 0.5%, 1%, 1.5% and 2% have been considered as parameters. Flexural behavior of steel fiber reinforced concrete (SFRC) has been assessed. Flexural strengths of SFRC vary with fiber type, volume fraction and aspect ratios, among all these fibers, concrete with hooked end fibers shows the best behaviorunder flexure. The ultimate flexural strengths of specimens are remarkably improved by 74%, 112% and 165% for straight, corrugated and hooked end steel fibers respectively. Moreover, the peak load, corresponding deflection and toughness of SFRCs increased with increase of fiber volume fraction up to 1.5%.

Gholampour and Ozbakkaloglu(2018),assessed the behavior of ultra-high strength micro steel fiber reinforced concrete under active confinement. In this study, two different volume fractions of fibers such as 1% and 2% have been considered with two different target compressive strengths of 50MPa and 100MPa. The effects of fiber volume fraction and confining pressure were examined through the axial compression tests on confined and confined SFRCs to evaluate its compressive behavior. This investigation has concluded that the axial strength and peak axial strain of SFRCs increased with the increase of fiber volume fraction and the post-peak branch trend of the axial stress-strain relationship was barely affected.

Lee et al. (2018),studied the structural behavior of reinforced concrete (RC) beams with and without steel fibers and stirrups. Structural behavior of RC beams has been experimentally investigated by conducting quasi-static, impact and blast loading with the addition of hooked end steel fibers at a total fiber volume fraction of 0.5% and 1% of concrete. The results inferred that the addition of steel fibers enhanced the static, impact and blast resistance of the RC beams in terms of higher load carrying capacity, higher energy absorption capacity and minimum residual displacement. The beam with the inclusion of both stirrups and 0.5% of steel fibers shows the best performance amongst all.

2.3 Literature Review on Polypropylene Fiber Reinforced Concrete

Karahan and Atis(2011),studied the durability properties of polypropylene fiber reinforced concrete incorporated with fly-ash. Some of the properties have been studied such as unit weight, workability of fresh concrete, compressive strength, modulus of elasticity, porosity, water absorption, sorptivity co-efficient, drying shrinkage and freeze-thaw resistance of hardened concrete with the inclusion of fiber volume fractions 0.05%, 0.10% and 0.20% along with the replacement of fly-ash 0%, 15% and 30% of total weight of cement. This research work has concluded that the addition of polypropylene fibers along with fly-ash reduced the unit weight as well as the workability of concrete and increased the porosity, water absorption and sorptivity co-efficient for all mixtures. And also, freeze-thaw resistance was significantly increased with an increase of fiber content as well as fly-ash content.

Kakooei et al. (2012),investigated the influence of polypropylene fibers on mechanical and durability properties of concrete through compressive strength, permeability and electrical resistivity of concrete. Polypropylene fiber reinforced concrete mixtures have been prepared with the addition of fibers in terms of weight per cubic meter from 0 to 2 kg/m^3. It is concluded that the compressive strength increases with the increase of polypropylene fiber whereas the permeability decreases with the increase of fiber content and the optimum fiber content is achieved as 1.5 kg/m^3.

Yahagari et al. (2016), impact resistance of polypropylene fiber reinforced concrete incorporated with palm oil shells has been investigated. Three different fiber volume fractions at 0.1%, 0.2% and 0.3% was used to evaluate the impact resistance by dropping two types of steel balls weighing 0.380 kg and 1.25 kg from the drop height of 360mm. The test results concluded that there was significant increase in impact resistance, energy absorption and crack resistance for polypropylene fiber reinforced concrete compared to plain concrete.

Hesami et al. (2016),investigated the mechanical behavior of self-compacting concrete incorporated with recycled tire rubber crumb and also reinforced with polypropylene fibers. In this experimental work, polypropylene fiber has been added in terms of total fiber volume fraction of concrete as 0.1%, 0.12% and 0.15% with the addition of tire rubber crumb as a partial replacement to sand as 5%, 10% and 15% in order to examine the mechanical properties. The hardened concrete tests resulted that tire rubber crumb decreases the compressive, tensile, flexural and abrasive strength of concrete without polypropylene fibers. And also this paper concluded that the presence of polypropylene fibers in rubberized concrete increased the overall performance.

Jun Li et al. (2016),assessed the effect of polypropylene fibers on the mechanical properties of light-weight aggregate concrete. The mechanical properties like compressive strength, splitting tensile strength, flexural strength, flexural toughness and impact resistance for polypropylene fiber reinforced concrete were determined. The fibers were added in terms of weight per cubic meter of concrete as 0, 5, 7, 9, 11 and 13 (kg/m^3). The addition of polypropylene fiber in light-weight aggregate concrete significantly improves the mechanical properties as well as post-cracking behavior. The recommended optimum fiber content is 9 kg/m^3.

Das et al. (2018), studied the influence of microfilament type polypropylene fibers with the incorporation of low strength recycled aggregate concrete on the basis parameters such as compressive strength, split tensile strength, flexural strength and modulus of elasticity. Experimental studies were carried out with the addition of total fiber volume fraction as 0.5%, 0.75% and 1% of concrete in both natural aggregate and recycled aggregate concretes. Recycled aggregate concrete was prepared with 100% replacement of recycled coarse aggregate with natural coarse aggregates. The experimental results inferred that the optimum fiber content is 0.5% and then decreases with further use of fibers**.**

Hanumesh et al. (2018),studied the behavior of recycled aggregate concrete with and without addition of polypropylene fiber. The natural aggregates were replaced with recycled aggregate at 0%, 25%, 50%, 75% and 100% along with the addition of polypropylene fiber at a total fiber volume fraction of 1% and 2% of concrete. It is concluded that the compressive, split tensile and shear strengths were increased for recycled aggregate content up to 25% replacement.

Deb et al. (2018), investigated the influence of polypropylene fibers on cementitious composites. Two different types of fibers such as fibrillated and monofilament polypropylene fibers have been used and the behavior has been evaluated through tensile strength, flexural strength and ductility characteristics. This study concludes that the addition of fibrillated fiber improves the flexural capacity as well as the tensile strength and the ductility, whereas the combination of both fibrillated and monofilament fibers improve the tensile strength and ductility characteristics.

2.4 Literature Review on Hybrid Fiber Reinforced Concrete

Qian and Stroevan (2000),studied the mechanical properties of steel-polypropylene hybrid fiber reinforced concrete containing fly-ash. Firstly, sizes of steel fiber, content of steel fiber and fly-ash have been optimized based on the mechanical properties ofhybrid fiber reinforced concrete. Static mechanical properties like compressive, split tensile and flexural strengths of hybrid fiber reinforced concrete have been determined. This work stated that the usage of fly-ash is necessary to disperse the fibers evenly in concrete. The addition of fibers had a significant influence on the compressive strength and flexural strength.

Yao et al. (2003),studied the mechanical properties of hybrid fiber reinforced concrete containing low fiber volume fractions. Two different types of fibers such as steel and carbon fibers have been used at a total fiber volume fraction of 0.5% of concrete. Mechanical properties have been determined by conducting compressive strength, split tensile strength, flexural strength and toughness index tests. This paper concluded that the addition of carbon-steel hybrid fibers to concrete improves the modulus of rupture and toughness.

Hsie et al. (2008), mechanical properties of polypropylene hybrid fiber reinforced concrete have been determined. Two different fibers used such as monofilament and staple fibers to examine the mechanical properties of hybrid fiber reinforced concrete. Monofilament fiber has been varied in terms of weight per cubic meter as 3 kg/m^3, 6 kg/m^3 and 9 $kg/m^3$of concrete and staple fiber at 0.6 kg/m^3 for all hybrid mixtures. Authors concluded that the addition of hybrid fibers made up of two non-metallic polypropylene fibers improved the mechanical properties and performance of concrete compared with mono polypropylene fiber reinforced concrete.

Alberti et al. (2014), determined the mechanical and fracture properties of self-compacting concrete incorporated with hybrid fibers such as polyolefin and steel fibers. Combination of steel and polyolefin fibers has been used randomly and its mechanical, fracture and workability properties were determined. It has been concluded that there was possibility to produce a self-compacting concrete with polyolefin and steel hybrid fiber which enhances the fresh properties and also improves the mechanical properties such as compressive strength and modulus of rupture.

Banthia et al. (2014), fiber synergy of hybrid fiber reinforced concrete in flexure and direct shear has been experimentally investigated. Two types of macro-steel fibers (Hooked end and double deformed steel fibers) and micro-cellulose fiber were used to examine the fiber synergy in direct shear and flexural strength test. This paper concluded that there was a significant improvement in shear strength by the addition of hooked end steel fiber whilst by adding cellulose fiber shear strength was barely affected. Shear strength and flexural strength of hybrid fiber reinforced concrete showed the better performance.

Yu et al. (2014),investigated the static properties and impact resistance of a green ultra-high performance hybrid fiber reinforced concrete. Combination of short and long steel fibers has been used with different fiber volume fractions such as 0.25%, 0.5% and 1% of concrete to examine the mechanical properties. Impact resistance and flexural strength of hybrid fiber reinforced concrete increased by about 23% and 46% compared to plain concrete.

Afroughsabet and Ozbakkalogu (2015),investigated the combined effect of steel and polypropylene fibers on the mechanical and durability properties of high strength concrete. All concrete mixtures were cast with the addition of mono steel fibers at a total fiber volume fraction 0.25%, 0.5%, 0.75% and 1% of concrete, mono polypropylene fibers at total fiber volume fraction of 0.15%, 0.3% and 0.45% of concrete and steel-polypropylene hybrid fibers with total fiber volume fraction of 1% in order to examine the effect of fiber hybridization. In fiber hybridization technique, total hybrid fiber volume fraction (1%) has been divided into three categories as 0.15:0.85, 0.30:0.70 and 0.45:0.55. Mechanical and durability properties have been determined by conducting compressive strength, split tensile strength, flexural strength, water absorption and electrical resistivity. High strength concrete was achieved by adding silica fume to the mixtures. Authors concluded that the addition of silica fume enhances the mechanical and durability properties of concrete and also the addition of mono steel and polypropylene fibers improve the mechanical properties of high strength concrete. Amongst all mixtures, the concrete contains 0.85% of steel and 0.15% of polypropylene fibers shows the best performance.

Yehia et al. (2016),investigated the mechanical and durability properties of self-compacting concrete exposed to early dry/wet cycles containing hybrid fibers. Mechanical properties have been investigated through compressive strength, split tensile strength, flexural strength and modulus of elasticity with the addition of mono steel, synthetic and hybrid fibers. Some of the durability parameters were determined such as rapid chloride penetration test with and without hybrid fibers. Mechanical properties of hybrid fiber reinforced self-compacting concrete were enhanced for exposed condition compared to non-exposed specimens. It has concluded that the addition of hybrid fibers to concrete improves the flexural and split tensile strength but there was no significant improvement in compressive strength.

Li et al. (2017),experimentally investigated the mechanical properties of hybrid fiber reinforced concrete. Three different types of fibers such as steel, basalt and polypropylene fibers have been used in order to determine the mechanical properties of hybrid fiber reinforced concrete. Mechanical property tests have been carried out to determine direct shear strength, uni-axial compressive strength, split tensile strength, uni-axial tensile strength and flexural strength of hybrid fiber reinforced concrete containing different dosages. It has been concluded that the addition of steel and basalt fibers improved the shear strength as well as shear toughness.

Tabatabaeian et al. (2017),investigated the influence of fiber hybridization on rheological, mechanical and durability properties of high strength self-consolidating concrete. Total hybrid fiber volume fraction as 0.5% and 1% of concrete has been used with combinations of mono hooked-end steel and polypropylene fibers in order to examine the workability, mechanical and durability properties. Mechanical properties such as compressivestrength, split tensilestrength and flexural strength and durability property was also assessed through electrical resistivity tests. It has been concluded that the addition of hybrid fibers reduces the fresh properties and improves the mechanical as well as durability properties of concrete.

EI-Din et al. (2017),experimentally investigated the mechanical properties of hybrid fiber reinforced concrete containing metakaoline. Mechanical properties have been determined through compressive strength, flexural strength and bond strength with the addition of two different total fiber volume fractions as 0.25% and 0.5% combined with 0.15% of metakaoline constantly. It concludes that the addition of steel-polypropylene hybrid fibers enhances the compressive, flexural and bond strength of the high strength concrete which has been produced with the inclusion of metakaoline and also a good correlation was made between the compressive, flexural and bond strength of all concrete mixtures.

Zhang et al. (2018),investigated the flexural performance of reinforced self-consolidated concrete beams incorporated with hybrid fibers. Three different types of fibers such as steel, macro-polypropylene and micro-polypropylene fibers have been used to produce hybrid fiber reinforced concrete. Twelve reinforced concrete (RC) beams have been cast to examine the flexural performance with the addition of mono fibers as well as hybrid fibers. Type of fibers, combination of fibers, fiber contents in combination of hybrid fiber and longitudinal reinforcement ratios were the major parameters considered in the study. Flexural behavior of RC beams was investigated by four point bending test. Cracking load, ultimate load and corresponding mid-span deflection, strain in longitudinal reinforcement and crack pattern were investigated. It is concluded that the addition of mono steel fiber and hybrid fibers enhanced the ultimate moment carrying capacity and reduces the deflection of reinforced self-consolidating beams. Also, the strain in longitudinal reinforcement, crack width and crack spacing significantly decreased with the increase of fiber content.

Teng et al. (2018),investigated the durability properties and flexural behavior of high performance hybrid fiber reinforced concrete. High performance concrete was produced by adding silica-fume and ground granulated blast furnace slag at the constant proportions of 10% and 30% of the cement by weight respectively. Flexural behavior and durability property tests have been carried out by conducting four-point bending test, rapid chloride penetration and electrical resistivity with the addition of mono hooked end fibers, hooked-end and polyvinyl alcohol fibers combined at different combinations of fiber volume fractions such as 0%, 0.6% and 1.2%. The experimental test results concluded that very high durable concrete was achieved by the addition of silica-fume and GGBS in concrete. The addition of fibers remarkably enhanced the compressive and flexural strength.

2.5 Literature Review on Engineered Cementitious Composites

Kim et al. (2007), investigated the tensile and fiber dispersion performance of engineered cementitious composites (ECC) containing ground granulated blast furnace slag (GGBS). ECC has been produced for the purpose of achieving high ductility under direct uni-axial tension without the addition of coarse aggregates. Mechanical properties such as compressive strength, flexural strength and uni-axial tensile strength have been determined in order to examine the performance of ECC. The micromechanical studies have also been performed to evaluate the fiber dispersion characteristics. ECC produced with cement, water, sand, GGBS and High range water reducing admixture (HRWRA), and the composite improves the ductility and strain hardening capacity behavior of the matrix.

Zhou et al. (2010), experimentally investigated the mechanical properties of PVA fiber reinforced engineered cementitious composite containing limestone powder and blast furnace slag. Mechanical properties such as compressive strength, flexural strength and direct tensile strength have been obtained with the addition of 2% total fiber volume fraction of composites along with limestone and blast furnace slag. All ECC specimens exhibit multiple cracking-behavior under four-point bending and uni-axial tension tests. Tensile strain capacity increases with the addition of limestone powder along PVA fiber content in composites.

Li and Li (2013),investigated the rheology and fiber dispersion of engineering cementitious composites. Mechanical properties and fresh properties such as mini-slump cone, marsh cone and V-funnel tests have been performed to examine the rheology of ECC mixtures with the addition of different percentage variation of PVA fibers. This study demonstrated that the designed ECC with PVA fiber has achieved robust strain hardening behavior and high tensile ductility combined with controlled material rheology during processing.

Altwair et al. (2012),investigated the flexural performance of green engineered cementitious composites containing high volume palm oil fuel ash. The flexural behavior of ECC mixtures with the addition of 2% total fiber volume fraction of PVA fiber and high volume palm oil fuel ash at 0%, 0.4%, 0.8% and 1.2% by mass of cement have been determined under four-point bending test. The experimental results inferred that the first cracking strength and width of cracks reduced by the addition of PVA fibers as well as high volume palm oil fuel ash.

Zhang et al. (2014),investigated the mechanical properties and self-healing behavior of micro-cracked engineered cementitious composites. The mechanical properties have been carried out through compressive, flexural and uni-axial tensile strength tests with the addition of 2% total fiber volume fraction of PVA fibers and different percentage variation of silica fume and fly-ash. In addition to this, sorptivity and rapid chloride penetration tests have also been carried out. Experimental results have been revealed that the compressive strength is decreased with the increase of fly-ash whereas deflection capacity of the same ECC mixtures showed opposite trend. Also, excellent capacity of crack control, deformability and self-healing behavior exhibited.

Felekoglu et al. (2014), studied the influence of matrix flowability, fiber mixing procedure and curing conditions on the mechanical performance of engineered cementitious composites incorporated with polypropylene fibers. Mechanical properties and fresh properties such as mini-slump cone, flowability and V-funnel passing ability tests have been conducted for all ECC mixtures with the addition of different percentage variation of polypropylene fibers. Authors concluded that the polypropylene ECC mixture possesses higher compressive strengths (30-70MPa) and tensile ductility (1.91-3.91%) which is very similar to ECC-PVA fibers. Also, ECC mixtures with the addition of polypropylene fibers have been achieved robust strain hardening and multiple-cracking behavior under uni-axial tensile strength test.

Said et al. (2015), investigated the flexural behavior of engineered cementitious composites slabs incorporated with PVA fibers experimentally. Flexural behavior of ECC has been determined through mechanical properties such as toughness index, compressive strength and flexural strength with the addition of 1%, 1.5%, 2%, 2.5% and 3% fiber volume fraction of matrix. Authors concluded that the compressive strength decreased with the increase of PVA fiber content whilst first crack and ultimate flexural strength increased with the increase of PVA fibers for all ECC mixtures.

Meng et al. (2017), investigated the mechanical behavior of PVA fiber reinforced engineered cementitious composites. Mechanical properties such as compressive strength and flexural strength with the addition of total fiber volume fraction of matrix at 2.2% have been considered along with local ingredients to examine the performance of ECC specimens. This paper has concluded that the addition of PVA fiber along with silica fume and fly-ash enhances the overall performance of composites.

Kang et al. (2017), studied the shear strength of engineered cementitious composites. ECC matrix was developed with fly-ash, GGBS, cement, fine aggregates and PVA fibers at a constant mix proportion with the variation of stirrup reinforcement ratios to examine the shear strength. Experimental results emphasized that the ECC could sustain higher shear forces than the conventional concrete because of the inclusion of fibers as well as cementitious materials.

Truk and Nehdi (2018), investigated the mechanical properties of engineered cementitious composites containing limestone powder, high-volume fly-ash and PVA fibers. Mechanical properties such as compressive strength and flexural strength with the addition of total fiber volume fraction of matrix as 2% have been considered to examine the performance of ECC. The compressive strength, flexural strength and fracture toughness were improved significantly with the addition of combined effects of limestone powder and high-volume fly-ash as well as because of the inclusion of PVA fiber to ECCs.

Soe et al. (2013),studied the impact resistance behavior of hybrid fiber engineered cementitious composite panels. A new hybrid fiber reinforced ECC panels were produced with the addition of 1.75% of PVA fiber and 0.58% of steel fiber to examine the impact resistance experimentally. All specimens were subjected to impact from small ogive-nose steel projectile which was fired from a gas gun travelling with an initial velocity ranging from 300 m/s to 657 m/s. From the impact test, the magnitude of the impact to the panel was evaluated from damage parameter such as crater diameter, scabbing diameter and penetration depth. This study has concluded that the new hybrid ECC material has an excellent impact resistance to projectile penetration, greater energy absorption, higher bridging capacity and better durability performance under multiple impacts.

Manvi and Kumar (2017), evaluated the mechanical properties of hybrid fiber engineered cementitious composites. The mortar based hybrid fiber ECC was produced with polypropylene and steel fibers to study its mechanical properties as well as stress-strain relationship. This paper concluded that the addition of hybrid fibers to cementitious composites enhances the mechanical properties such as compressive, flexural and split tensile strength by bridging and minimizing the cracks.

Ali et al. (2017),investigated the flexural behavior and impact resistance of engineered cementitious composites incorporated with hybrid fiber such as PVA and shape memory alloy fibers. Mechanical properties such as compressive strength, flexural strength, uni-axial tensile strength and impact resistance have been determined to examine the effect of hybrid fibers in cementitious composite with the different percentage volume fraction of fibers in matrix. Authors concluded that the addition of 2% PVA and 1% shape memory alloy fibers achieved highest tensile capacity and also ECC matrix changed the failure mode of ECC specimens.

Wu and Li (2017),investigated the thermal and mechanical behaviors of carbon fiber reinforced polymer (CFRC) – engineered cementitious composites under elevated temperatures. CFRP sheets were directly bonded to the concrete substrate adopted with polymer adhesives in order to strengthen the specimens. All specimens were exposed to the temperatures up to 500°C. This paper concluded that the beam specimen with CFRP sheets enhances the strain hardening capacity and flexural strength. And also, concluded that the interface between concrete substrate and CFRP plate was sensitive to the elevated temperature.

Alonge et al. (2017), studied the durability and mechanical properties of hybrid fiber engineered cementitious composites incorporated with metakaoline, nano-silica and epoxy. Hybrid fiber ECC specimens with the addition 10% of metakaoline, 1% of nano-silica and 1% of epoxy resins were examined to investigate the durability properties such as water absorption (both seawater and normal water), intrinsic air permeability, porosity and chloride penetration tests and also mechanical property tests have been carried out. Authors concluded that the addition of cementitious materials reduces water absorption, porosity, air permeability and chloride ions to the extent of 2.78%, 13.62%, 39.57% and 43.67%, respectively when compared to conventional concrete.

Pourfalah (2018),investigated the behavior of engineered cementitious composites exposed to elevated temperature incorporated with mono and hybrid fibers. The effect of mono steel and PVA fibers and hybrid (steel-PVA) fibers of ECC matrix has been determined through compression and flexural strength tests at different temperatures ranging from 20°C to 600°C. Hybrid ECC specimens produced very less debris at a temperature 200°C Under axial compression compared to mono ECC specimens and also the load carrying capacity and deflection of hybrid ECC specimens were less vulnerable when compared to mono ECC specimens at a temperature of 100°C. Authors concluded that the behavior of mono ECC specimen was brittle in nature whereas hybrid ECC specimens exhibited a very high deflection softening behavior.

2.6 Literature Review on Functionally Graded Reinforced Concrete

Maalej et al. (2003), investigated the structural response of functionally graded concrete beams using ductile fiber reinforced cementitious composite (DFRCC) material. Reinforced concrete (RC) beams and functionally graded concrete beams with the addition of DFRCC layer in the tension zone (one-third of the beam depth) were cast and tested under monotonic flexural loading to examine the behavior. DFRCC beams consists of materials like cement, fly-ash, fine aggregates, water and high-range water reducing admixture. DFRCC exhibited high strain-hardening behavior under tensile and flexural loadings. This study concludes that using DFRCC material in functionally graded beams was very effective in reducing the development of cracks particularly in the tension zone and increased the load carrying capacity of the beams.

Maalej and Leong (2005), investigated the flexural performance of functionally graded reinforced concrete (FGRC) beams using engineered cementitious composites and also strengthened with FRP plate. All FGRC beams were produced with ECC material incorporated in tension zone along with FRP plate attached in the bottom layer of the beam using epoxy. This paper concludes that ECC had delayed debonding of the CFRP and resulted in effective use of the CFRP material to minimize the deflection loss.

Shen et al. (2008), investigated the functionally graded concrete beam incorporated with steel fibers. FGRC beams were produced with a four layered cementitious composites with the increased fiber volume fractions as 0%, 0.67%, 1.33% and 2% from the bottom to top layers. Mechanical properties such as compressive strength and flexural strength have been determined. This paper concludes that FGRC beams with different volume fraction of fibers exhibited about 50% higher flexural strength compared to homogeneous FGRC beams with the same overall fiber volume fraction.

Zhang et al. (2006), studied the flexural performance of layered ECC concrete composite beam. Functionally graded concrete beams were produced with three different layered ECC materials in the tension zone of each 25mm thick and subjected to four point flexural load. This paper concludes that the application of ECC layer in the beam enhances the both flexural strength and ductility as well. The degree of improvement was observed with the increase of ECC layers in the beam.

Leung et al. (2007), studied the fatigue enhancement of functionally graded concrete beams with engineered cementitious composites (ECC) layers. Functionally graded concrete beams were produced with three different layered ECC material in the tension zone (25mm and 50mm each) subjected to static and fatigue flexural loads. From the static results, it is observed that the addition of ECC material in the tension zone of a beam increased its ultimate flexural strength with the increase of layer thickness. And also, ECC layers significantly enhanced the fatigue life of the beam under four-point loading.

Maalej et al. (2010), investigated the effect of cracking, corrosion and repair on the frequency response of functionally graded reinforced concrete beams using engineered cementitious composites. All reinforced concrete (RC) beams were produced with ECC material (1.5% of polypropylene and 0.5% of steel fibers) in the tension zone up to one-third of beam depth to examine the flexural performance and also cracking behavior. Fundamental frequency of FGRC beams were determined using Fourier transform and Hilbert-Huang transform. The results of this study revealed that the overall flexural performance of the FGRC beams were enhanced compared to reinforced concrete beams without ECC.

Bajaj et al. (2013),assessed the flexural behavior of functionally graded beam containing high-volume fly-ash. All FGRC beams were cast with ECC at different depth variation such as 0mm, 25mm, 50mm, 75mm and 100mm of high-volume fly-ash concrete in the tension zone to improve the ductility performance under flexural and impact loadings. High-volume fly-ash concrete has been produced with different percentage variation of fly-ash 20%, 35% and 55% with replacement of cement for M20and M30 grade of concrete in order to evaluate the overall flexural performance under four-point loading condition. The results revealed that there is 12.86% and 3.56% increase in compressive and flexural strength respectively in functionally graded beams.

Mastali et al. (2015), experimentally assessed the impact resistance of functionally graded reinforced concrete slabs under drop weight and projectile impacts. FGRC curved slabs were cast with five different layer thickness of 20mm each with the addition of steel at fiber volume fraction of 2%, 1%, 0.5%, 1% and 2% from first layer to fifth layer to evaluate the impact resistance. This paper has concluded that the FGRC leads to more reduction in penetration depth compared to entirely reinforced concrete slabs with constant fiber volume fraction specimens.

Naghibdehi et al. (2015),investigated the flexural fatigue behavior of functionally graded concrete under cyclic loading condition. Functionally graded concrete was developed with five different layers of ECC material prepared with steel and polypropylene (0%, 0.5%, 1%, 1.5% and 2%) and (0%, 0.25%, 0.5%, 0.75 and 1%) of total fiber volume fraction of composites, respectively. Authors concluded that the use of functionally graded concrete with the addition of ECC layers in the tension zone increases the fatigue behavior.

Liu et al. (2018),investigated the flexural behavior of functionally graded concrete using fibers and recycled aggregate concrete. Functionally graded concrete beams were prepared with fiber reinforced concrete layer in the bottom zone of half depth and another half depth of top layer was filled with recycled aggregate concrete to evaluate the flexural performance under four-point loading condition. This paper has concluded that the post-cracking flexural performance of functionally graded concrete beam was lower than that of the conventional fiber reinforced concrete.

2.7 Literature Review on Damage Assessment of Reinforced Concrete Beams

Capozucca (2009), investigated the damage assessment of RC beams strengthened with NSM CFRP rods experimentally. RC beams were cast and tested under four-point flexural load in order to obtain ultimate load and later the dynamic response under free-free condition at different damage levels was monitored. The strengthened RC beams using NSM CFRP rods were later subjected to bending test under same path to evaluate the flexural behavior and dynamic response. This paper concludes that the strengthened RC beam improves the load deflection response and ultimate flexural load. It has also been observed that the variations in natural frequency values recorded during the tests were well correlated with the damage levels.

Capozucca (2013), studied the performance of RC beams strengthened with CFRP plate through dynamic tests. Six RC beams were analysed experimentally, three beams of reinforced concrete and the other three were strengthened with CFRP plate in the compression zone. The dynamic response under free-free condition is obtained using impact hammer technique. This paper has concluded that there was a small variation in natural frequency values of the beam strengthened with CFRP plate compared with control RC beams.

Capozucca et al. (2015), investigated the static and dynamic behavior of RC beams strengthened with NSM CFRP rectangular rods. Assessment of RC beams has been carried through free vibration analysis; one beam was strengthened with rectangular CFRP rods and the other two beams were strengthened with double notches CFRP rectangular rods at two sections. This paper concludes that the variation of natural frequency increases under high loads and notched CFRP barely reduced the flexural strength with the propagation of longitudinal cracks. Also, variation of natural frequency values was less for the beams strengthened with CFRP rods compared with control RC beams.

Capozucca et al. (2016), investigated the static and dynamic response of undamaged and damaged RC beams strengthened with near surface mounted (NSM) CFRP rods under flexural vibration. Four RC beams were cast with and without CFRP rods and tested under monotonic flexural test and dynamic test in two different boundary conditions such as free-free and hinged-hinged conditions to monitor the damage. Damage of the beam has been assessed through non-destructive experimental tests by measuring dynamic parameters such as natural frequency and mode shapes. Dynamic parameters have been determined for RC beams at four different damage levels in two different constraints using dynamic analyzer. This paper concludes that the natural frequency decreases with the increase of damage. Also, the variation of natural frequency measures reaches 10% for the first four modes of vibration in case of hinged end condition only at high damage levels.

Pimentel et al. (2017), investigated the damage assessment of reinforced concrete slabs under impact tests. A simply supported slab was built and the damage was induced by applying static loads in three stages. At the end of each stage, modal test was conducted using impact hammer to evaluate the changes of the fundamental natural frequency. This paper has concluded that the change innatural frequency values indicate the level of damage occurred in the RC slab.

Allahrari et al. (2018), investigated the dynamic properties of composite slabs from the measured frequency response functions. Normal weight aggregate concrete and light weight aggregate concrete have been cast and tested to determine static behavior and dynamic parameters such as natural frequency, damping ratio and mode shape under free-free condition. Dynamic characteristics have been assessed by means of non-destructive technique with hammer excitation. This paper concludes that the damping ratios and natural frequencies of the light weight aggregate concrete decreases when compared to those that of the plain concrete.

Capozucca (2018), investigated the damaged RC beams strengthened with glass fiber reinforced polymer (GFRP) plate through dynamic tests. Two RC beams were analysed experimentally, one beam of reinforced concrete and the other was strengthened with GFRP plate in the compression zone in order to examine the dynamic response under free-free constraint. This paper has concluded that the damaged beam strengthened with GFRP plate limits the occurrence of damage. This is indicated by the less variation of frequency values even for high bending moment.

2.8 Summary of Literature Review

Following observations were made from the detailed literature survey:

- Many researchers have studied the effect of mono fibers (steel and polypropylene) on strength and durability characteristics of normal and high strength concrete. Also, studied the effect of fiber hybridization on strength characteristics using metallic and non-metallic fibers at different fiber volume fractions.

- Some researchers have been focused on the evaluation of mechanical properties of engineered cementitious composites (ECC) using mono and hybrid fibers.
- Flexural and fatigue performance of functionally graded concrete beams with layered ECC materials have also been assessed by few researchers.
- Dynamic assessment of reinforced concrete beams using carbon fiber reinforced polymer (CFRP) rods, CFRP and GFRP sheets have also been studied through various methods such as vibration technique, acoustic emission technique and modal strain energy method.

Many researchers have been developed mono and HFRC using non-metallic and metallic fibers on mechanical behavior. FGRC beams have been developed using ECC material to evaluate flexural behavior. It has been observed from the literature that, the dynamic behavior of reinforced concrete beams strengthened with mono and hybrid fibers have not been carried out. Further static and dynamic behavior of functionally graded reinforced concrete beams using ECC material needs to be studied. Based on the detailed literature review, an experimental program has been planned to evaluate the damage assessment of reinforced concrete (RC) beams strengthened with steel fibers, polypropylene fibers and hybrid fibers (steel and polypropylene). Also the damage behavior of functionally graded concrete beams using hybrid fiber engineered cementitious composite material is evaluated under static and dynamic loading.

CHAPTER 3

SCOPE AND OBJECTIVES OF THE INVESTIGATION

3.1 Scope of the Investigation

Significantly most of the researchers have been studied the effect of inclusion of mono and hybrid fibers in concrete to assess the mechanical and durability properties. Also, damage assessment of reinforced concrete (RC) beams has been studied by some researchers without the fiber effect through vibration monitoring. After going through the thorough literature, the necessity of static and dynamic behavior of hybrid fiber reinforced and engineered cementitious composites is identified. Accordingly a detailed experimental program has been planned to evaluate the strength characteristics of mono steel andmono polypropylene fiber reinforced concrete and hybrid fiber reinforced concrete. Mechanical properties of engineered cementitious composites (ECC) have also been determined. Further the research is focused to assess the static and dynamic behavior of RC beams strengthened with mono and hybrid fibers and also the behavior of FGRC beams using ECC.Static tests are normally adequate for describing the load carrying capacity of members but dynamic tests through vibration monitoring are useful to detect the damage under service load conditions. The basic principle of vibration monitoring is to correlate the damage to the change in dynamic characteristics. Since the dynamic characteristics are the functions of the physical properties of the structures, therefore any change in physical properties due to damage leads to change in the dynamic behavior of structures. Once the damage is identified and quantified, repair and maintenance works can be properly programmed to avoid catastrophic failure of structures.

3.2 Objectives of the research work

The aim of the present research work is to investigate the static and dynamic behavior of hybrid fiber reinforced engineered cementitious composites. The specific objectives of the investigation are

- To evaluate the mechanical and dynamic properties of mono and hybrid fiber reinforced concrete.
- To study the static and dynamic behavior of reinforced concrete beam strengthened with mono fibers (Steel and polypropylene fibers) and hybrid fibers.
- To determine the mechanical properties of engineered cementitious composites with different percentage variation of steel and polyvinyl alcohol fibers.
- To study the static and dynamic behavior of functionally graded reinforced concrete beamswith layered engineered cementitious composites.
- Modeling of reinforced concrete beams strengthened with mono fibers, hybrid fibers and modelingof FGRC beams with ECC layers using FEM software (ABAQUS).

3.3 Research Methodology

To achieve the above mentioned objectives, the present experimental investigation is planned and carried out in three different phases.

- **Phase-I:**First phase of experimental program aimed to evaluate the mechanical and dynamic properties of mono and hybrid fiber reinforced concrete. Fiber dosage of mono steel is varied from 0.0, 0.5, 0.75, 1.0 and 1.25%, fiber dosage of mono PP varied from 0.0, 0.1, 0.2, 0.3 and 0.4%. Also, three types of hybrid combinations were considered to prepare HFRC i.e. SF 25% + PP 75%, SF 50% + PP 50% and SF 75% + PP 25% at a total fiber volume fraction of 0.25, 0.5 and 0.75% to evaluate the properties of hybrid fiber reinforced concrete. Static mechanical properties like compressive strength, split tensile strength and flexural strength were determined for two different grades of concrete (M25 and M50) with the inclusion of above mentioned fiber volume fractions. Dynamic properties like natural frequency and damping ratios were also determined for the same mixes. Later stage RC beams with the inclusion of optimum dosage of mono and hybrid fibers have been cast and assessed the static and dynamic behavior. Dynamic behavior of undamaged and damaged RC beams strengthened with mono steel and PP fibers and also hybrid fibers (steel and PP) was investigated using impact hammer technique. The envelopes of the FRF's obtained by the experimental modal analysis and the variation in natural frequency and damping values are determined from the curve fitted FRF's using modal analysis software and the results are correlated with the damage level.

- **Phase-II:**Second phase of investigation is carried out to develop engineered cementitious composite (ECC), it is required to study the mechanical properties of ECC with different percentage variation of mono steel and polyvinyl alcohol (PVA) fibers and hybrid fibers. ECC is developed using mono steel and PVA fibers at 2% fiber volume fraction with different combinations i.e. SF 1% + PVA 1%, SF 0.5% + PVA 1.5% and SF 1.5% + PVA 0.5% at a total fiber volume fraction of 2% and the results are compared with the ECC without fibers. For these mixes compressive strength, flexural strength and uni-axial tensile strength were obtained. From the mechanical properties results, the optimum dosage of hybrid fiber to prepare ECC is achieved and the same is used in the further study. Later stage FGRC beams with layered ECC material in tension zone have been cast and tested to assess its static and dynamic behavior. Static behavior of FGRC beams is assessed by testing the beam under four point monotonic loading. Dynamic behavior at undamaged and different damage levels is carried out using impact hammer technique under free-free condition.

- **Phase-III:** In this phase, modeling of RC beams reinforced with mono steel and PP fibers using FEM is done for the undamaged condition of the beams; further modeling is done for RC beam with hybrid fibers and FGRC beams using ECC. The results obtained by numerical study are compared with the experimental values.

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 General

This chapter consistsof information regarding concrete material, mix proportions, casting, curing and methodology for testing of concrete specimens incorporated with mono fibers, hybrid fiber and engineered cementitious composite materials.

4.2 Materials used

The properties of various materials used in this investigation are as follows,

4.2.1 Cement

Cement is a binder material which used as basic ingredient of concrete or mortar. Ordinary Portland cement (OPC) of 53 grade confirming to IS:269-2015 was used in the study which has specific gravity of 3.15 and bulk density of 1140kg/m^3.

4.2.2 Fly-ash

Fly-ash is a by-product obtained from the burning of pulverized coal in electric power generation plants. Fly-ash is a fine powder which is 100 times finer than Portland cement and chemically reacts with the calcium hydroxide released in the hydration process of cement and improves the properties of concrete. In this experimental investigation, class-F fly-ash was added at 10% and 12% by weight in order to attain the desired properties of concrete in fresh and hardened state.

4.2.3 Micro-silica

Micro-silica is an amorphous polymorph of silicon dioxide. It is one of the most commonly used mineral admixture composed of very fine solid glassy spheres of silicon-di-oxide particles with an average size of 150nm and a specific surface area of 20m^2/g. Micro-silica is a locally available material which was used as the supplementary cementitious material with the constant micro-silica to cement ratio in order to produce ECC mortars with and without hybrid fibers. Micro-silica used in this study is shown in Figure 4.1.

Figure 4.1Micro-silica

4.2.4 Silica Sand

Silica sand is also known as manufactured sand which has been made according to the requirements of building construction. It isone of the most commonly used sand and also made either by crushing sandstone or taken from naturally occurring locations such as beaches and rivers. Maximum and average grain sizes of silica sand used in the mixtures are of 0.2mm and 0.5mm, respectively in order to replace fine aggregates for the preparation of ECC mortars. Silica sand used in this study is shown in Figure 4.2.

4.2 (a) Silica sand of size 0.5mm **4.2 (b) Silica sand of size 0.2mm**

Figure 4.2Silica sand

4.2.5 Fine Aggregate

Locally available river sand confirming to IS 383 (BIS, 2016) was used, the specific gravity and fineness modulus of fine aggregates are 2.68 and 2.64 respectively.

4.2.6 Coarse Aggregate

Well graded crushed granite confirming to IS 383(BIS, 2016) was used in the experimental investigation having specific gravity and fineness modulus are 2.78 and 7.1 respectively.

4.2.7 Water

Water has significant impact on cement hydration. Potable water was used for casting and curing of concrete.

4.2.8 Super-plasticizer

In this experimental investigation, in order to attain proper workability in fresh ECC mortar matrix after the addition of fibers, poly-carboxylate ether based super-plasticizers (HRWRA-High range water reducing admixture) and Hydroxypropyl methyl cellulose (HPMC), aviscosity modifying agent were used according to ASTM C-494. The viscosity of HPMC is related to the size of the molecular weight, and the larger the molecular weight is the higher the viscosity will be mortar mixture. The addition of HPMC in mortar enhances the properties such as workability, water-retaining property, adhesive property, slip resistance and package.

4.2.9 Fibers

Non-metallic fibers of polypropylene (PP), poly vinyl alcohol (PVA) and metallic fibers of hooked end steel fibers were used. Fibers used in the study are shown in Figure 4.3. Physical and material properties of the fibers used are shown in Table 4.1.

4.3 (a) Polypropylene **4.3 (b) Polyvinyl alcohol** **4.3 (c) Hooked-end steel**

Figure 4.3Fibers used in the study

Table 4.1 Physical and Material Properties of Steel, PP and PVA fibers

Fiber type	**Shape of fibers**	**Length (mm)**	**Diameter (mm)**	**Aspect ratio**	**Tensile strength (MPa)**	**Modulus of elasticity (GPa)**	**Density (kg/m^3)**	**% of elongation**
Steel	Hooked-end	35	0.5	70	1100	210	7850	2
PP	Straight	12	0.038	315	420	5	990	11
PVA	Straight	12	0.04	300	1600	41	1290	5.3

4.3 Concrete Mix Proportions

4.3.1 Mix Design for Fiber Reinforced Concrete

The purpose of the study was to investigate the static and dynamic performance of fiber reinforced concrete and functionally graded reinforced concrete beams using engineered cementitious composites. The concrete mix design was done according to Indian Standard code of practice (IS: 10262-2009). In this experimental investigation, two different grades of concretes M25 and M50 were used. The mix proportions of M25 and M50 grades of concrete are illustrated in Table 4.2.

Table 4.2 Mix proportions of M25 and M50 grades of concrete

Designation	Cement (kg/m^3)	Fly-ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)
M_{25}	380	38	720	1101	180
M_{50}	412	50	643	1212	142

4.3.2Mix Design for Engineered Cementitious Composites

The mix proportions of the standard ECC mixture was arrived and modified in the present experimental investigation through several trials. The mix proportions of ECC is tabulated in Table 4.3 which has been used to study the behavior of functionally graded concrete beams incorporated with different layer thickness of ECC material in the tension zone.

Table 4.3 Mix proportions of ECC

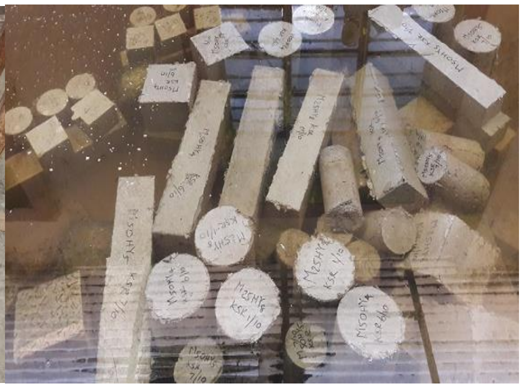
Designation	Cement (kg/m^3)	Micro-silica (kg/m^3)	Silica sand 0.5mm (kg/m^3)	Silica sand 0.2mm (kg/m^3)	Water (kg/m^3)	HRWRA (kg/m^3)	HPMC (kg/m^3)
ECC	967	251	405	270	365.4	7	0.8703

4.4 Mixing, Casting and Curing of specimens

4.4.1 Casting of Specimens for Phase-I (SFRC, PPFRC and HFRC)

The mixing process started with the dry mixing of the coarse and fine aggregates for one minute. Later cement was added and then the fibers were added to the mixture and again mixing was continued for another two more minutes till the fibers were dispersed properly. Super-plasticizer mixed with water was added to the dry mix and the mixing of all materials continued for two more minutes. Then the fresh concrete was transformed into the steel molds such as cubes, cylinders and prisms and was compacted thoroughly. All specimens were demolded after 24 hours and then immersed in water at room temperature for 28 days. Mix preparation, casting and curing of concrete specimens are shown in Figure 4.4.

4.4 (a) Dry mix of concrete **4.4 (b) Wet mix of concrete**



4.4 (c) Casting of specimens **4.4 (d) Curing of specimens**

Figure 4.4Mix preparations, casting and curing of concrete specimens

4.4.2 Casting of Specimensfor Phase-II (ECC)

Initially, cement, micro-silica and silica sand were mixed thoroughly for two minutes. Then, water is introducedalong with HRWRA (super-plasticizers) and mixed for another three minutes. Then, the non-metallic PVA fibers and metallic steel fibers were added into the mortar and the mixing was continued until the fibers were uniformly dispersed.Then, the fresh ECC mortar was kept into the steel molds without compaction to evaluate the mechanical properties.All the specimens were demolded after 24hours and then cured in water for 28 days.Figure 4.5 shows the preparation, casting and curing of ECC specimens.

4.5 (a) Dry mix of ECC

4.5 (b) Wet mix of ECC

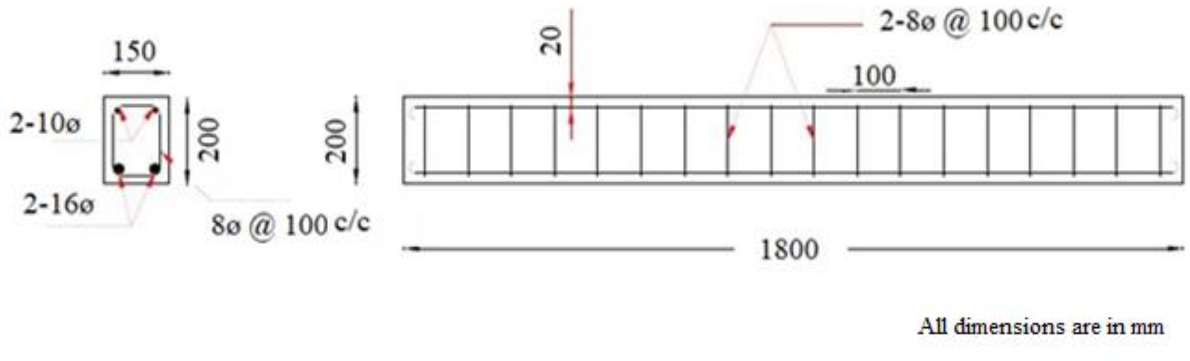
4.5 (c) Casting of

4.5 (d) Curing of

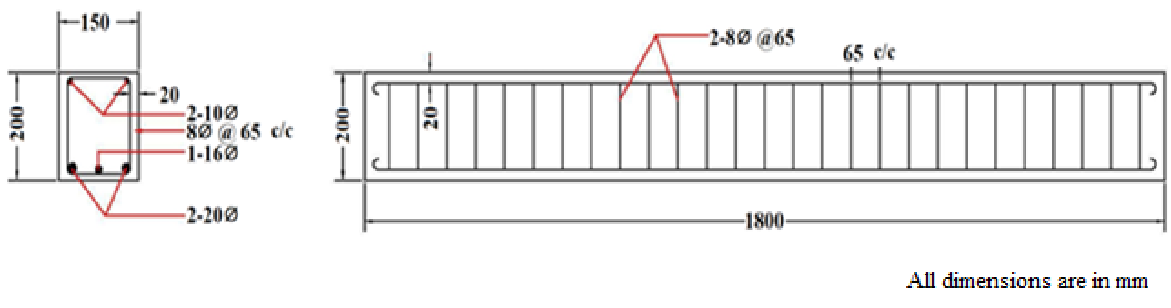
Figure 4.5Preparation, casting and curing of ECC specimens

4.5 Casting of RC and FGRC Beam

In this experimental investigation, reinforced concrete beams of length 1800mmand cross-section 150mm wide and 200mm deep were cast. All the beams have been designed as under-reinforced sections. Each beam is reinforced with HYSD bars Fe500 grade steel and the detailing of RC beams is shown in Figure 4.6 corresponds to M25 and M50 grade concrete. Figure 4.7 shows the reinforcement cages prepared for casting. Total 30 beams were cast and tested.



4.6 (a) Detailing of RC beams – M25 concrete



4.6 (b) Detailing of RC beams – M50 concrete

Figure 4.6 Reinforcement detailing of RC beams

Figure 4.7 Reinforcement cages prepared for casting

Mono fibers (steel and PP) and hybrid fibers were added in RC beams to evaluate the effectiveness of fibers against the damage induced. Figure 4.8 shows the casting of RC beams. Forcasting of FGRC beams, ECC layers incorporated with steel and PVA fibers was cast first at the bottom (tension zone) of the mould. After 55 minutes, concrete of M25 grade or M50 grade was added then in order to circumvent mixing of two materials as well as to create proper bonding between two layers. Figure 4.9 shows the preparation sequence of FGRC beams. Figure 4.10 shows the curing of RC and FGRC beams.

4.8 (a) Steel moulds for casting of RC beam

4.8 (b) Finished RC beam

Figure 4.8 Casting of RC beams

4.9 (a) Reinforcement cage in the mould **4.9 (b) ECC – after first layer of casting**

4.9 (c) Finished FGRC beam surface **4.9 (d) Demolded FGRC beam**

Figure4.9 Preparation sequences of FGRC beams with ECC

Figure 4.10Curing of RC and FGRC beams

4.6Testing of Specimens

In the present investigation, tests were conducted to evaluate the mechanical behavior of SFRC, PPFRC and HFRC. Tests carried out to determine compressive strength, split tensile strength and flexural strength of respective mixes. Tests on ECC have also been carried out to determine compressive strength, flexural strength and uni-axial tensile strength. All tests were conducted in accordance with the bureau of Indian standard codes of practice.

4.6.1 Static Experimental Test Methods for FRC

The static test methods for evaluating performance of mono and hybrid fiber reinforced concrete have been conducted on hardened concrete specimens.

4.6.1.1 Compressive strength test

To evaluate the performance of fiber reinforced concrete composite, three cubes of standard size (150mmx150mmx150mm) were cast for each type of mixture and tested after 28 days of its curing period under direct compression using 3000kN compression testing machine in accordance with bureau of Indian standard code (IS 516:1959). Initially, the cube specimens were loaded in a testing machine under load control, which has applied perpendicularly to the direction of casting in order to avoid eccentricity of loading. Typical view of compression test setup is shown in Figure 4.11.

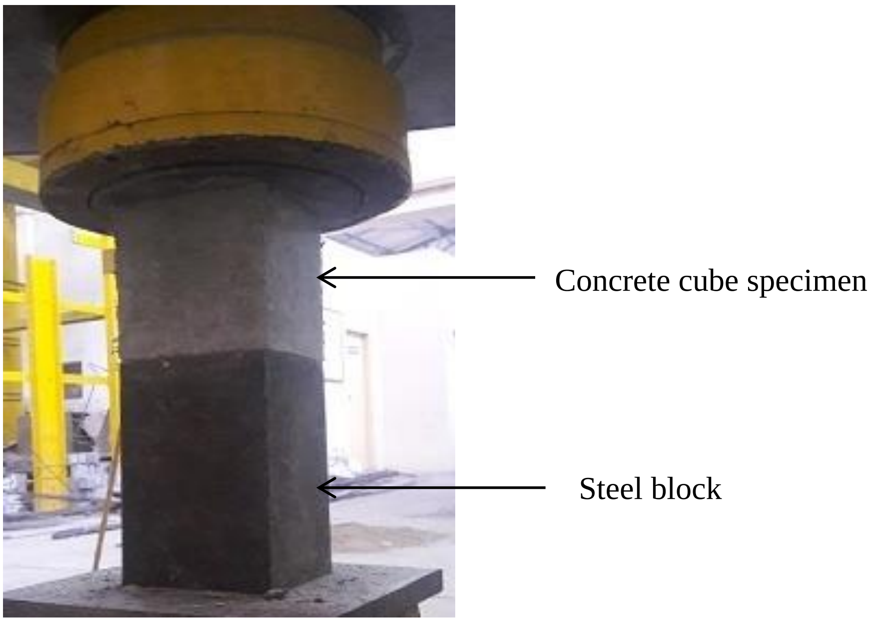


Figure 4.11Compression strength test setup

4.6.1.2 Splitting tensile strength test

Split tensile strength is one of the basic and important properties of concrete. A method of determining the tensile strength of concrete using a cylinder which splits across the vertical diameter, it is an indirect method to assess the tensile strength of concrete. To evaluate the composite performance of fiber reinforced concrete, three cylinders of standard size (150mm diameter and 300mm height) for each mixture were cast and tested under compression machine of 3000kN capacity. The load was applied without shock and increased continuously at a nominal rate until failure. Split tensile strength test setup is shown in Figure 4.12.

Figure 4.12Split tensile strength test setup

4.6.1.3 Flexural strength test

In order to investigate the flexural performance of fiber reinforced concrete, four-point bending test was carried out for each percentage variation of fiber in concrete mixtures. The specimen of size (500mmx100mmx100mm) was used to obtain flexural strength. Experimental setup for flexural strength is shown in Figure 4.13, which is recommended in bureau of Indian standard code of practice (IS 516: 2004), a standard test method for flexural strength of concrete. All specimens were tested under a dynamic universal testing machine with a capacity of 1000kN and specimens were loaded until failure. The test is carried out in displacement control at a rate of 0.20mm/min.

Figure 4.13Flexural strength test setup

4.6.2 Tests performed on ECC

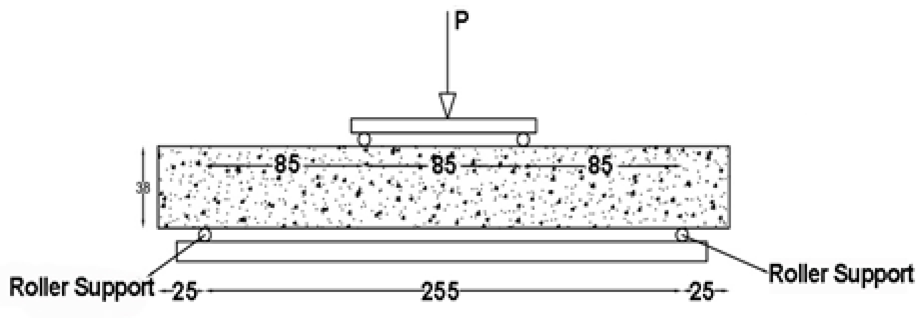
4.6.2.1 Compressive strength test

To evaluate the performance of ECC incorporated with mono and hybrid fibers, three cubes of standard size (70.6mmx70.6mmx70.6mm) were cast for each type of mixture and tested in compression testing machine of 3000kN capacity after 28 days in accordance with bureau of Indian standard code (IS 516- 2004). The compressive strength test setup is shown in Figure 4.14 for ECC mortar specimens.

Figure 4.14 Compressive strength test setup of ECC mortar specimen

4.6.2.2 Flexural strength test

To characterize the behavior of non-fibrous, mono-fiber and hybrid fiber reinforced cementitious composites; four-point bending test has been conducted after 28 days of curing period. The specimen of size (305mmx76mmx38mm) was used in this experimental program. The experimental test setup is shown in Figure 4.15. All prismatic specimens have been tested under displacement control at a loading rate of 0.25mm per minute until failure of specimen using dynamic UTM of capacity 1000kN.



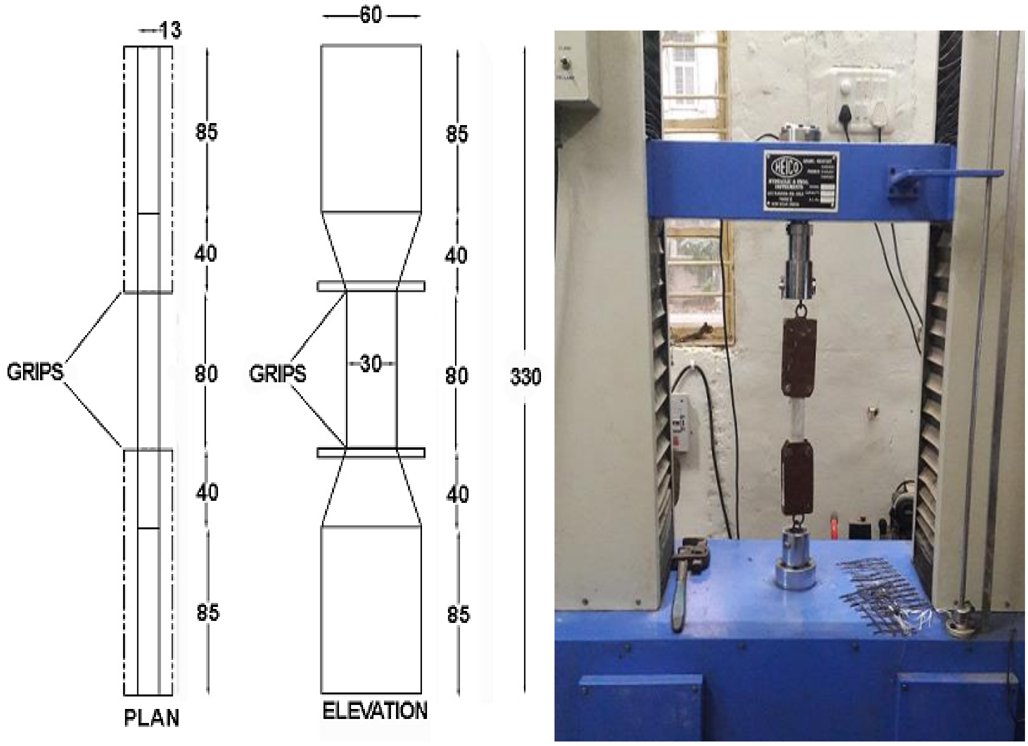
4.15 (a) Schematic view

4.15 (b) Test setup

Figure 4.15Flexural strength test setup of ECC mortar specimen

4.6.2.3 Uni-axial tensilestrength test

A uni-axial tensile test was carried out to evaluate the behavior of ECC under direct tension. Adog bone specimens of gauge length 80mm and cross-section of 30mmx13mm were cast and tested for tensile strength of ECC. Three similar dog bone shape specimens of aforementioned size were cast and tested. The specimen was fixed between specially designed grips at both the ends as shown in Figure 4.16. The specimen was attached to the machine with the help of two J-rings provided in the top as well as at the bottom end for applying tensile force. The gauge length of the specimen is 80mm.



4.16 (a) Specimen details **4.16 (b) Test setup**

Figure4.16Uni-axial tensile strength test setup of ECC mortar specimen

4.6.3 Static Load Tests of RC and FGRC Beams

This test is carried out to evaluate the flexural behavior of RC beams strengthened steel fiber, polypropylene fiber and hybrid fibers and FGRC beams.All beams were tested under flexure using testing machine of 1000kN capacity. Total 30 RC beams were cast and tested with the optimized dosage of mono steel, mono polypropylene, hybrid fibers and ECC material. Among 30 RC beams, 6 RC beams were cast without fibers and the remaining 24 RC beams were classified into 6 different categories, where each category comprises of 4 RC beams which were cast using mono steel fiber, mono PP, hybrid fiber, ECC-1 layer, ECC-2 layers and ECC-3 layers respectively (i.e. 4 SFRC, 4 PPFRC, 4 HFRC, 4 FGRC-ECC-1, 4 FGRC-ECC-2 and 4 FGRC-ECC-3). The beam specimens were placed on the steel supports with rollers on each side and the load was applied through two-point loading system as shown in Figure 4.17. Three dial gauges were used to measure the deflection atmid span point and locations corresponding to loading points. The load is applied till the specimen fails under flexure.During the testing load, corresponding deflections were measured and also cracks pattern is marked on the surface of the specimen at different load increments.

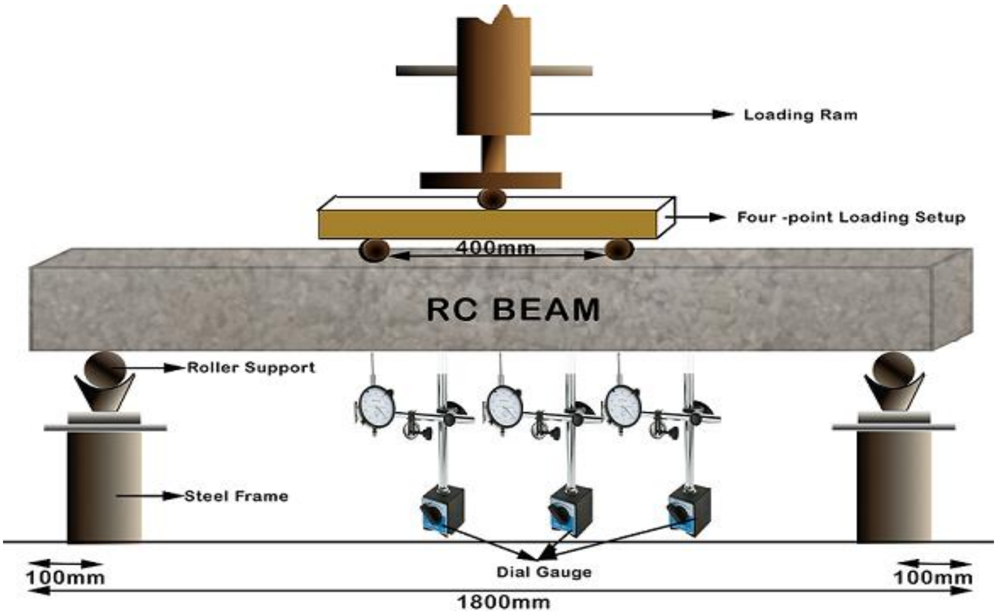


Figure 4.17a Schematic view of static flexuretest setup of RC beam

Figure 4.17bTesting of RC beam under flexure

4.6.4 Dynamic Test of RC and FGRC Beams

It is necessary to take into consideration the dynamic properties of concrete in the analysis and review of the safety of important structures such as high-rise buildings, bridges and dams etc. In general, direct determination of dynamic properties of concrete requires loading representative or core samples to failure, hence evaluation of dynamic properties of concrete will get delayed. Therefore, non-destructive testing like impact hammer technique implies very useful to carry out the response of a structure without damaging or altering the structure being tested. Also, it will be useful to monitor the condition of structures. Therefore, impact hammer technique is used in the present investigation to determine the dynamic properties of beams and also to detect the damage induced in the beams.

In this experimental work, dynamic testing is carried out with impact hammer for obtaining the dynamic characteristics such as natural frequency, damping and mode shape.The top surface of the beam was marked with excitation points. The number of excitation points was selected such that they represent the vibration modes of interest, beams were tested under free-free condition using impact hammer. The force is applied to the beam with an impact hammer fitted with force transducer and the response is measured using piezoelectric accelerometer. In this case, an accelerometer had a fixed position at one node and the impact hammer was roved along the excitation points. At each point impact test was repeated '3' times in order to avoid statistical errors. The schematic view of experimental setup for dynamic testing is shown in the Figure 4.18.The instruments used in this study were the PCB impact hammer of weight 320g having sensitivity 0.00225V/N for exciting the specimens as shown in Figure 4.19, an accelerometer of weight10g having sensitivity 1000mV/g as shown in Figure 4.20 to measure the response and 8-channel OROS dynamic analyzer used as shown in Figure 4.21for obtaining FRFs and coherence functions. The mass and tip hardness of the impact hammers were varied to give the desired magnitude and duration of the force pulse at all test locations on the beam.

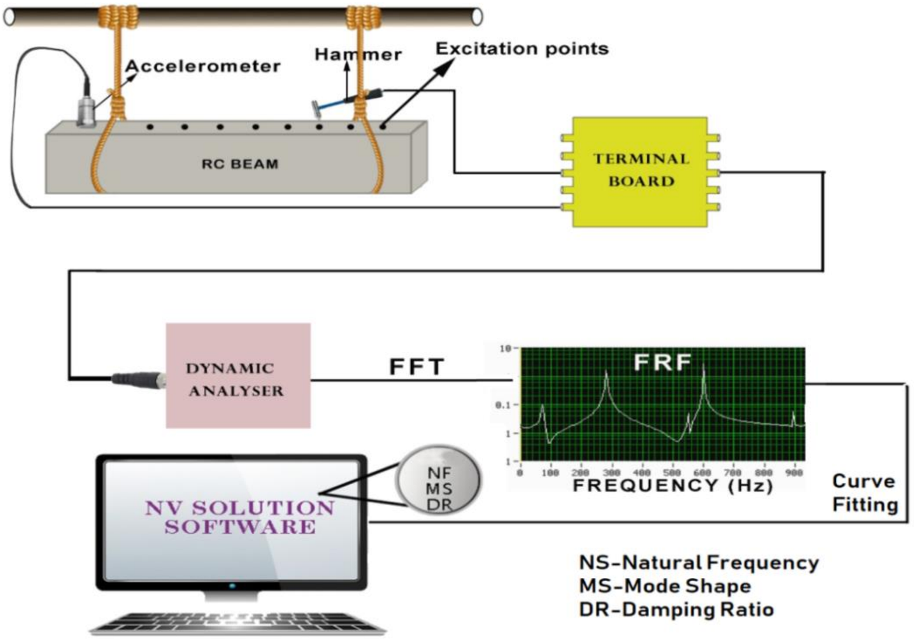


Figure 4.18 Schematic view of dynamic test setup

Figure 4.19Impact hammer **Figure 4.20Accelerometer**

Figure 4.21OROS dynamic analyzer

In order to investigate the dynamic characteristics of mono and hybrid fiber reinforced concrete, prisms of 500mmx100mmx100mm size have been cast and tested. A prismatic beam specimen was cast and tested for each concrete mixture to assess their fundamental natural frequencies and damping ratios. Each specimen has been marked with six excitation points along symmetric centre line of the specimen. All the specimens were tested in a free-free condition by keeping the accelerometer at second node which was fixed and the specimens were excited using an impact hammer at all other nodes, the corresponding FRF's were recorded to evaluate the natural frequency, damping ratio and mode shape.Figure 4.22 shows the screen shot of dynamic testing. The Frequency Response Function (FRF) obtained from the dynamic analyzer is fed into smart office-NV solution software to curve fit the FRF. Curve fitted FRF is shown in Figure 4.23 obtained from the modal analysis software from which natural frequency, damping ratio and mode shapes were obtained.

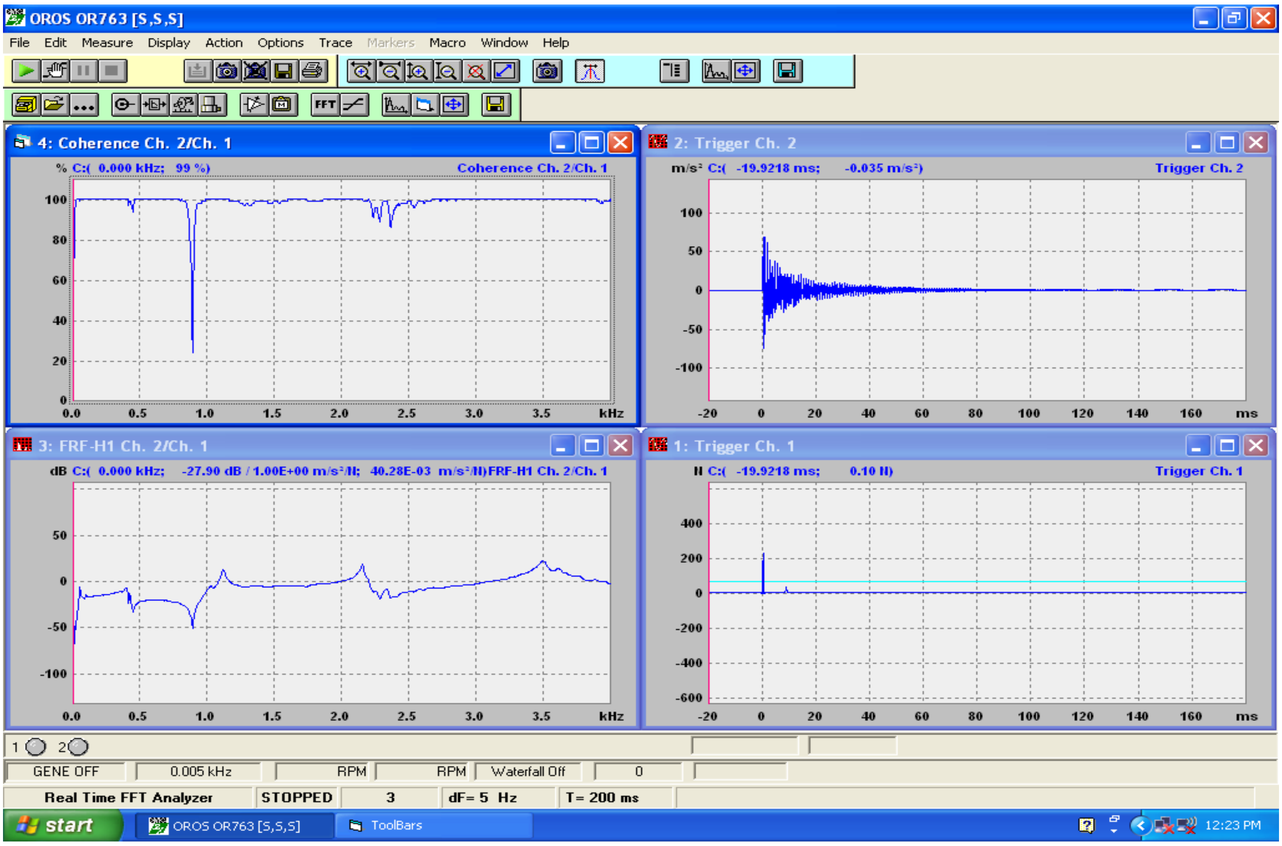


Figure 4.22Screen shot of dynamic testing

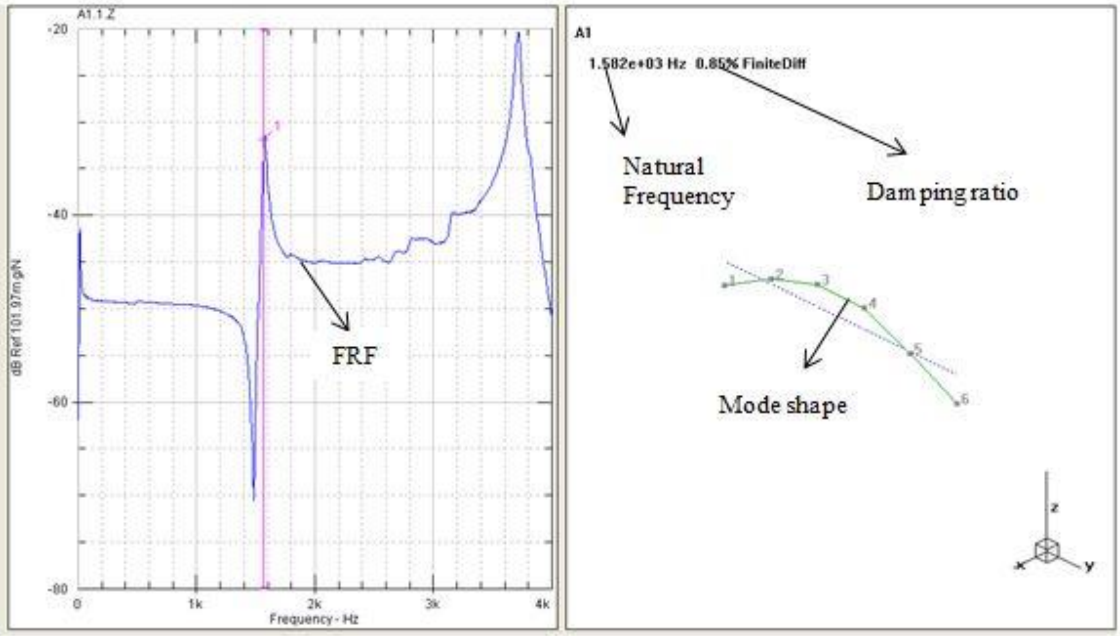


Figure 4.23Frequency response function with first mode shape

Modal testing was also performed on both undamaged and damaged RC beam specimens using impact hammer technique in free-free condition. Aforementioned procedure has been followed to assess the dynamic characteristics of RC beams from undamaged state to final damage state. Initially,30 excitation points were marked on the surface of the specimen and all specimens were tested in free-free condition by keeping the accelerometer at eighth node point and the specimen was excited using an impact hammer at all the points and the corresponding FRF's were recorded to evaluate the natural frequency, damping ratio and mode shapefrom undamaged state to final damage state. At each damage state, specimen is unloaded and the dynamic testing is carried out. The damage states designated as D_0 (undamaged condition), D_1 (damage at 50% of ultimate load), D_2 (damage at 70% of ultimate load) and D_3 (damage at 90% of ultimate load) of respective beam specimens. Later the dynamic characteristics were compared from undamaged state to final damaged state to achieve the correlation between variations in dynamic characteristics with the damage induced.

CHAPTER 5

PHASE-I: MECHANICAL BEHAVIOR AND DYNAMIC ASSESSMENT OF MONO AND HYBRID FIBER REINFORCED CONCRETE

5.1 General

The performance of mono fiber such as steel and polypropylene (PP) and hybrid fiber reinforced concrete under static and dynamic loading are presented in this chapter. This chapter is divided into two main parts. The first part focuses on the evaluation of mechanical properties such as compressive strength, split tensile strength and flexural strength of mono and hybrid fiber reinforced concrete. In addition to that, dynamic properties such as natural frequencies, damping ratios and mode shapes have also been determined. The second part consists of assessment of static and dynamic behavior of reinforced concrete (RC) beams strengthened with mono and hybrid fibers. The performance of mono and hybrid fiber reinforced concrete beams is compared with control RC beams.

The nomenclature of the mix Id's and amount of fibers used for mono and hybrid FRC are presented in Table 5.1 and Table 5.2, respectively.

Table 5.1 Nomenclature and fiber dosages of mono FRC

Mix No	Mix designation	Fiber dosages (%)	
		Steel Fiber (SF)	Polypropylene Fiber (PP)
1	M_{C}	-	-
2	$M_{SF0.5}$	0.50	-
3	$M_{SF0.75}$	0.75	-
4	$M_{SF1.00}$	1.00	-
5	$M_{SF1.25}$	1.25	-
6	$M_{PP0.1}$	-	0.10
7	$M_{PP0.2}$	-	0.20
8	$M_{PP0.3}$	-	0.30
9	$M_{PP0.4}$	-	0.40

Nomenclature
"M_{C}"represents control concrete. "$M_{SF0.5}$" – SF represents type of fiber and 0.5 represents the fiber dosage in terms of volume fraction of concrete.

Table 5.2Nomenclature and fiber dosages of HFRC

Mix No	Mix designation	Total fiber dosage (%)	Steel Fiber (%)	PP Fiber (%)
1	$M_{HY0.25(1)}$	0.25	0.0625 (25%)	0.1875 (75%)
2	$M_{HY0.25(2)}$		0.125 (50%)	0.125 (50%)
3	$M_{HY0.25(3)}$		0.1875 (75%)	0.0625 (25%)
4	$M_{HY0.5(1)}$	0.5	0.125 (25%)	0.375 (75%)
5	$M_{HY0.5(2)}$		0.25 (50%)	0.25 (50%)
6	$M_{HY0.5(3)}$		0.375 (75%)	0.125 (25%)
7	$M_{HY0.75(1)}$	0.75	0.1875 (25%)	0.5625 (75%)
8	$M_{HY0.75(2)}$		0.375 (50%)	0.375 (50%)
9	$M_{HY0.75(3)}$		0.5625 (75%)	0.1875 (25%)

Nomenclature
"M_{HY}" – represents hybrid fiber. "0.25" – represents the fiber dosage in terms of total volume fraction of 0.25%. "(1) – represents the type of hybrid combination (25% SF + 75% PP). "(2) - represents the type of hybrid combination (50% SF + 50% PP). "(3) - represents the type of hybrid combination (75% SF + 25% PP).

5.2 Results and Discussions

5.2.1 Compressive Strength of Mono and Hybrid FRC

The effect of fibers at varied fiber volume fraction on the performance of composites has been obtained. The compressive strength of mono FRC and its strength effectiveness was compared with control mix. The results are presented in Table 5.3. Results comprise of average of three similar specimens tested for each mixture.

Table 5.3Compressive strength of mono FRC

Mix designation	M25		M50	
	f_{ck} (MPa)	Percentage increase (%)	f_{ck} (MPa)	Percentage increase (%)
M_C	34.87	-	57.53	-
$M_{SF0.5}$	36.34	4.2	59.41	3.3
$M_{SF0.75}$	38.24	9.7	61.85	7.5
$M_{SF1.00}$	***39.12***	***12.2***	***62.93***	***9.4***
$M_{SF1.25}$	38.45	10.3	61.25	6.5
$M_{PP0.1}$	36.09	3.5	58.93	2.4
$M_{PP0.2}$	36.52	4.7	60.58	5.3
$M_{PP0.3}$	***37.7***	***8.1***	***61.45***	***6.8***
$M_{PP0.4}$	36.26	4.0	59.84	4.0

f_{ck} – Compressive strength

Compressive strength results emphasize that the increase in volume fraction of steel and PP fibers led to increase in compressive strength up to 1% and 0.3% fiber volume fraction respectively. The reason might be attributed to the ability of fibers to restrain internal cracks in composite matrix. The maximum improvement in compressive strength of SFRC was about 12.2% and 9.4% for M25 and M50 grade concrete respectively compared with non-fibrous concrete. These maximum values of compressive strength have been attained for the steel fiber at 1% fiber volume fraction. Similar trend was observed by *Bywalski et al. (2015).*

Also, the maximum compressive strength of PPFRC was increased by about 8.1% and 6.8% for M25 and M50 grade of concrete respectively compared with non-fibrous concrete. Maximum values of compressive strength have been attained for PPFRC at 0.30% fiber volume fraction as shown in Table 5.3. Compressive strength results shows that the addition of steel fibers performed better compared to that of PP fibers and control concrete.

The compressive strength of HFRC and its strength effectiveness was compared with control mix. The results are presented in Table 5.4. The mechanical property test results of HFRC specimens shows that the addition of hybrid fibers (steel and PP) resulted an increase of compressive strength than that of non-fibrous as well as mono FRCs. But the overall performance of HFRC in compressive strength is not significant. Test results also stipulated that, the compressive strength of HFRCs increased with an increase in total fiber volume.

Table 5.4Compressive strength of HFRC

Mix designation	M25		M50	
	f_{ck} (MPa)	Percentage increase (%)	f_{ck} (MPa)	Percentage increase (%)
$M_{C\text{-control mix}}$	34.87	-	57.53	-
$M_{HY0.25(1)}$ -25%SF&75%PP	35.96	3.1	59.63	3.7
$M_{HY0.25(2)}$ -50%SF&50%PP	36.78	5.5	60.25	4.7
$M_{HY0.25(3)}$ -75%SF&25%PP	37.59	7.8	60.96	6.0
$M_{HY0.5(1)}$ -25%SF&75%PP	38.92	11.6	61.84	7.5
$M_{HY0.5(2)}$ -50%SF&50%PP	39.53	13.4	62.85	9.2
$M_{HY0.5(3)}$ -75%SF&25%PP	***40.16***	***15.2***	***63.86***	***11.0***
$M_{HY0.75(1)}$ -25%SF&75%PP	39.63	13.7	61.74	7.3
$M_{HY0.75(2)}$ -50%SF&50%PP	38.76	11.2	60.83	5.7
$M_{HY0.75(3)}$ -75%SF&25%PP	38.09	9.2	60.19	4.6

From Table 5.4, it is observed that an increase in compressive strength of HFRC up to total fiber volume fraction 0.5% for the mixture $M_{HY0.5(3)}$containing 75% of steel and 25% of PP fibers. Nonetheless, any further increasing in the fiber volume fraction decreases the compressive strength. Also by increasing steel fiber and decreasing PP fiber in a total fiber volume fraction, compressive strength of HFRCs increases up to 0.5% fiber volume fraction. The maximum percentage strength improvement of HFRC is 15.2% for M25 and 11% for M50 grade concrete for the mixture $M_{HY0.5(3)}$. The reason may be imputed that the steel and PP fibers can arrest macro and micro cracks respectively developed in the interface between coarse aggregate and mortar and leads to an increase of compressive strength. Similar trend was observed by *Mastali et al. (2018)*.

5.2.2Split Tensile Strength of Mono and Hybrid FRC

Unlike concrete in compression, strength effectiveness of fiber is more in split tensile strength of the concrete. Results for the split tensile strength and percentage strength improvement of mono FRC compared to control concrete are presented in Table 5.5.

Table 5.5Split tensile strength of mono FRC

Mix designation	**M25**		**M50**	
	f_{st} (MPa)	**Percentage increase (%)**	**f_{st} (MPa)**	**Percentage increase (%)**
M_C	3.39	-	4.36	-
$M_{SF0.5}$	3.81	12.4	4.97	14.0
$M_{SF0.75}$	4.05	19.5	5.33	22.2
$M_{SF1.00}$	***4.53***	***33.6***	***5.64***	***29.4***
$M_{SF1.25}$	4.29	26.5	5.11	17.2
$M_{PP0.1}$	3.53	4.1	4.52	3.7
$M_{PP0.2}$	3.84	13.3	4.77	9.4
$M_{PP0.3}$	***4.21***	***24.2***	***5.36***	***22.9***
$M_{PP0.4}$	3.62	6.8	4.93	13.1

f_{st} – Split tensile strength

The splitting tensile strength was determined for different fiber dosages and also for non-fibrous concrete at an age of 28-days. From the results the maximum load which was taken by the cylinder were considered as splitting tensile strength evaluation.At this load the specimens were broken into two pieces for non-fibrous concrete whereas for SFRC, PPFRC and HFRC specimens were held together even after cracks were formed and the test was continued up to more than the maximum load. The test results indicated that the addition of steel fibers exhibited a better performance than that of control concrete. From the experimental results, it has been observed that the addition of steel fiber increases the split tensile strength compared with control concrete and similar trend is observed for PPFRC composites. The maximum percentage strength improvement of mono SFRC is 33.6% and 29.4% respectively for M25 and M50 grade concrete at 1% fiber dosage whereas for PPFRC it is 24.2% and 22.9% respectively for M25 and M50 grade concrete at 0.3% fiber dosage. There is a decrease in strength observed with more fiber dosage; this may be due to the cement matrix replaced by more number of fibers and also due to poor workability. From the Table 5.5 it is observed that strength effectiveness of metallic fibers is more compared to non-metallic fibers. This may be due to metallic fibers are longer in length and having high modulus of elasticity compared to non-metallic PP fibers.

Results of split tensile strength and its percentage strength improvement of HFRC compared to control concrete are presented in Table 5.6. It is observed that the percentage strength improvement of HFRC is maximum at 0.5% total fiber volume fraction for the mix $M_{HY0.5(3)}$with the combination of 75% of steel and 25% of PP fibers for both the grades of concrete. There is a decrease in strength observed with more fiber dosage; this may be due to the less confining effect provided by the fibers because of the higher volume or weight of fibers available in the matrix.

Table 5.6Split tensile strength of HFRC

Mix designation	M25		M50	
	f_{st} (MPa)	Percentage increase (%)	f_{st} (MPa)	Percentage increase (%)
M_C	3.39	-	4.36	-
$M_{HY0.25(1)}$ -25%SF&75%PP	3.84	13.3	4.82	10.6
$M_{HY0.25(2)}$ -50%SF&50%PP	4.26	25.7	5.26	20.6
$M_{HY0.25(3)}$ -75%SF&25%PP	4.47	31.9	5.89	35.1
$M_{HY0.5(1)}$ -25%SF&75%PP	4.68	38.1	6.08	39.4
$M_{HY0.5(2)}$ -50%SF&50%PP	4.89	44.2	6.14	40.8
$M_{HY0.5(3)}$ -75%SF&25%PP	***5.12***	***51.0***	***6.54***	***50.0***
$M_{HY0.75(1)}$ -25%SF&75%PP	4.76	40.4	6.24	43.1
$M_{HY0.75(2)}$ -50%SF&50%PP	4.62	36.3	5.08	16.5
$M_{HY0.75(3)}$ -75%SF&25%PP	4.36	28.6	4.92	12.8

The maximum percentage strength improvement of HFRC at 0.5% total fiber volume fraction is 51% for M25 and 50% for M50 grades of concrete. The results indicated that the addition of hybrid fibers exhibited a better performance than that of control concrete without fibers. This is may be due to the combination of hooked end steel and PP fibers together prevented the initiation and propagation of micro as well as macro cracks.

5.2.3Flexural Strengthof Mono and Hybrid FRC

Flexural strength of mono FRC and its strength improvement compared with control concrete are presented in Table 5.7. The four point bending tests were carried out on three similar prismatic specimens for each percentage variation of fiber dosage in order to evaluate the flexural strength. It is observed that flexural strength of mono FRC is more compared to control concrete.

Table 5.7Flexural strength of mono FRC

Mix designation	M25		M50	
	f_{ft} (MPa)	Percentage increase (%)	f_{ft} (MPa)	Percentage increase (%)
M_{C}	4.74	0.0	5.34	0.0
$M_{SF0.5}$	5.42	14.3	6.32	18.4
$M_{SF0.75}$	6.04	27.4	6.89	29.0
$M_{SF1.00}$	***6.76***	***42.6***	***7.43***	***39.1***
$M_{SF1.25}$	6.28	32.5	6.98	30.7
$M_{PP0.1}$	5.02	5.9	5.61	5.1
$M_{PP0.2}$	5.51	16.2	6.12	14.6
$M_{PP0.3}$	***6.07***	***28.1***	***7.13***	***33.5***
$M_{PP0.4}$	5.39	13.7	6.23	16.7

f_{ft}- Flexural strength

Percentage strength improvement in mono SFRC is 42.6% for M25 and 39.1% for M50 concrete at an optimum dosage of 1% fiber volume fraction whereas percentage increase of flexural strength in PPFRC is 28.1% for M25 and 33.5% for M50 at an optimum dosage 0.3% fiber volume fraction. Percentage increase of flexural strength is more for SFRC compared PPFRC specimens. The reason may be due to higher stiffness and anchorage mechanism of hooks at end of steel fiber delayed the propagation of cracks. Similar kind of observation was found by *Mohammedhosseini et al. (2017)*.

Results of flexural strength of HFRC and its strength improvement compared with control concrete are presented in Table 5.8. Fiber effect of flexural strength is more compared to compressive strength and split tensile strength due to fibers in concrete delay the crack formation and propagation. From Table 5.8, it is observed that increase in flexural strength is more with the fiber hybridization compared to mono FRC. This is because of shorter length PP fibers control the growth of plastic shrinkage cracks at early stage of concrete and longer length steel fiber prevented the propagation of cracks further. The optimum hybrid combination is achieved at 0.5% total fiber volume fraction with the combination of 75% of steel and 25% of PP fibers for the mix $M_{HY0.5(3)}$. The maximum strength improvement in flexural strength compared to control mix is 56.8% for M25 and 55.9% for M50 concrete at an optimum fiber dosage of 0.5%. PP fibers are short and having lower tensile strength and elastic modulus whereas steel fibers are long and having higher tensile strength and elastic modulus which will bridge both micro and macro-cracks resulting in significant improvement of flexural strength.

Table 5.8Flexural strength of HFRC

Mix designation	M25		M50	
	f_{ft} (MPa)	Percentage increase (%)	f_{ft} (MPa)	Percentage increase (%)
$M_{C\text{-control mix}}$	4.74	-	5.38	-
$M_{HY0.25(1)}$ -25%SF&75%PP	5.63	18.8	5.98	11.2
$M_{HY0.25(2)}$ -50%SF&50%PP	6.23	31.4	6.57	22.1
$M_{HY0.25(3)}$ -75%SF&25%PP	6.49	36.9	7.58	40.9
$M_{HY0.5(1)}$ -25%SF&75%PP	6.72	41.8	7.72	43.5
$M_{HY0.5(2)}$ -50%SF&50%PP	7.16	51.1	7.98	48.3
$M_{HY0.5(3)}$ -75%SF&25%PP	***7.43***	***56.8***	***8.39***	***55.9***
$M_{HY0.75(1)}$ -25%SF&75%PP	7.01	47.9	8.13	51.1
$M_{HY0.75(2)}$ -50%SF&50%PP	6.89	45.4	7.52	39.8
$M_{HY0.75(3)}$ -75%SF&25%PP	6.47	36.5	7.29	35.5

5.2.4Effect of Fibers on Mechanical Properties of Mono and Hybrid FRC

Strength effectiveness of SFRC, PPFRC and HFRC on different grades of concrete are graphically presented in Figure 5.1 to 5.3 for both the grades of concrete. It is observed that there is marginal improvement in compressive strength for mono FRC and HFRC but significant improvement in split tensile strength and flexural strength for mono FRC and HFRC compared with control concrete. It is also observed from the experimental results, as the grade of the concrete increases, less improvement in compressive strength is observed and this may be due to failure mode in standard strength concrete through the aggregate rather than matrix, therefore reinforcement effect of fibers is not fully utilized. It is observed from the Table 5.1 and 5.2 performance of SFRC is better compared to PPFRC with respect to compressive, split tensile and flexural strength. This may be due to effectiveness of steel fiber in arresting the cracks than PP fiber, since PP fiber is small in length, sometimes pull-out of fiber takes place as shown in Figure 5.4 and 5.5. The effectiveness of hybrid fiber is clearly visible from the Figure 5.3a and 5.3b more improvement in compressive, split tensile and flexural strength is observed compared to control concrete and mono FRC. The reason may be due to availability of both short and long length of fibers at all stress levels which can arrest the cracks at early and later stage of loading.

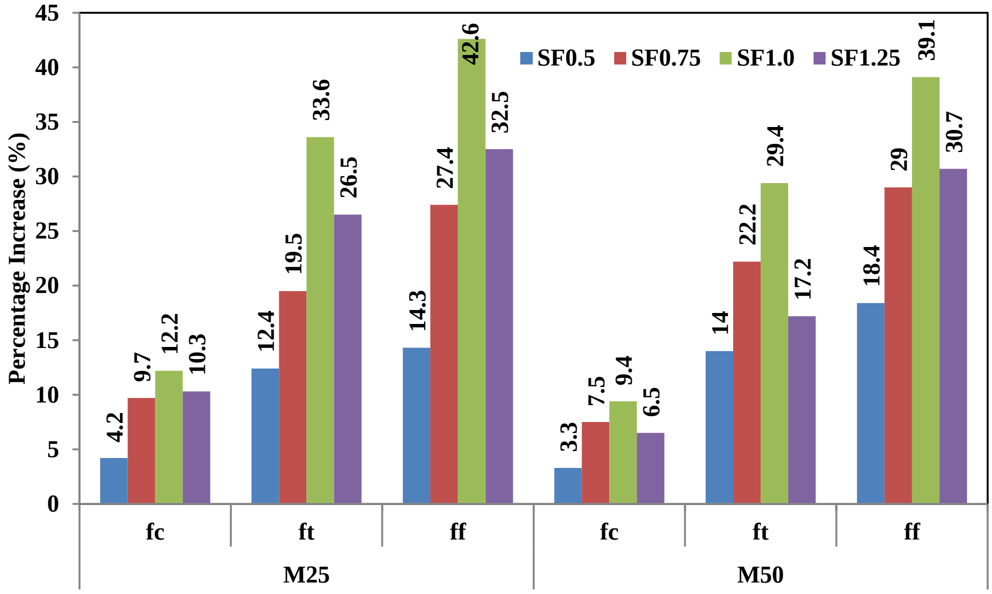


Figure 5.1Strength effectiveness of SFRC

Note: Graph drawn between percentage improvement on y-axis and grade of concrete on x-axis which is reference line.

(fc – Compressive strength, ft – Split tensile strength, ff – Flexural strength)

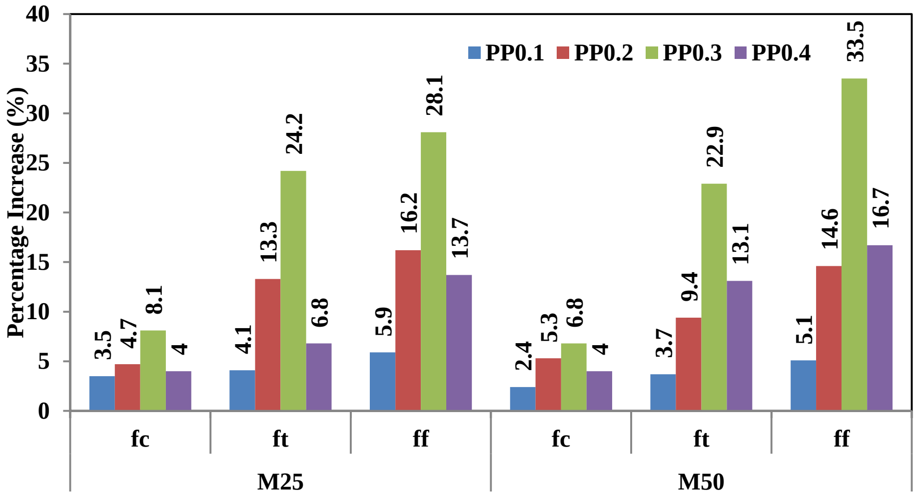


Figure 5.2Strength effectiveness of PPFRC

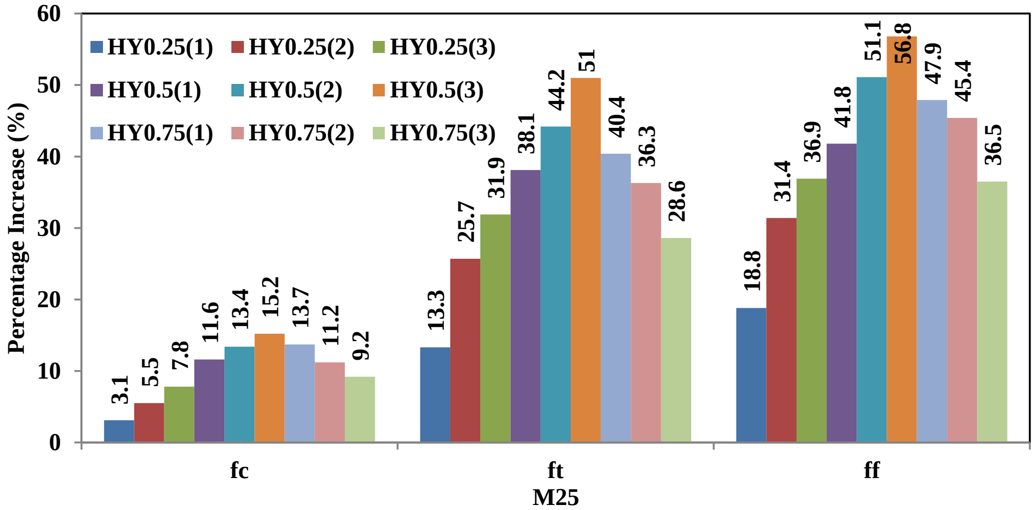


Figure 5.3aStrength effectiveness of HFRC-M25 concrete

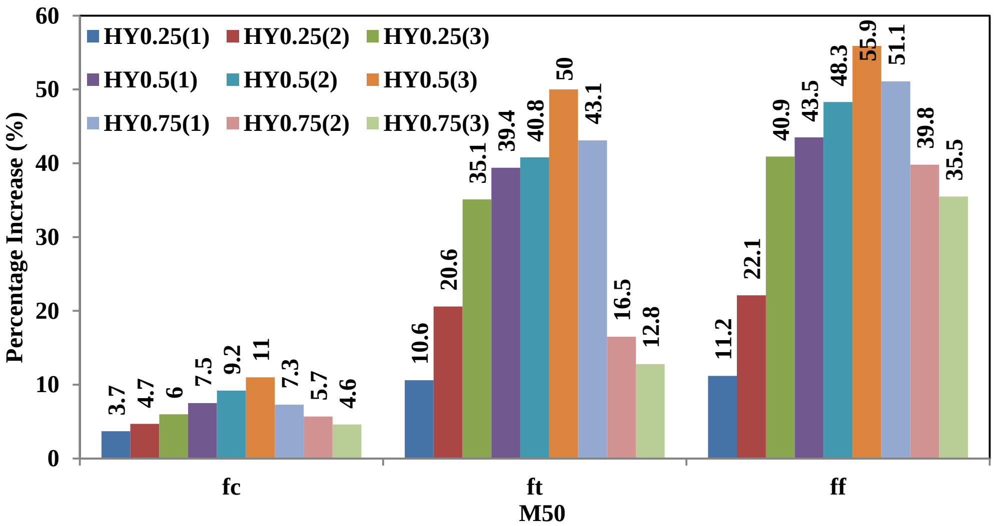


Figure 5.3bStrength effectiveness of HFRC-M50 concrete

Figure 5.4 Flexural failure of SFRC specimen

Figure 5.5 Flexural failure of PPFRC specimen

5.3Dynamic Properties of Mono and Hybrid FRC

Modal testing is a common method of characterizing the vibrations of a structure by imparting a known force and measuring the response of the structure. By measuring both the input force imparted to the structure and the corresponding, the frequency response of the structure can be calculated. Dynamic parameters such as natural frequency, damping ratio and mode shapes are the essential technical information required in engineering analysis and design. Therefore, dynamic properties of non-fibrous concrete, mono FRC and hybrid FRC specimens have been determined using impact hammer test. The test procedure to determine the dynamic characteristics such as natural frequency, damping ratio and mode shapes is explained in chapter 4 and section 4.6.4. In order to determine the dynamic properties prismatic beams have been cast for all set of mixtures and tested in free-free condition.

Dynamic test results of mono FRC in free-free condition are shown in Table 5.9. Damping ratio of mono FRC prismatic beams increases with the addition of fiber content whereas natural frequency decreases with an increase of fiber content, however it was not less than the control concrete.

Table 5.9Dynamic property test results of mono FRC

Mix designation	M25				M50			
	Natural frequency (f)		Damping ratio (ζ)		Natural frequency (f)		Damping ratio (ζ)	
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
M_C	1398	3428	0.48	0.34	1398	3428	0.48	0.34
$M_{SF0.5}$	1449	3482	0.51	0.37	1432	3486	0.51	0.38
$M_{SF0.75}$	1433	3470	0.55	0.41	1429	3474	0.54	0.41
$M_{SF1.00}$	1425	3452	0.57	0.43	1421	3462	0.56	0.43
$M_{SF1.25}$	1409	3439	0.62	0.46	1409	3451	0.59	0.45
$M_{PP0.1}$	1432	3486	0.51	0.38	1542	3716	0.58	0.45
$M_{PP0.2}$	1429	3474	0.54	0.41	1531	3705	0.61	0.48
$M_{PP0.3}$	1421	3462	0.56	0.43	1526	3695	0.65	0.52
$M_{PP0.4}$	1409	3451	0.59	0.45	1514	3681	0.67	0.54

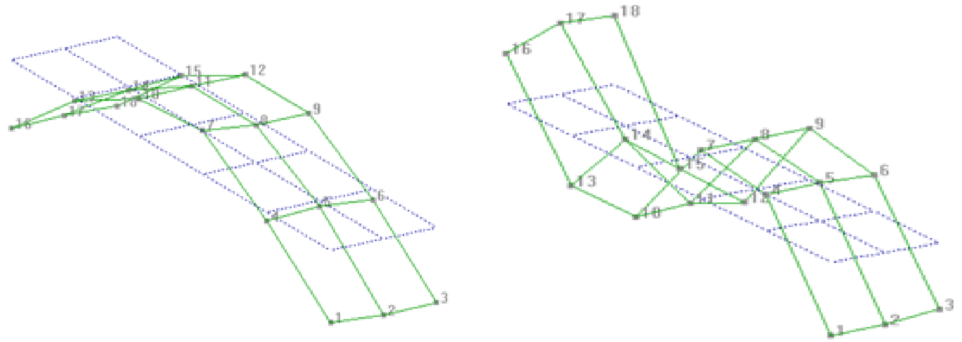
From the dynamic property test results of SFRC (Table 5.9), it is observed that the percentage improvement of SFRC in natural frequency was about 3.6% for M25 and 4% for M50 grade concrete respectively at 0.5% fiber volume fraction in first mode of vibration. Similarly the natural frequency values increased by about 1.6% for M25 and 2% for M50 grade concrete respectively at same fiber volume fraction in second mode of vibration. Thereafter, the addition of mono steel fibers in concrete mixtures led to decrease in natural frequency. The reason may be due to the rate of increase in mass is more than the rate of increase in stiffness. Damping ratio of SFRC was improved by about 29.2% for M25 and 19.6% for M50 grade concrete in first mode of vibration and 35.3% for M25 and 28.6% for M50 grade concrete in second mode of vibration respectively at 1.25% fiber volume fraction. Damping ratio increases with the increase of steel fiber content, the reason may be attributed that the friction developed in the interface between concrete and fibers. From the results it is observed that the natural frequency of PPFRC at 0.1% fiber volume fraction was improved by about 2.4% for M25 and 4.1% for M50 in first mode of vibration and 1.7% for M25 and 1.9% for M50 grade of concrete in second mode of vibration respectively. Damping ratio of PPFRC was improved by about 22.9% for M25 and 19.64% for M50 grade concrete in first mode of vibration and 32.3% for M25 and 28.6% for M50 grade concrete in second mode of vibration respectively at 0.4% fiber volume fraction. Similar reason has been observed for the mixtures with the addition of PP fibers.

Dynamic test results of HFRC in free-free condition are shown in Table 5.10. From the results it is observed that the natural frequency decreased with the increase of total fiber volume fraction whereas damping ratio increased with the increase of fiber content.

Table 5.10Dynamic property test results of HFRC

Mix designation	M25				M50			
	Natural frequency (f)		Damping ratio (ζ)		Natural frequency (f)		Damping ratio (ζ)	
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
M_C	1398	3428	0.48	0.34	1482	3643	0.56	0.42
$M_{HY0.25(1)}$	1461	3504	0.51	0.36	1551	3744	0.59	0.44
$M_{HY0.25(2)}$	1455	3493	0.52	0.39	1543	3737	0.61	0.47
$M_{HY0.25(3)}$	1448	3486	0.54	0.41	1539	3725	0.63	0.51
$M_{HY0.5(1)}$	1441	3481	0.57	0.42	1533	3718	0.66	0.52
$M_{HY0.5(2)}$	1434	3474	0.58	0.45	1527	3705	0.69	0.57
$M_{HY0.5(3)}$	1429	3469	0.6	0.47	1519	3691	0.73	0.59
$M_{HY0.75(1)}$	1421	3452	0.61	0.49	1511	3682	0.76	0.6
$M_{HY0.75(2)}$	1415	3448	0.63	0.51	1503	3674	0.77	0.63
$M_{HY0.75(3)}$	1409	3439	0.65	0.52	1496	3663	0.81	0.64

Also, it is observed that the increase of metallic steel fiber proportion from 25% to 75% in each total fiber fraction the natural frequency is decreased and the damping ratio is increased. Natural frequency of HFRC was improved by about 4.5% for M25 and 4.7% for M50 grade concrete in first mode of vibration and 2.2% for M25 and 2.8% for M50 grade concrete in second mode of vibration respectively at 0.25% total fiber fraction with the combination of 25% steel and 75% PP fibers. It is also observed that the damping ratio of HFRC was increased by about 35.4% for M25 and 44.6% for M50 grade concrete and 52.9% for M25 and 52.4% for M50 grade concrete respectively at 0.75% total fiber fraction with the combination of 75% steel and 25% PP fibers. Typical mode shapes of FRCs are shown in Figure 5.6.



5.6 (a) First mode **5.6 (b) Second mode**

Figure 5.6 Typical mode shapes of prismatic beam specimens

5.4Testing of Reinforced Concrete Beams

In the present experimental phase, static and dynamic behavior of RC beams strengthened with mono and hybrid fibers for two different grades of concrete have been studied. The optimum dosage of fiber has been arrived through the mechanical property tests as shown in section 5.2 is incorporated in RC beams. The control reinforced concrete (RC) beam without fiber, RC beam with steel fiber reinforced concrete (SFRC), RC beam with polypropylene fiber reinforced concrete (PPFRC) and RC beam with hybrid fiber reinforced concrete (HFRC) were cast. Designations of control RC, SFRC, PPFRC and HFRC beams are illustrated in Table 5.11. Static behavior of RC, SFRC, PPFRC and HFRC beams has been studied under four point flexure test.

Table 5.11 Designation of RC, SFRC, PPFRC and HFRC beam specimens

S. No	Beam designation	Beam type	Type of test
1	M25Control-S	RC	Static
2	M25Control-D	RC	Dynamic
3	M50Control-S	RC	Static
4	M50Control-D	RC	Dynamic
5	M25Steel-S	SFRC	Static
6	M25Steel-D	SFRC	Dynamic
7	M50Steel-S	SFRC	Static
8	M50Steel-D	SFRC	Dynamic
9	M25Polypropylene-S	PPFRC	Static
10	M25Polypropylene-D	PPFRC	Dynamic
11	M50Polypropylene-S	PPFRC	Static
12	M50Polypropylene-D	PPFRC	Dynamic
13	M25Hybrid-S	HFRC	Static
14	M25Hybrid-D	HFRC	Dynamic
15	M50 Hybrid-S	HFRC	Static
16	M50 Hybrid-D	HFRC	Dynamic

Dynamic tests using impact hammer is also carried out on similar beam specimens in different damage states designated as D_0, D_1, D_2 and D_3. Initially all the beams were tested to obtain the ultimate state flexural strength (Pu). Later damage has been induced in the specimens at different damage levels D_1 (50% of Pu), D_2 (50% of Pu) and D_3 (50% of Pu). At each damage level, beams were unloaded and dynamic testing using impact hammer is performed in order to obtain dynamic characteristics such as natural frequency, damping ratio and mode shapes. Later the dynamic characteristics were compared between undamaged state and at different damage states to correlate the damage and variation of dynamic characteristics. Also, the effectiveness of mono fiber and hybrid fibers on damage has been studied.

5.4.1Static Analysis of RC Beams Strengthened with Mono and Hybrid Fibers

All the beam specimens have been subjected to monotonic static load through two points at a distance of 400mm between them. Experimental results of static load test for control RC, SFRC,PPFRC and HFRC beams for M25 and M50 grade concretes are shown in Table 5.12. The load versus mid-span deflection plot is shown in Figure 5.7 for RC, SFRC, PPFRC and HFRC beams.

Table 5.12a Static test results of RC, SFRC, PPFRCand HFRC beams - M25 concrete

Beam designation	Ultimate load (kN)	% Increase of load	Maximum deflection (mm)
M25Control-S	122.5	-	48
M25Steel-S	145	18.36	56
M25Polypropylene-S	132.5	8.16	51
M25Hybrid-S	148	20.80	54

Table 5.12b Static test results of RC, SFRC, PPFRCand HFRC beams – M50 concrete

Beam designation	Ultimate load (kN)	% Increase of load	Maximum deflection (mm)
M50Control-S	208.5	-	46
M50Steel-S	243	16.54	56
M50Polypropylene-S	233.5	11.99	54
M50 Hybrid -S	248	18.94	52

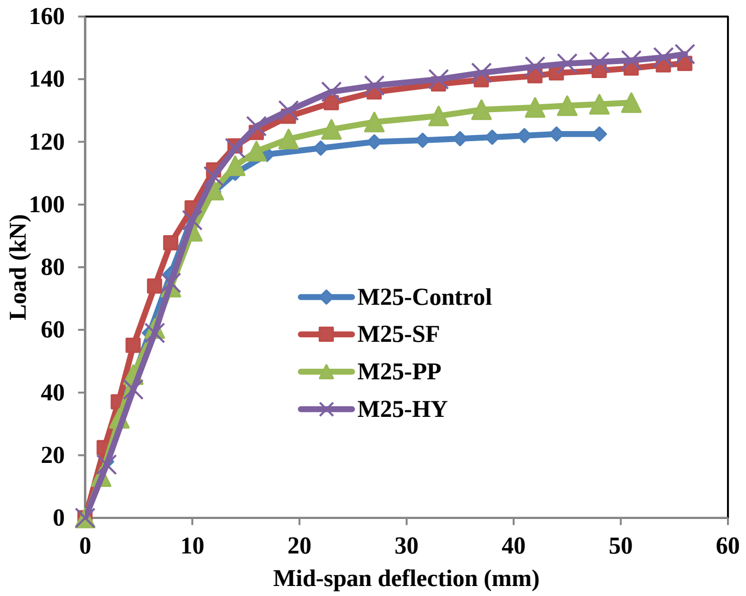


Figure 5.7a Load versus mid-span deflection behavior of RC, SFRC, PPFRC and HFRC beams - M25 concrete

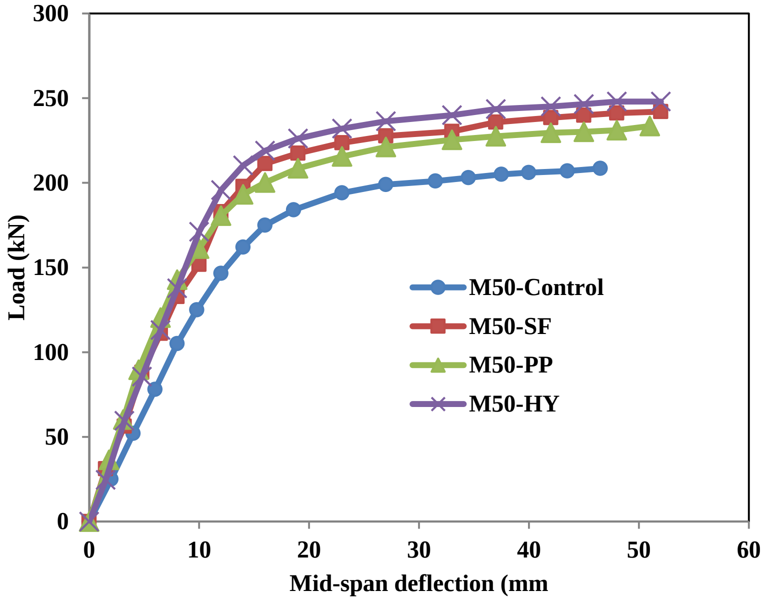


Figure 5.7b Load versus mid-span deflection behavior of RC, SFRC, PPFRC and HFRC beams - M50 concrete

From the graphs, it can be observed that, in the elastic region, the applied load was very low and the deflection of the beam was also less. With the increase of load, there was an extrinsic decrease in the stiffness of the beam due to the formation of hair-line cracks in the tension zone for the control RC beams. When the load increases, cracks propagate towards the neural axis and also hair-line cracks were formed in the compression zone under the load points.

Exclusively cracks were widened and propagated towards the compression zone in control RC beams with the increase of load.

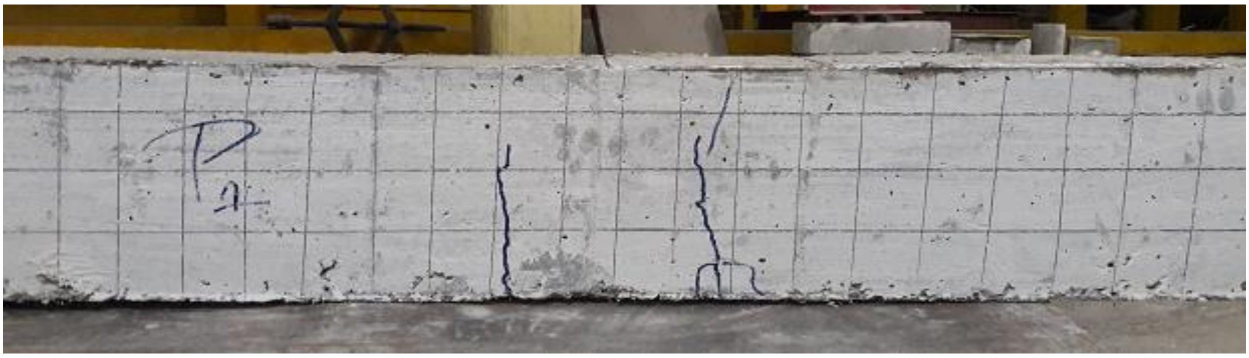
The maximum percentage strength improvement in RC beam with steel fibers is 18.36% for M25 and 16.54% for M50 concrete at 1% fiber volume fraction compared with control RC beams. Similar kind of observation was found by *Mohammedhosseini et al. (2017)*. The reason is due to the addition of hooked end steel fibers in RC beam which can arrest the formation and propagation of macro-cracks further. Also due to the improved stiffness of the RC beam with the addition of steel fibers than the control RC beams led to higher load carrying capacity. The formation and propagation of cracks were vey less for RC beam with steel fibers compared with control RC beams as shown in Figure 5.8. For RC beams strengthened with steel fibers,with the increase of load, cracks formed in the tension zone are very less, also the propagation of cracks in the tension zone of the beam were effectually restricted by the steel fiber as shown in Figure 5.8a and 5.8b. Load carrying capacity of RC beam strengthened with PP fibers was increased by about 8.16% for M25 and 11.99% for M50 grade concrete at 0.3% fiber volume fraction and this is due to the fiber-bridging action provided by the numerous short discrete PP fibers. Similar observations were made by *Meda et al. (2012)*. The length of PP fiber is less and having lower modulus of elasticity which would be capable to restrict the growth of micro-cracks in the initial cracking stage. Also, the addition of non-metallic PP fibers could effectively bridge the crack and limit its propagation and crack widening, which resulted in increased load carrying capacity when compared with control RC beams. It is evident from the test results the performance of RC beams strengthened with steel fiber is better than the beam strengthened with PP fiber.

The percentage flexural strength improvement of RC beam strengthened with hybrid fibers (steel and PP) was about 20.8% for M25 and 18.94% for M50 grade concrete at 0.5% total fiber volume fraction with the combination of 75% of steel and 25% of PP fibers compared with control RC beams. The reason is due to the incorporation of hybrid fiberseffective in bridging the micro as well as macro cracks and also delayed the propagation of cracks further. It is also observed that the percentage increase in load carrying capacity of RC beams with hybrid fibers was about 2.1% and 11.7% when compared with RC beams strengthened with steel and PP fibers respectively for M25 grade concrete. Similarly percentage strength improvement of RC beam with hybrid fibers was increased by about 2% and 6.2% when compared with RC beams strengthened with steel and PP fibers respectively for M50 grade concrete. This is due to a high stiffness response with the addition of both metallic steel and non-metallic PP fibers which could arrest micro cracks in the initial stage and macro cracks at all stress levels. Figure5.8 shows the failure patterns of RC, SFRC, PPFRC and HFRC beams under monotonic loading condition after complete failure. Formation of cracks in RC beams with hybrid fibers are very less compared to RC beams with mono steel and PP fibers as well as control RC beams as shown in Figure 5.8. Similar kind of observation was found by Taha A. EI-Sayed (2019).

5.8 (a) Control RC beam after complete failure

5.8 (b) SFRC beam after complete failure

5.8 (c) PPFRC beam after complete failure



5.8 (d) HFRC beam after complete failure

Figure 5.8 Failure patterns of control RC, SFRC, PPFRC and HFRC beams

5.4.2. Dynamic Behavior of RC Beams Strengthened with Mono and Hybrid Fibers

Dynamic tests using impact hammer is performed to measure the dynamic characteristics for all the beams at different damage states and the results were compared with the behavior of undamaged conditions. Dynamic tests have been conducted at the end of each degrees of damage referred as D_1, D_2 and D_3 in free-free condition. Dynamic parameters such as natural frequency, damping ratio and mode shapes have been obtained from the set of frequency response function (FRF). Generally, the form of FRFs used in the experimental technique is inertance which is a measure of the amplitude in terms of acceleration for the given excitation. The aforementioned beam has been analyzed by dynamic tests at undamaged level (D_0) which was followed by each damage levels from D_1, D_2 and D_3 as 50%, 70% and 90% of ultimate load respectively. Totally thirty nodes (excitation points) were marked on the surface of the each RC beam in order to estimate the damage behavior through the dynamic testing. Accelerometer was kept at one of the nodes and impact has been given at all the other nodes. Frequency response functions (FRF's) were plotted for all nodes in undamaged as well as different damage states. After curve fitting the measured FRF's, natural frequency and damping ratio values at different damage levels of control RC beam (without fibers) are illustrated in Table 5.13 and Table 5.14 for M25 and M50 concrete. From the dynamic test results the natural frequency decreases with the increase of damage whereas the damping ratio increases with the damage induced in the beam. Similar kinds of observations were found by *Capozucca (2009)*.

Table 5.13a Natural frequency values of control RC beam (f) - M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	221.3	-	579.7	-	1051	-	1608	-	2211	-	2836	-
D_1	61.25	200.2	9.5	534.8	7.7	961	8.6	1489	7.4	1993	9.9	2612	7.9
D_2	85.75	182.5	17.5	509.4	12.1	938	10.8	1436	10.7	1891	14.5	2517	11.2
D_3	110.2	173.8	21.5	497.1	14.2	916	12.8	1360	15.4	1771	19.9	2356	16.9

f_1 – Mode 1, f_2 – Mode 2, f_3 – Mode 3, f_4 – Mode 4, f_5 – Mode 5, f_6 – Mode 6

Table 5.13b Damping ratio values of control RC beam (ζ) - M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.93	-	0.61	-	0.55	-	0.43	-	0.4	-	0.35	-
D_1	61.25	0.97	4.3	0.67	9.8	0.59	7.3	0.46	7.0	0.44	10.0	0.39	11.4
D_2	85.75	1.06	14.0	0.71	16.4	0.62	12.7	0.51	18.6	0.47	17.5	0.43	22.9
D_3	110.2	1.15	23.7	0.76	24.6	0.67	21.8	0.53	23.3	0.51	27.5	0.46	31.4

ζ_1 – Mode 1, ζ_2– Mode 2, ζ_3– Mode 3, ζ_4– Mode 4, ζ_5– Mode 5, ζ_6– Mode 6

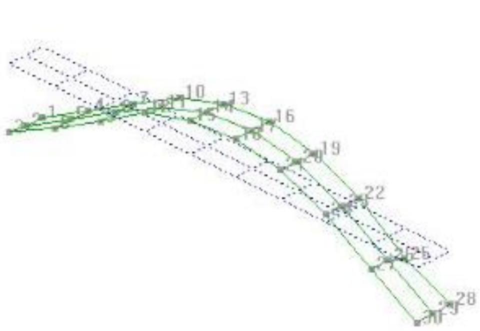
Table 5.14a Natural frequency values of control RC beam (f) – M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	236.3	0.0	614.3	0.0	1120	0.0	1708	0.0	2348	0.0	3008	0.0
D_1	104.2	207.1	12.4	569.2	7.3	1002	10.5	1530	10.4	2201	6.3	2745	8.7
D_2	145.9	197.1	16.6	549.4	10.6	953	14.9	1441	15.6	2082	11.3	2648	12.0
D_3	187.65	187.9	20.5	533.6	13.1	921	17.8	1399	18.1	1940	17.4	2546	15.4

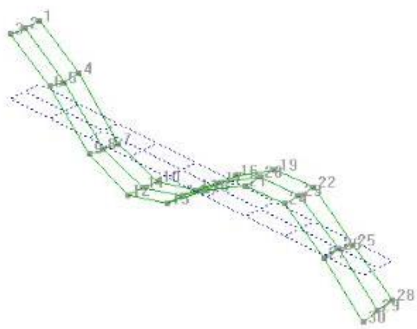
Table 5.14b Damping ratio values of control RC beam (ζ) – M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.8	-	0.48	-	0.44	-	0.34	-	0.32	-	0.3	-
D_1	104.25	0.86	7.5	0.52	8.3	0.49	11.4	0.39	14.7	0.36	12.5	0.34	13.3
D_2	145.95	0.89	11.3	0.57	18.8	0.5	13.6	0.41	20.6	0.39	21.9	0.37	23.3
D_3	187.65	0.95	18.8	0.6	25.0	0.53	20.5	0.44	29.4	0.41	28.1	0.4	33.3

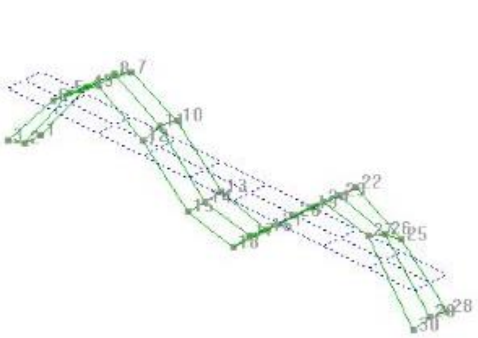
It is observed that the maximum variation in natural frequency and damping ratio was found at first and sixth mode of vibration respectively. From the dynamic test results it is observed that the maximum percentage variation in natural frequency of control RC beam from undamaged state to final damage state in first mode of vibration is 21.5% for M25 and 20.5% for M50 grade concrete. Similarly the maximum percentage variation in damping ratio of control RC beam from undamaged state to final damage state in sixth mode of vibration is 31.4% for M25 and 33.3% for M50 grade concrete. Figure 5.9shows the first six modes shapes of vibration of tested beams. The envelope of frequency response functions (FRFs) is shown in Figure 5.10for control RC beam at undamaged state.It is indicated that peak frequency is at the same level whatever may be the input-output locations, it does not depend on the force applied. Figure 5.11 shows the envelope of FRF's for different damage levels of control RC beam.



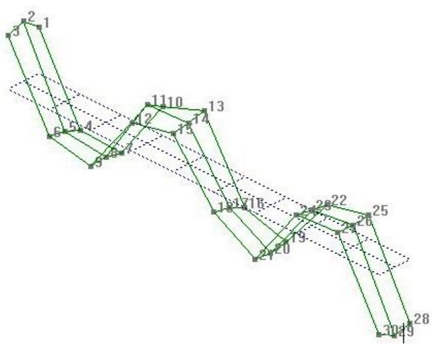
(a) First mode shape



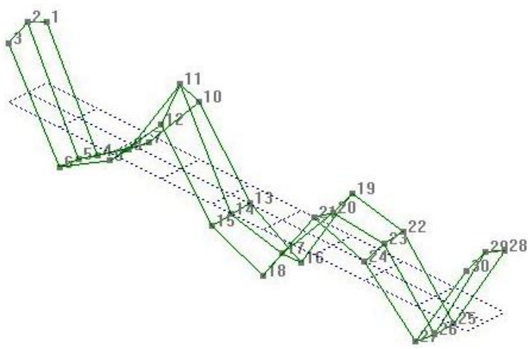
(b) Second mode shape



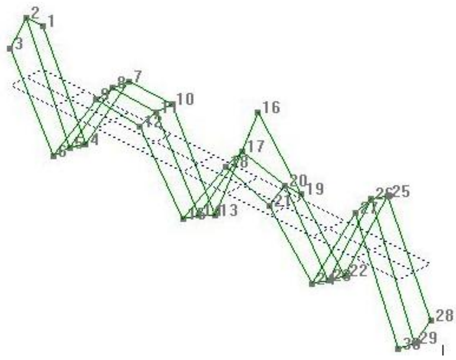
(c) Third mode shape



(d) Fourth mode shape



(e) Fifth mode shape



(f) Sixth mode shape

Figure 5.9First six modes of vibration of RC beam

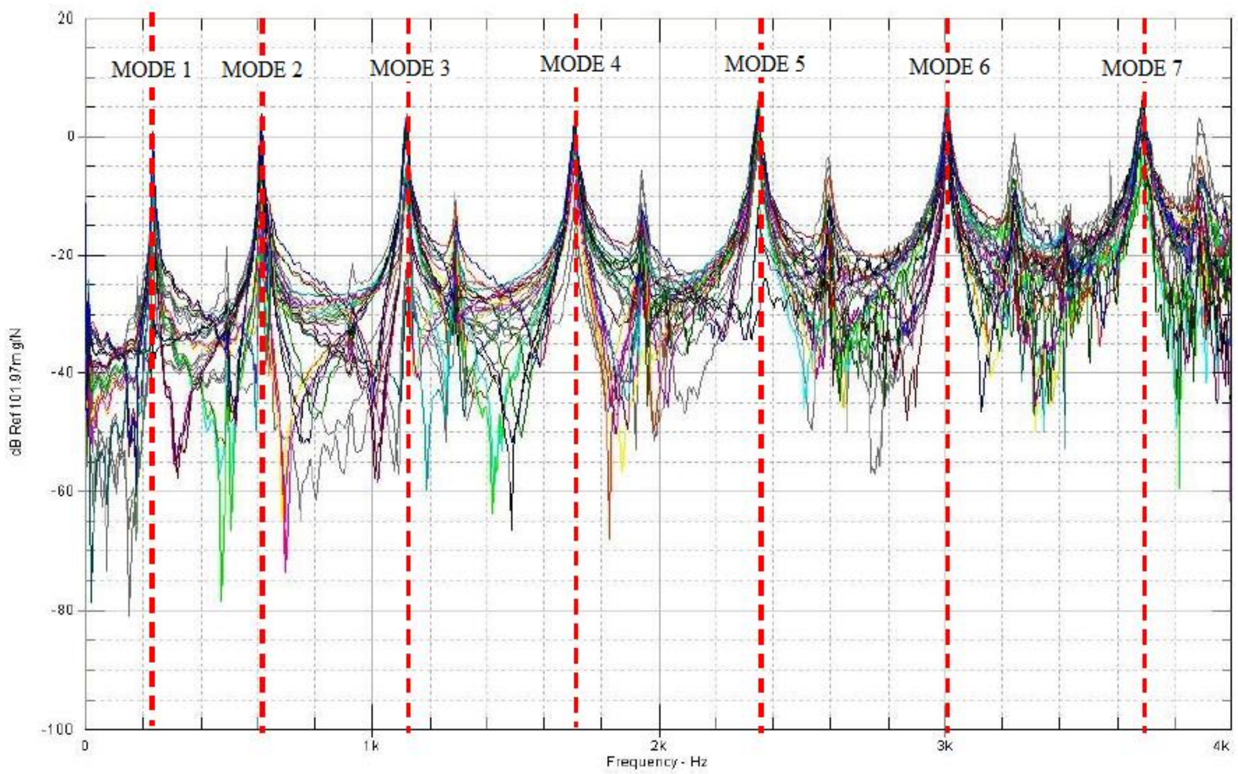


Figure 5.10 Frequency response function of control RC beam at undamaged state

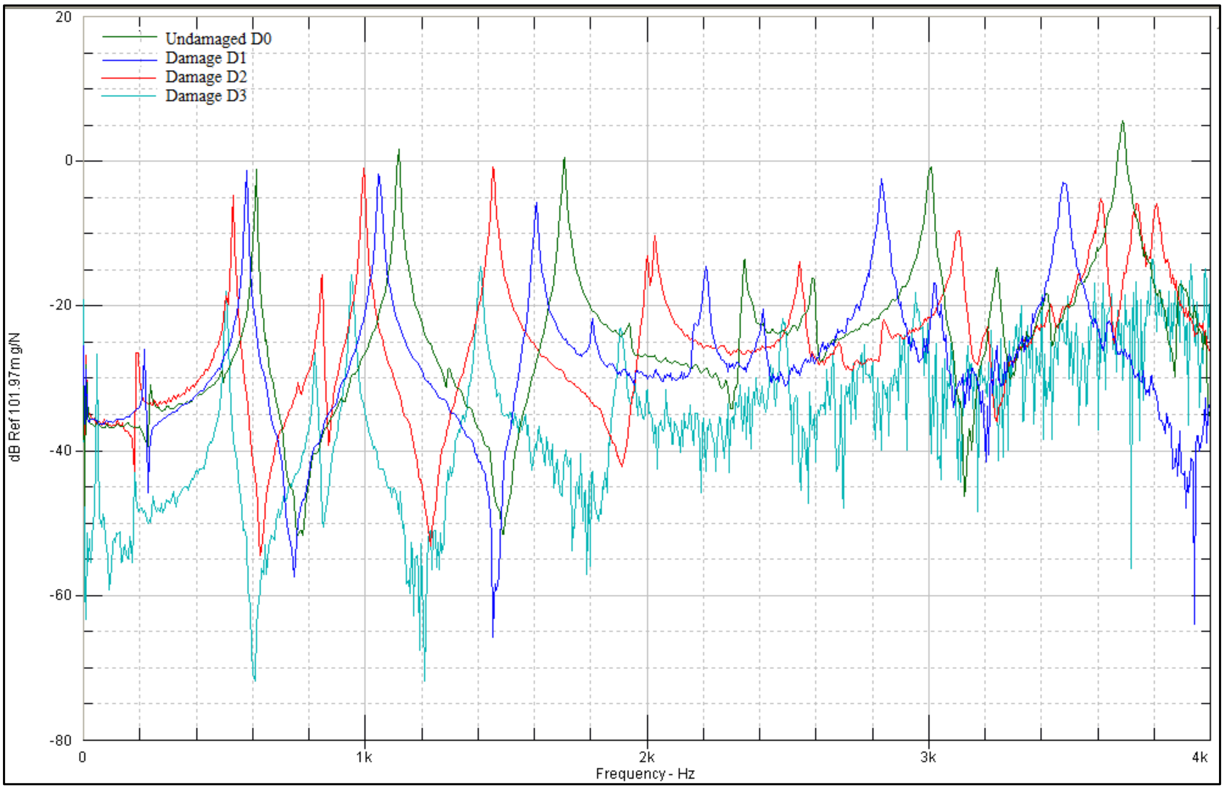


Figure 5.11 Frequency response function of control RC beam at different damage levels

From the envelope of FRF's diagrams (Figure 5.11), a clear shift in peaks of FRF's towards left is observed from D_0 to D_3which indicated the decrease of natural frequency from undamaged state to final damage state. It also observed that the frequency variation is very low up to application of 50% load, later higher frequency variations were observed with damage induced beyond 50% of ultimate load.

Similar dynamic testing is carried out onSFRC and PPFRC beams at different damage levels.Natural frequency and damping ratio values for SFRC and PPFRC beams areshown in Tables 5.15 to 5.18 for M25 and M50 concrete. The higher differences were observed (Natural frequency and damping ratio) in all the modes of vibration starting from D_2 to D_3, when the flexural load reaching ultimate load.

Table 5.15a Natural frequency values of SFRC beam (f) - M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	226	-	583.6	-	1079	-	1681	-	2271	-	2897	-
D_1	72.5	212.3	6.1	542.4	7.1	1000	7.3	1574	6.4	2112	7.0	2716	6.2
D_2	101.5	195.5	13.5	521.2	10.7	973	9.8	1518	9.7	2038	10.3	2645	8.7
D_3	130.5	182.2	19.4	508	13.0	955.1	11.5	1441	14.3	1908	16.0	2490	14.0

Table 5.15b Damping ratio values of SFRC beam (ζ) - M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	1.01	-	0.64	-	0.56	-	0.52	-	0.43	-	0.39	-
D_1	72.5	1.04	3.0	0.69	7.8	0.59	5.4	0.55	5.8	0.46	7.0	0.43	10.3
D_2	101.5	1.08	6.9	0.71	10.9	0.61	8.9	0.57	9.6	0.48	11.6	0.45	15.4
D_3	130.5	1.11	9.9	0.74	15.6	0.64	14.3	0.61	17.3	0.5	16.3	0.46	17.9

Table 5.16a Natural frequency values of SFRC beam (f) – M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	245.2	-	639	-	1160	-	1755	-	2397	-	3066	-
D_1	121.5	229.8	6.3	603.1	5.6	1086	6.4	1621	7.6	2285	4.7	2894	5.6
D_2	170.1	212.6	13.3	589	7.8	1062	8.4	1586	9.6	2191	8.6	2744	10.5
D_3	218.7	201.5	17.8	569.8	10.8	1041	10.3	1533	12.6	2105	12.2	2623	14.4

Table 5.16b Damping ratio values of SFRC beam (ζ) – M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.75	-	0.51	-	0.41	-	0.36	-	0.33	-	0.31	-
D_1	121.5	0.79	5.3	0.54	5.9	0.43	4.9	0.4	11.1	0.36	9.1	0.34	9.7
D_2	170.1	0.82	9.3	0.56	9.8	0.45	9.8	0.42	16.7	0.37	12.1	0.37	19.4
D_3	218.7	0.86	14.7	0.59	15.7	0.48	17.1	0.44	22.2	0.39	18.2	0.39	25.8

Table 5.17a Natural frequency values of PPFRC beam (f) - M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	228.4	-	590.8	-	1043	-	1615	-	2225	-	2845	-
D_1	66	218.5	4.3	562.3	4.8	1009	3.3	1567	3.0	2107	5.3	2684	5.7
D_2	92.4	203.5	10.9	536.9	9.1	988	5.3	1512	6.4	2038	8.4	2617	8.0
D_3	118.8	188.4	17.5	520.2	11.9	970	7.0	1427	11.6	1968	11.6	2476	13.0

Table 5.17b Damping ratio values of PPFRC beam (ζ) - M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.97	-	0.56	-	0.49	-	0.45	-	0.43	-	0.41	-
D_1	66	0.99	2.1	0.59	5.4	0.51	4.1	0.47	4.4	0.44	2.3	0.44	7.3
D_2	92.4	1.02	5.2	0.61	8.9	0.53	8.2	0.48	6.7	0.47	9.3	0.45	9.8
D_3	118.8	1.05	8.2	0.64	14.3	0.55	12.2	0.51	13.3	0.49	14.0	0.47	14.6

Table 5.18a Natural frequency values of PPFRC beam (f) – M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	243.4	-	633.3	-	1147	-	1745	-	2380	-	3059	-
D_1	116.75	231.1	5.1	604.7	4.5	1087	5.2	1643	5.8	2286	3.9	2943	3.8
D_2	163.45	218.6	10.2	594.2	6.2	1068	6.9	1609	7.8	2214	7.0	2862	6.4
D_3	210.15	209.4	14.0	573.9	9.4	1052	8.3	1574	9.8	2136	10.3	2750	10.1

Table 5.18b Damping ratio values of PPFRC beam (ζ) – M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.85	-	0.59	-	0.55	-	0.41	-	0.39	-	0.35	-
D_1	116.75	0.89	4.7	0.61	3.4	0.57	3.6	0.44	7.3	0.41	5.1	0.38	8.6
D_2	163.45	0.92	8.2	0.63	6.8	0.58	5.5	0.46	12.2	0.42	7.7	0.41	17.1
D_3	210.15	0.96	12.9	0.65	10.2	0.61	10.9	0.47	14.6	0.44	12.8	0.42	20.0

From the dynamic test results it is observed that the maximum percentage variation in natural frequency of RC beam strengthened with steel fibers from undamaged state to final damage state in first mode of vibration is 19.4% for M25 and 17.8% for M50 grade concrete. Similarly the maximum percentage variation in damping ratio of SFRC beam from undamaged state to final damage state in sixth mode of vibration is 17.9% for M25 and 25.8% for M50 grade concrete. It is observed that the maximum percentage variation in natural frequency of RC beam strengthened with PP fibers from undamaged state to final damage state in first mode of vibration is 17.5% for M25 and 14% for M50 grade concrete. Similarly the maximum percentage variation in damping ratio of RC beam with PP fibers from undamaged state to final damage state in sixth mode of vibration is 14.6% for M25 and 20% for M50 grade concrete. It has also been observed that the percentage decrease of natural frequency is lesser for RC beams with PP fibers compared with control RC and SFRC beams. The reason may be attributed that the critical fiber volume fraction as 0.3% incorporated in the RC beam reduces the multiple micro-cracks developed in the initial loading stage and also it changes the fracture into a pseudo ductile material which can absorb transient overload and shocks with little visible damage. So, the PP fiber in the RC beams improved the cracking behavior and also reduces the damping variations than the control RC and SFRC beams. Figure 5.12 shows the envelope of FRF for different damage levels of RC beams strengthened with steel fibers.

Similarly, dynamic testing is carried out onHFRC beams at different damage levels.Natural frequency and damping ratio values for HFRC beams are tabulated in Table 5.19 and 5.20 for M25 and M50 concrete.

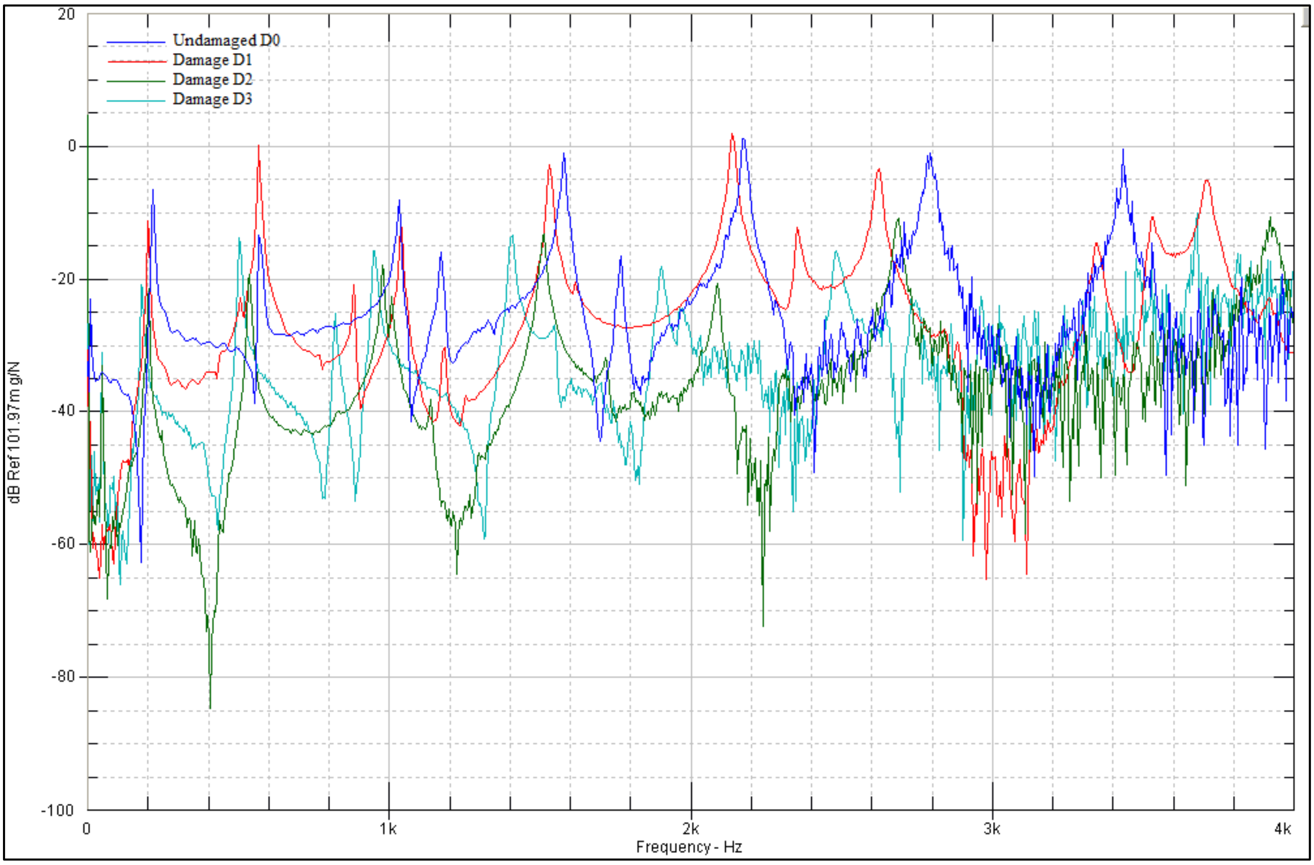


Figure 5.12 Frequency response function of RC beam strengthened with mono steel fibers at different damage levels

Table 5.19a Natural frequency values of HFRC beam (f) - M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	227	-	608	-	1107	-	1694	-	2294	-	3029	-
D_1	74	220	3.1	596.3	1.9	1089	1.6	1666	1.7	2276	0.8	2929	3.3
D_2	103.6	205.1	9.6	572	5.9	1060	4.2	1605	5.3	2153	6.1	2847	6.0
D_3	133.2	192.6	15.2	556	8.6	1036	6.4	1536	9.3	2098	8.5	2711	10.5

Table 5.19b Damping ratio values of HFRC beam (ζ) - M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	1.05	-	0.82	-	0.76	-	0.68	-	0.61	-	0.43	-
D_1	74	1.06	0.9	0.83	1.2	0.77	1.3	0.69	1.5	0.62	1.6	0.44	2.3
D_2	103.6	1.07	1.9	0.84	2.4	0.78	2.6	0.71	4.4	0.64	4.9	0.45	4.7
D_3	133.2	1.08	2.9	0.86	4.9	0.79	3.9	0.73	7.4	0.65	6.6	0.47	9.3

Table 5.20a Natural frequency values of HFRC beam (f) – M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	239.5	-	627	-	1136	-	1732	-	2363	-	3036	-
D_1	124	230	4.0	604	3.7	1089	4.1	1666	3.8	2292	3.0	2965	2.3
D_2	173.6	219	8.6	594	5.3	1076	5.3	1609	7.1	2218	6.1	2879	5.2
D_3	223.2	210	12.3	574	8.5	1052	7.4	1575	9.1	2146	9.2	2762	9.0

Table 5.20b Damping ratio values of HFRC beam (ζ) – M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.91	-	0.69	-	0.49	-	0.44	-	0.36	-	0.32	-
D_1	124	0.92	1.1	0.7	1.4	0.5	2.0	0.45	2.3	0.37	2.8	0.33	3.1
D_2	173.6	0.95	4.4	0.71	2.9	0.51	4.1	0.46	4.5	0.38	5.6	0.34	6.3
D_3	223.2	0.97	6.6	0.73	5.8	0.53	8.2	0.47	6.8	0.39	8.3	0.36	12.5

From the dynamic test results of RC beams with hybrid fibers (Table 5.19 and 5.20), it is observed that the maximum percentage variation in natural frequency of RC beam strengthened with hybrid fibers from undamaged state to final damage state in first mode of vibration is 15.2% for M25 and 12.3% for M50 grade concrete. Similarly the maximum percentage variation in damping ratio of RC beam with hybrid fibers from undamaged state to final damage state in sixth mode of vibration is 9.3% for M25 and 12.5% for M50 grade concrete. It has been observed that the percentage drop in natural frequency is less for RC beams strengthened with hybrid fibers when compared with mono FRC and control RC beams. The reason may be attributed that the addition of both metallic steel and non-metallic fibers in the RC beams reduces micro as well as macro cracks in the initial stage of loading which significantly increases the stiffness of the beam. Therefore, damage tolerance is very high for RC beams with hybrid fibers when compared with mono FRC and control RC beams. Figure 5.13 shows the envelope of FRF for different damage levels of HFRC beam.

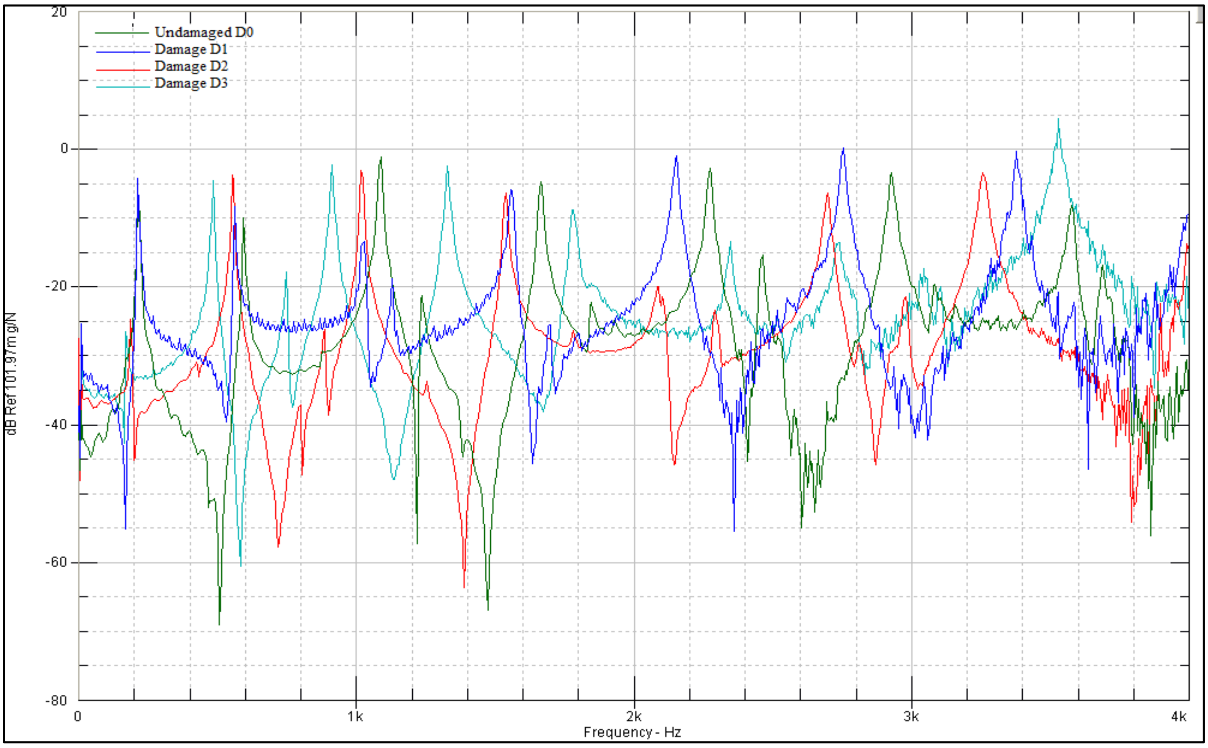


Figure 5.13 Frequency response function of RC beam strengthened with hybrid fibers at different damage levels

From the FRF diagram, the peaks in FRF shifted towards the left side which shows the decrease on natural frequency values recorded at undamaged degree to the final damage degree. Similar observations were made by *Capozucca (2013)*.

5.4.3 Comparison of Dynamic Behavior on RC, SFRC, PPFRC and HFRC

Comparison of natural frequency values of control RC, SFRC, PPFRC and HFRC for M25 and M50 grade concrete is shown in Figure 5.14. From the Figure, it is observed that the maximum percentage variation in natural frequency is very less for RC beam with hybrid fibers compared to that of RC beams with steel and PP fibers as well as control RC beams. Percentage variation of HFRC beam in first mode of vibration is 15.2% for M25 and 12.3% for M50 grade concrete from undamaged to final damage state which is lesser than control RC and RC beams with mono fibers. It is evident that the effectiveness of hybrid fibers are very effective to prevent the damage. Similar trend is observed in all damage states and in all modes of vibration.

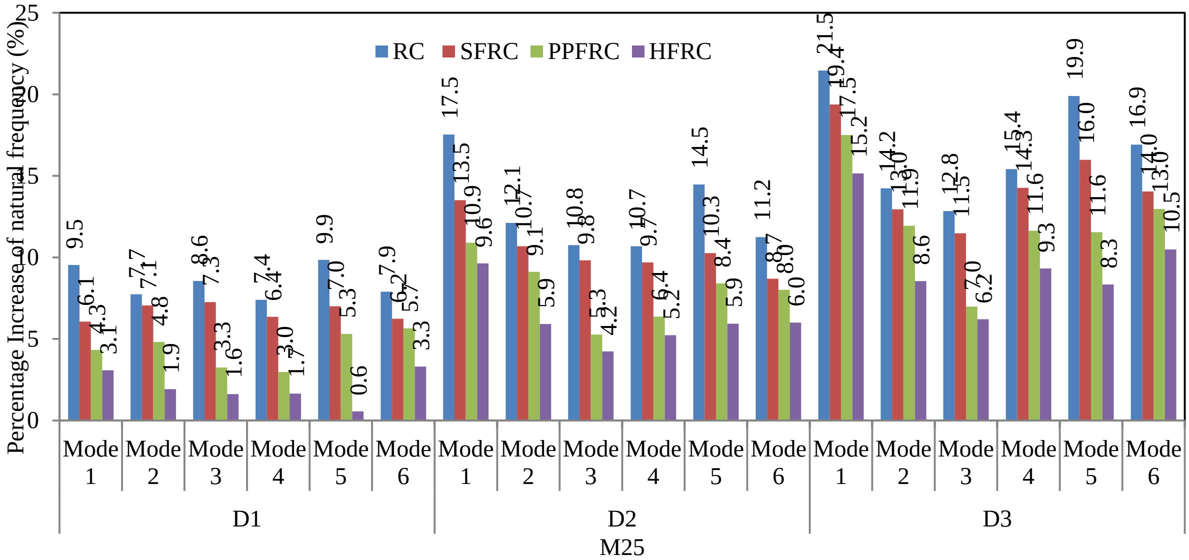


Figure 5.14a Comparison of natural frequency values of control RC, SFRC, PPFRC and HFRC – M25 concrete

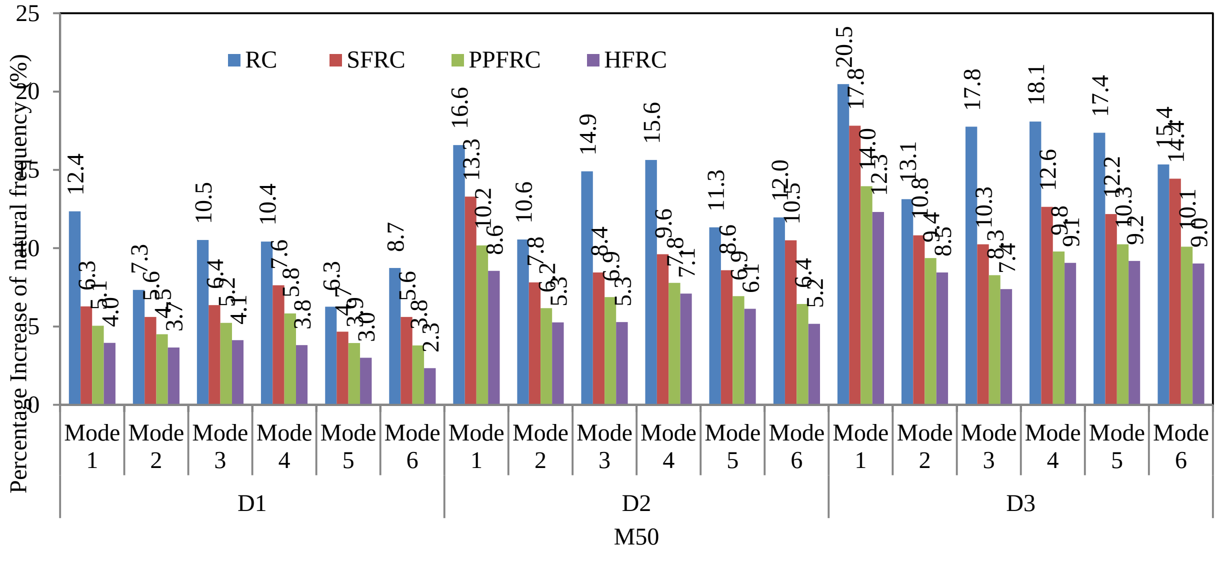


Figure 5.14b Comparison of natural frequency values of control RC, SFRC, PPFRC and HFRC – M50 concrete

Comparison of damping ratio values of control RC, SFRC, PPFRC and HFRC for M25 and M50 grade concrete is shown in Figure 5.15. From the Figure, it is observed that the maximum percentage variation in damping ratio is very less for RC beam with hybrid fibers compared to that of RC beams with steel and PP fibers as well as control RC beams.

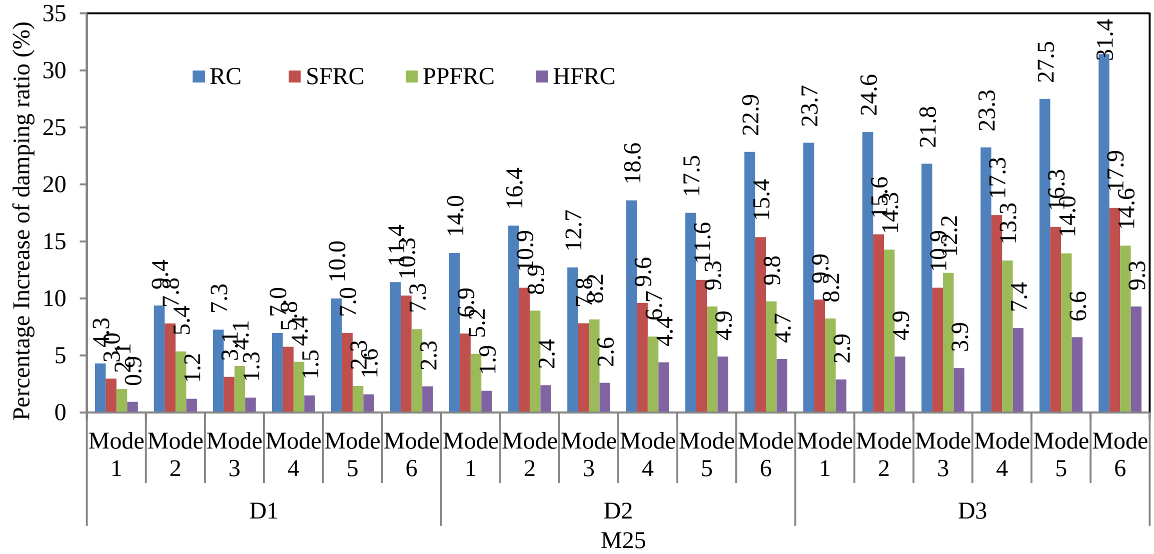


Figure 5.15a Comparison of damping ratio values of control RC, SFRC, PPFRC and HFRC – M25 concrete

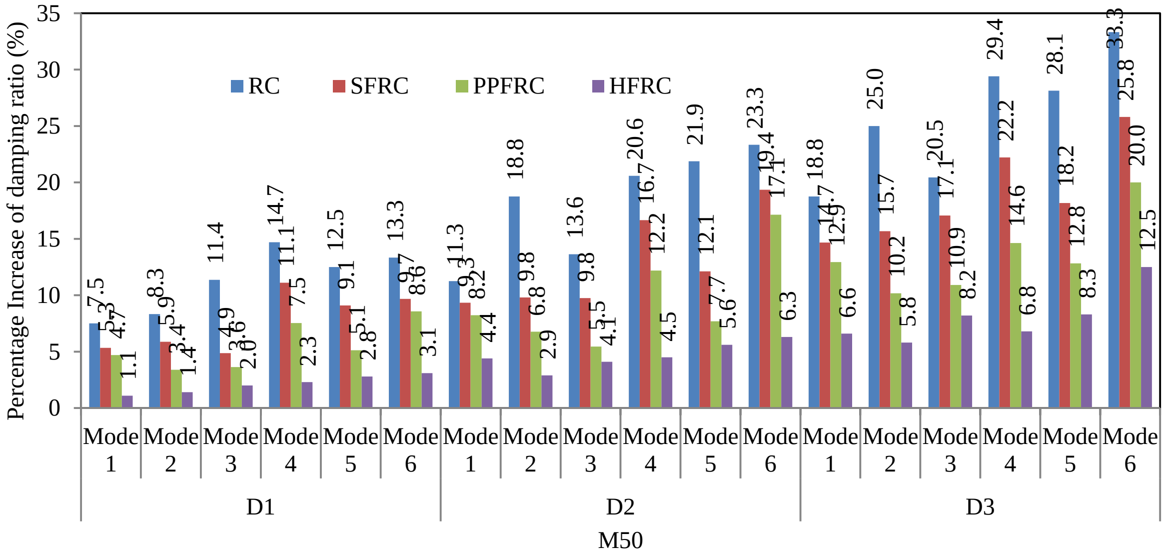
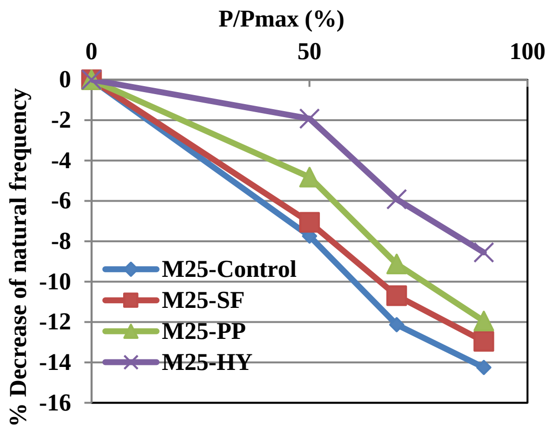


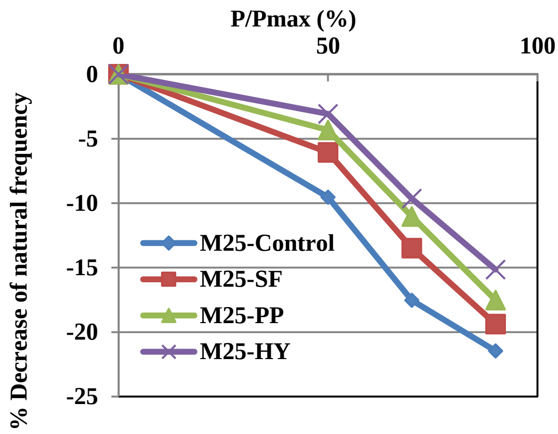
Figure 5.15b Comparison of damping ratio values of control RC, SFRC, PPFRC and HFRC – M50 concrete

Percentage variation of HFRC beam in sixth mode of vibration is 9.3% for M25 and 12.5% for M50 grade concrete at third damage degree which is lesser than control RC and RC beams with mono fibers.

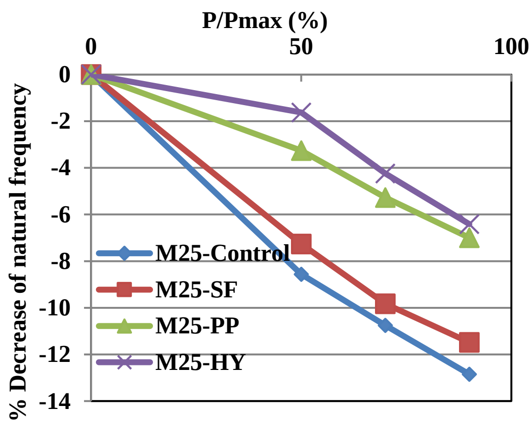
In order to observe the effectiveness mono and hybrid fibers against the damage in different damage levels, eventually, comparison of P/Pmax versus frequency variation ratio for RC, SFRC, PPFRC and HFRC beams at each damage level for six different modes of vibration are plotted as shown in Figure 5.16 for M25 and M50 grades of concrete.From the Figure, it can be observed that up to first damage level (50% of ultimate load) the change in stiffness of the beam with fibers is not significantly reduced than the beam without fibers. The reason may be that the load applied is within the serviceable limit, the minor cracks formed have been arrested by the fibers (mono and hybrid) in the beam. If the applied load is beyond 50% of ultimate load i.e. D_2 and D_3 damage level, more stiffness degradation perceived which is observed by the more drop in natural frequency values in all types of beams. Even in damage levelD_2 and D_3, the fiber effect is more pronounced in arresting cracks as shown in Figure 5.16.Figure 5.17 displays the P/Pmax ratio versus damping ratios of RC, SFRC, PPFRC and HFRC beams for undamaged as well as each damage levels for all six vibration modes for M25 and M50 grades of concrete.Similar trends were observed by *Capozucca (2018)*. More increase of damping ratio values observed from initial damage to final damage in all the modes, but more change in damping observed in control concrete beam compared to beam with fibers.



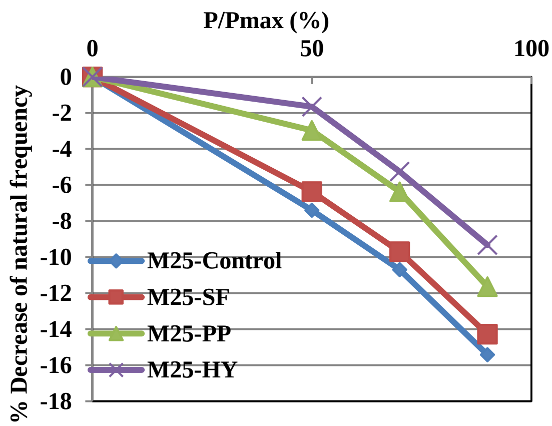
(a) First vibration mode



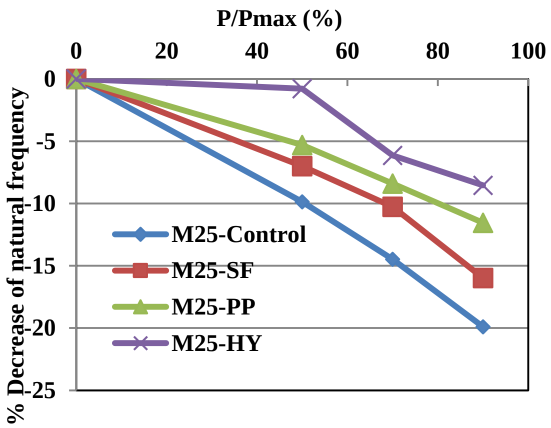
(b) Second vibration mode



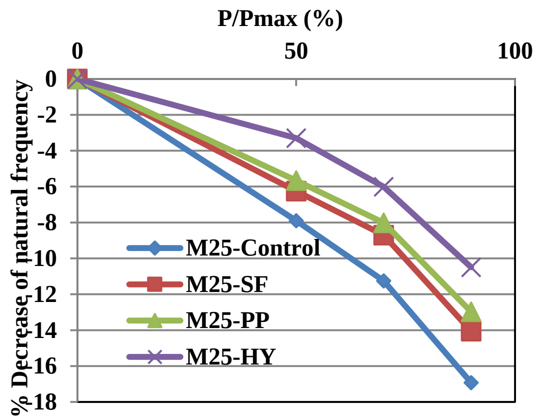
(c) Third vibration mode



(d) Fourth vibration mode

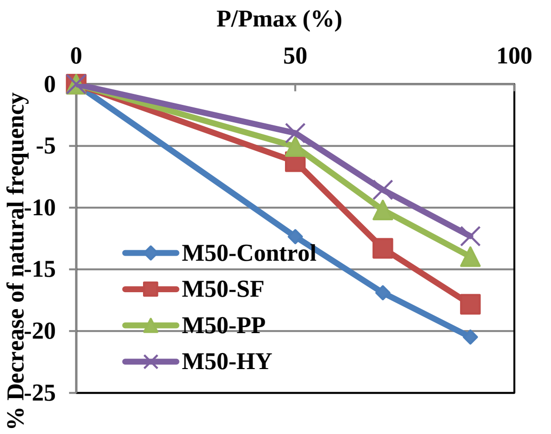


(e) Fifth vibration mode

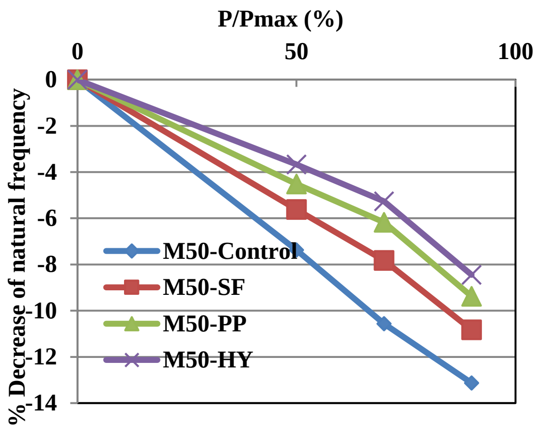


(f) Sixth vibration mode

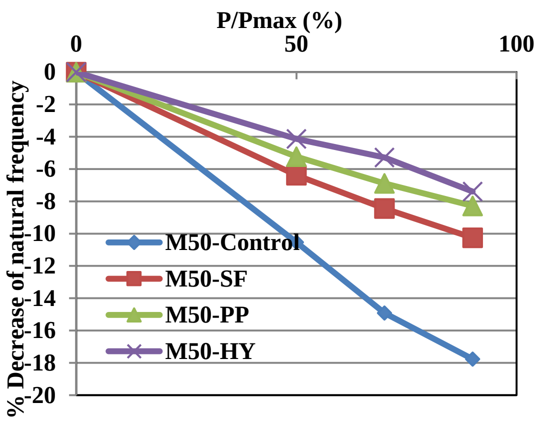
Figure 5.16a Comparison of P/Pmax ratio versus frequency variation ratio for RC, SFRC PPFRC and HFRC beams for M25 concrete



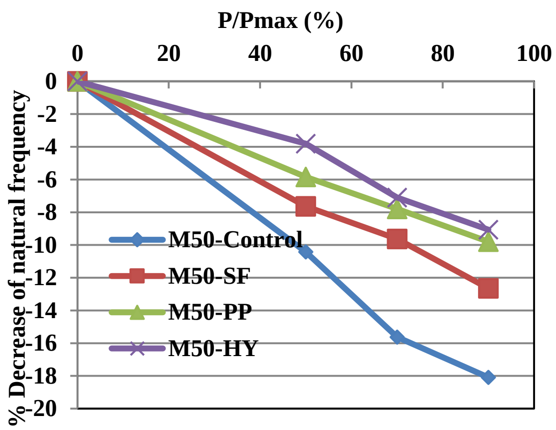
(a) First vibration mode



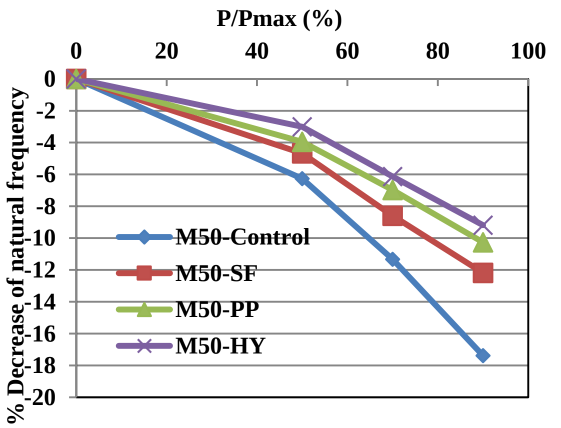
(b) Second vibration mode



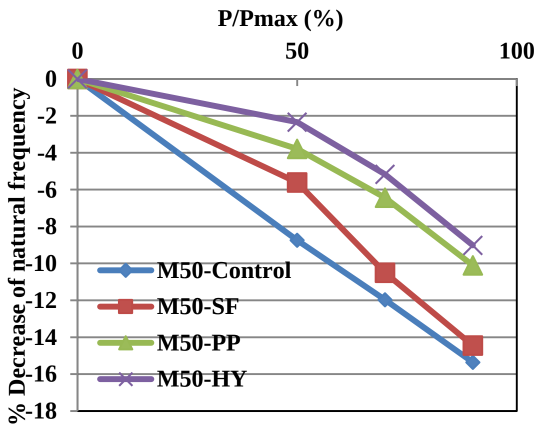
(c) Third vibration mode



(d) Fourth vibration mode

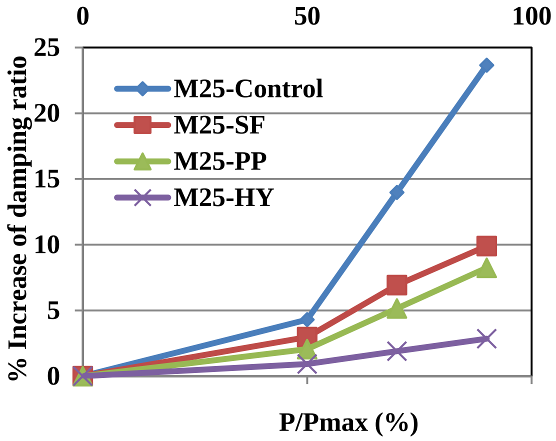


(e) Fifth vibration mode

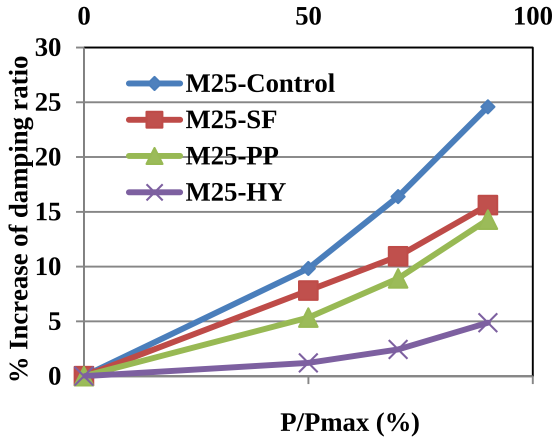


(f) Sixth vibration mode

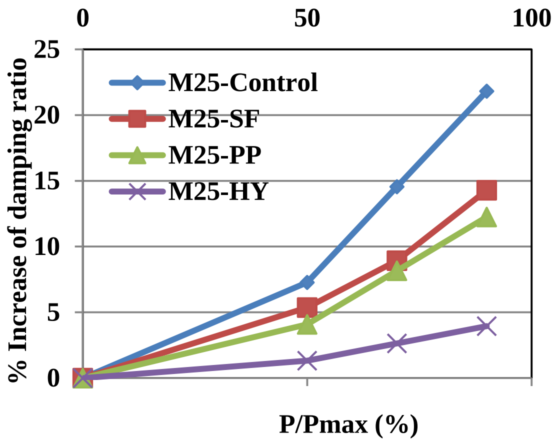
Figure 5.16b Comparison of P/Pmax ratioversus frequency variation ratio for RC, SFRC, PPFRC and HFRC beams for M50 concrete



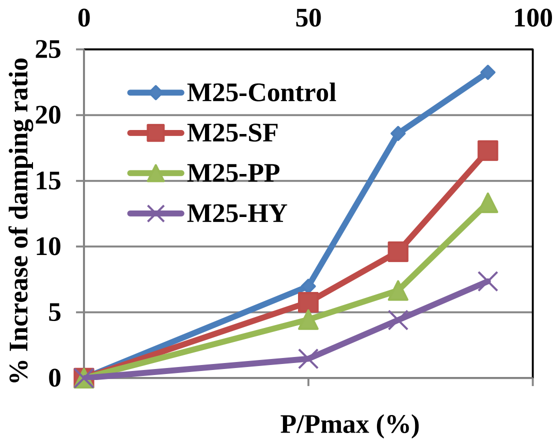
(a) First vibration mode



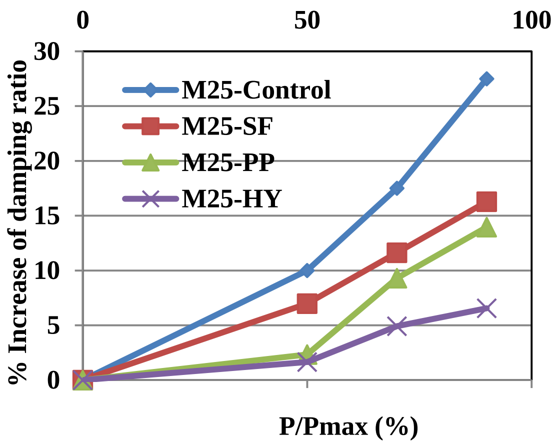
(b) Second vibration mode



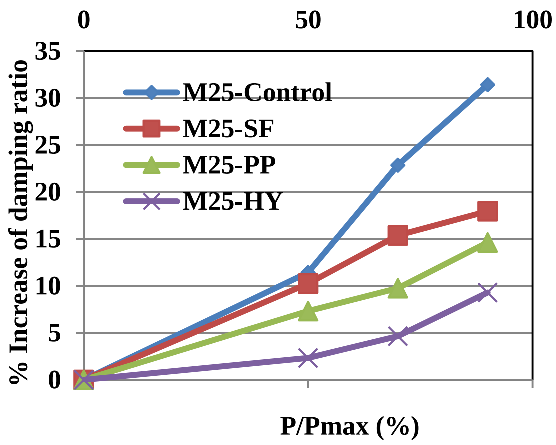
(c) Third vibration mode



(d) Fourth vibration mode

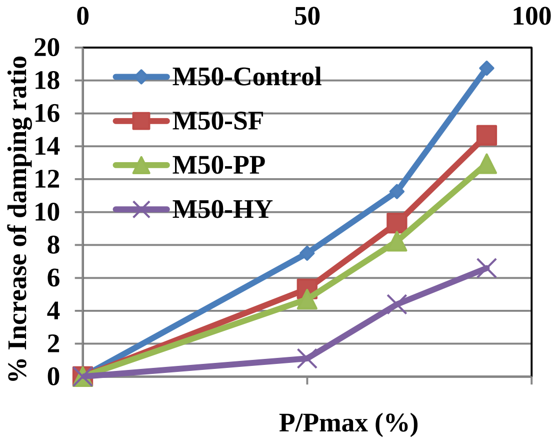


(e) Fifth vibration mode

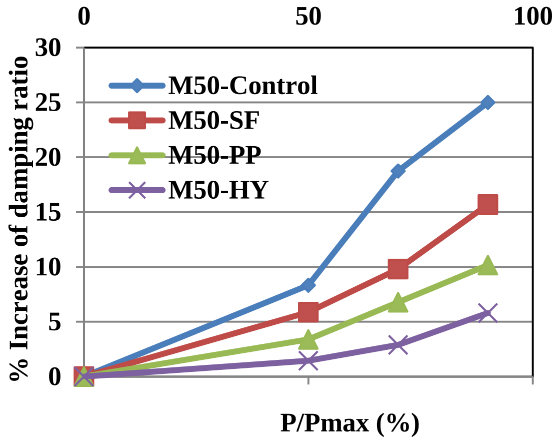


(f) Sixth vibration mode

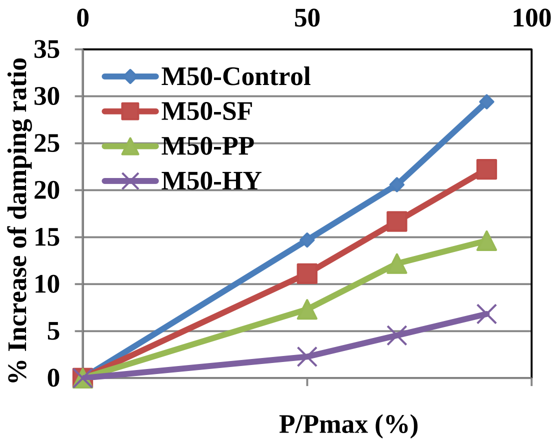
Figure 5.17a P/Pmax ratio versus damping ratios of RC, SFRC, PPFRC and HFRC beams for M25 concrete



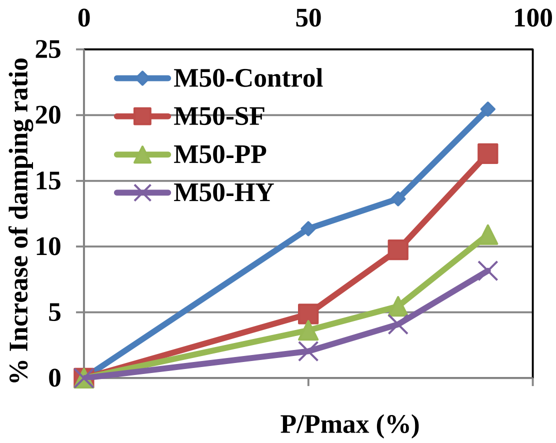
(a) First vibration mode



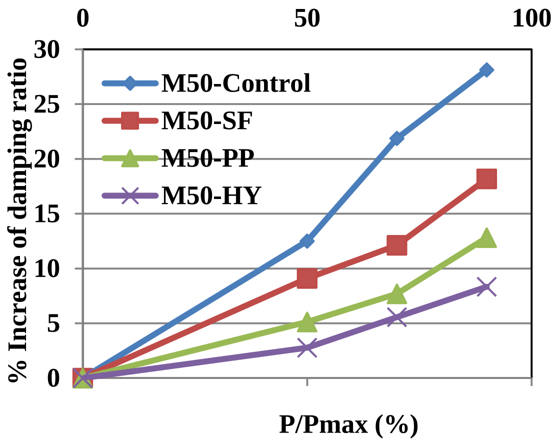
(b) Second vibration mode



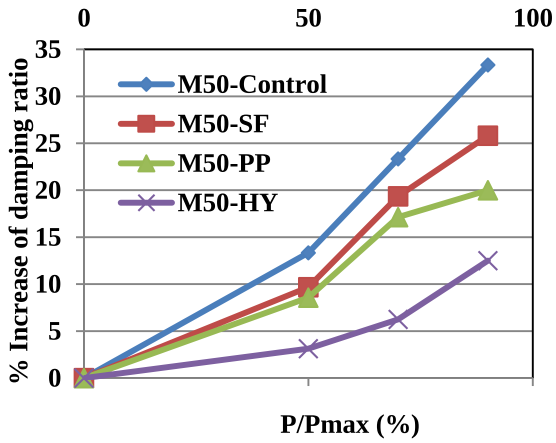
(c) Third vibration mode



(d) Fourth vibration mode



(e) Fifth vibration mode



(f) Sixth vibration mode

Figure 5.17b P/Pmax ratio versus damping ratios of RC, SFRC, PPFRC and HFRC beams for M50 concrete

5.5Concluding Remarks from Phase - I

In this chapter mechanical and dynamic properties of mono (steel and PP) and hybrid fiber reinforced concrete have been studied and the results were compared with control concrete. Also the static and dynamic assessment of RC beams strengthened with mono and hybrid fibers have also been determined and the results were compared with control RC beams. Following conclusions are drawn in this phase of experimental investigation.

Static test results emphasize that,

- Optimum dosage of mono steel and PP fibers achieved at 1% and 0.3% of total fiber volume fraction. Thereafter there is decrease in strength characteristics observed in both M25 and M50 grade concrete mix. The reason may be due to more number of fibers replaced the cement matrix.
- Addition of steel fibers to concrete marginally improves the compressive strength whereas split tensile strength and flexural strength improved up to 33.6% and 42.6%, respectively for M25 composite and 29.4% and 39.1%, respectively for M50 composite at 1% of fiber volume fraction compared with non-fibrous concrete.
- The addition of polypropylene fibers to concrete marginally improves the compressive strength whereas split tensile strength and flexural strength improved up to 24.1% and 28.1%, respectively for M25 composite and 22.9% and 33.5%, respectively for M50 composite at 0.3% volume fraction compared with non-fibrous concrete.
- The mechanical properties of steel fiber reinforced concrete improved when compared with control as well as polypropylene fiber reinforced concrete. Higher tensile strength and modulus of elasticity of steel fibers are the two main factors that contribute towards the better performance of concrete reinforced with steel fibers.

- The hybrid combination at 0.5% total fiber volume fraction with 75% steel and 25% PP considered to be best proportion in the composite in all the strength parameters, among all the fiber volume fractions considered.
- The addition of hybrid fibers to concrete slightly improves the compressive strength, whereas split tensile strength and flexural strength increased by about 51% and 56.8%, respectively for M25 composite 50% and 55.9%, respectively for M50 compositeat a total fiber volume fraction of 0.5% compared with non-fibrous concrete.
- The hybrid fibers consists of steel and polypropylene in M25 and M50 concrete mixtures, resulted an enhanced behavior in terms of compressive, splitting tensile and flexural strength compared with mono FRC and control concrete. This may be due to the synergic effect from the combination of high elastic modulus steel fiber and low elastic modulus polypropylene fibers.

Dynamic test results shows that,

- The natural frequency of SFRC specimen with the addition of 0.5% of steel fiber was increased by about 3.6% and 1.57% for first and second mode, respectively for M25 concrete and 4.04% and 2%respectively for M50 concrete compared with control concrete.
- Similarly, the natural frequency of PPFRC specimen with the addition of 0.1% of PP fiber was increased significantly about 2.43% and 1.7% for the first two modes of vibrationrespectively for M25 concrete and 4.11% and 1.9%respectively for M50 concrete compared with control concrete.
- Damping ratio of SFRC specimen with the addition of 1.25% of steel fiber was increased by about 29.16% and 35.29% for first and second mode, respectively for

M25 concrete and 19.64% and 28.5%respectively for M50 concrete when compared with non-fibrous concrete.

- Damping ratio of PPFRC specimen with the addition of 0.4% of PP fiber was increased by about 22.19% and 32.35% for first and second mode, respectively for M25 concrete and 19% and 28.7%respectively for M50 concrete compared with non-fibrous concrete.
- The natural frequency of HFRC specimens with the addition of 0.25% of total fiber volume fraction containing 25% of steel and 75% of PP fibers was increased by about 4.5% and 2.2% for first and second mode, respectively for M25 concrete and 4.65% and 2.77%respectively for M50 concrete compared with non-fibrous concrete.
- Damping ratio of HFRC specimen with the addition of 0.75% of total fiber volume fraction containing 75% of steel and 25% of PP fibers was increased by about 35.41% and 52.95% for the first and second mode of vibrations, respectively for M25 concrete and 44.65% and 52.4%respectively for M50 concrete when compared with non-fibrous concrete.

Results of static and dynamic assessment of RC beams shows that,

- Regarding static behavior of RC beams, the addition of mono steel and PP fibers were led to an increase in ultimate strength about 18.36% and 8.1% respectively for RC beams strengthened with steel and polypropylene fibersat its optimum fiber volume fraction when compared with control RC beams of M25 concrete.
- Ultimate strength of RC beams with the addition of steel and PP fibers were increased by about 16.54% and 12% respectively for RC beams strengthened with steel and polypropylene fibers at its optimum fiber volume fraction when compared with control RC beams of M50 concrete. The reason is due to the confinement effect provided by the fibersat all stress levels in concrete.

- Ultimate load carrying capacity of RC beams improved up to 20.80% and 18.94% respectively for M25 and M50 grade concrete with the addition of hybrid fibers at 0.5% total fiber volume fraction (75% steel and 25% PP) when compared with control RC beams. This is due to the ability of fibers to restrain the extension of cracks, reduce the extent of stress concentration and delayed the growth of cracks.
- From the experimental dynamic behavior of RC beams, from undamaged state (D_0) to final damage state (D_3), the natural frequencies of RC, SFRC, PFRC and HFRC beams decreased by about 21.4%, 19.38%, 17.51% and 15.15%, respectively in first mode of vibration where more drop in natural frequency is observed in corresponding beam for M25 grade of concrete.
- The damping ratio of RC, SFRC, PPFRC and HFRC beams increased by 31.42%, 17.94%, 14.63% and 12.12% at sixth mode, respectively for M25 grade of concrete.
- The natural frequencies of RC, SFRC, PFRC and HFRC beams decreased by about 20.48%, 17.82%, 13.96% and 12.31%, respectively in first mode of vibrationfor M50 grade of concrete.The decrease in natural frequency attributed to the decrease in stiffness of RC beams with the damage induced.
- The damping ratio of RC, SFRC,PPFRC and HFRC beams increased by approximately 33.33%, 25.81%, 20% and 16.12% at sixth mode, respectively for M50 grade of concrete. Damping is increased due to the damage induced; the reason is due to internal slippage or sliding during vibration.
- It is observed that the natural frequency decreases with the increase of damage level, whereas damping ratio increases with the increase of structural damage for all beams. The decrease in natural frequency attributed to the decrease in stiffness of RC beams with the damage induced. Damping is increased due to the damage induced, the reason is due to internal slippage or sliding during vibration. Flexure or shear cracks

that accompanied with the yielding of the reinforcements were able to be detected based on the reduction of natural frequency.

- The percentage decrease in natural frequency and the percentage increase in damping ratio for RC beam strengthened with mono steel and PP fiber is more compared with beams strengthened with hybrid fibers. The intensity and the occurrence of damage is very less for the beams strengthened with hybrid fibersfrom undamaged state to final damage state. This clearly indicates the effectiveness of hybrid fibers in preventing the damage.

CHAPTER 6

PHASE-II: MECHANICAL BEHAVIOR OF ECC AND DYNAMIC ASSESSMENT OF FGRC BEAMS

6.1 General

The class of ultra-ductile fiber which is reinforced with cementitious composites is ably known as engineered cementitious composite (ECC). Experimental results and discussion of engineered cementitious composites (ECC) are presented in this chapter. Mechanical properties of ECC have been determined with different percentage variation of polyvinyl alcohol and steel fibers in order to determine the optimum dosage of fibers, further functionally graded reinforced concrete (FGRC) beams have been cast. Also static and dynamic behavior of FGRC beams with the incorporation of different ECC layers in the tension zone have been studied and the results are compared with control RC beams without ECC.

6.2 Mechanical Properties of ECC

The mix Id's and dosage of the fibers used for mono and hybrid ECC are presented in Table 6.1.

Table 6.1 Designation of ECC specimens

S. No	Mix designation	Total fiber dosage (%)	Polyvinyl alcohol PVA (%)	Steel fiber SF (%)
1	ECC-Control	0	0	0
2	ECC0-2	2	0	2
3	ECC2-0	2	2	0
4	ECC1-1	2	1	1
5	ECC1.5-0.5	2	1.5	0.5
6	ECC0.5-1.5	2	0.5	1.5

6.2.1 Mini-Slump Cone Test

All ECC mixtures were mixed with the same procedure as discussed in section 4.4. The workability of fresh ECC mortar was determined using mini-slump come. A truncated cone mold with a bottom diameter of 92.08mm and a top diameter of 43.5mm and height of 75.78 mm has been used to evaluate the workability of each set of mixtures as shown in Figure 6.1.

Figure 6.1 Typical view of mini slump cone test

The cone was kept in the horizontal base plate and the fresh mortar has been poured and tamped lightly to bleed off any entrapped air pockets, and the cone was then lifted up gently.

The slump flow deformation was defined as the dimension of the spread when the mortar stops flowing. The mini-slump flow diameter for each ECC mixtures is illustrated in Table 6.2. From the results it is observed that the addition of polyvinyl alcohol (PVA) fibers reduces the workability of the composite matrix.

Table6.2Mini-slump flow results of ECC

S. No	Mix designation	Mini-slump flow diameter (cm)
1	ECC-Control	29.0
2	ECC0-2	25.2
3	ECC2-0	23.4
4	ECC1-1	22.6
5	ECC1.5-0.5	21.4
6	ECC0.5-1.5	22.2

6.2.2Compressive Strength test

The results of compressive strength of mono and hybrid ECC mixtures are presented in Table 6.3 and compared with control ECC (without fibers).The value of compressive strength recorded in the table is the average of three similar cubes tested in under direct compression.

Table6.3 Compressive strength results of ECC

S. No	Mix designation	Compressive strength (MPa)	Percentage Increase (%)
1	ECC-Control	51.28	-
2	ECC0-2	57.01	11.2
3	ECC2-0	54.14	5.6
4	ECC1-1	59.13	15.3
5	ECC1.5-0.5	61.95	20.8
6	ECC0.5-1.5	58.05	13.2

From the experimental compressive strength results, it is observed that the maximum percentage strength increase is 11.2% for ECC mixture with mono steel fibers and 5.6% for ECC mixture with mono PVA fibers compared with control ECC. It is also observed that the maximum strength improvement is 20.8% for the ECC mixture containing 1.5% of PVA and 0.5% of steel fiber at total fiber volume fraction of 2%. Percentage increase in compressive strength is more with fiber hybridization when compared with mono ECC as well as control ECC mixtures. Reason might be imputed due to the self-cementing properties of micro-silica or silica sand to attain higher compressive strength and also because of the inclusion of PVA and steel fibers to the mortar matrix. The strength effectiveness of hybrid fibers is comparatively better than that of the mono and non-fibrous cementitious composites.

6.2.3Flexural Strength Test

Flexural strength has been examined under four-point bending test on a prismatic specimen of size (305mm x 76mm x 38mm). The flexural strength values of ECC mixtures are shown in Table 6.4.

Table6.4Flexural strength results of ECC

S. No	Mix designation	Flexural strength (MPa)	Percentage Increase (%)
1	ECC	8.15	-
2	ECC0-2	10.10	23.9
3	ECC2-0	10.87	33.4
4	ECC1-1	11.25	38.0
5	ECC1.5-0.5	12.68	55.6
6	ECC0.5-1.5	10.36	27.1

It is observed that percentage increase in flexural strength is more compared with the compressive strength because of fibers in concrete delay the crack formation and propagation thereby flexural strength increases substantially. The maximum percentage increase of flexural strength is 23.9% for ECC mixture with mono steel fibers and 33.4% for ECC mixture with mono PVA fibers. It is observed that the maximum flexural strength is observed at 2% total fiber volume fraction with the combination of 1.5% of PVA and 0.5% of steel fibers. The maximum percentage increase in flexural strength is 55.6% for hybrid fiber ECC mixture and the reason is at low stress-levels, PVA fibers present in ECC mortar control the propagation of micro-cracks and plastic shrinkage cracks and long length steel fibers control the cracks at high stress levels and improve the strength properties at post-cracks regions which is responsible for the improvement in flexural strength. Similar observation was found by *Altwairet al. (2012)*.

The flexural stress versus mid-span deflection of engineeredcementitious composites with different percentage variation of PVA and steel fibers are shown in Figure 6.2.In general engineered cementitious composite material shows an elastic and plastic behavior under flexural loading.

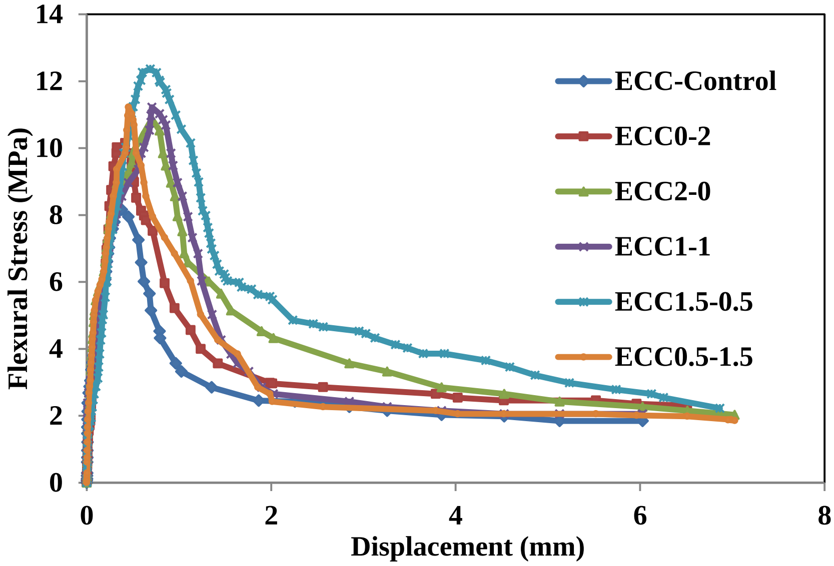


Figure 6.2 Flexural stress versus deflection of ECC mixtures

It is observed from the above Figure 6.2, load versus deflection curve tends to be linearly elastic with the flexural loading till the first crack occurs and after that there was a little sudden drop in stress due to cracking of cementitious composites as well as yielding of fibers.As the fiber content increases, difficulty in dispersing the PVA fibers which in turn result in low workability and less homogeneity of matrix. Increase in PVA fibers led to a slight increase in post cracking strength. The higher flexural strength in the hybrid composites is contributed by the higher bond at the interface between fine aggregates and cement matrix as well as the interface between steel and PVA fibers. Figure 6.3 shows the failure pattern of ECC specimens. It is observed that the ductility of ECC with mono and hybrid fibers is improved substantially.

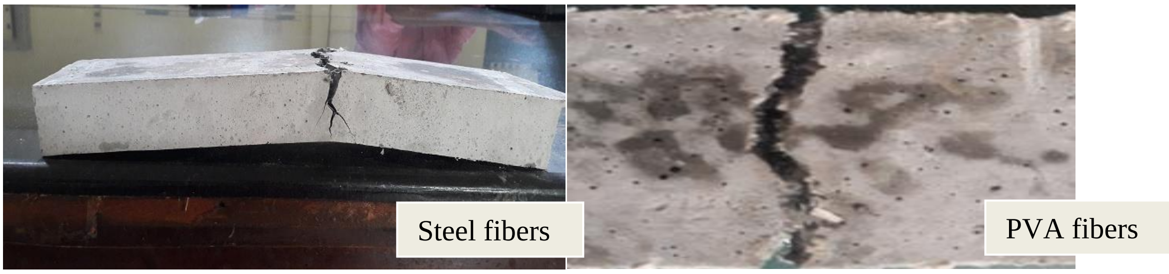


Figure 6.3Flexural failure patterns of ECC specimens

6.2.4Uni-axial Tensile Strength

Tensile behavior was measured by uni-axial tension test which has been performed on dog bone shaped coupon specimens and the results obtained are illustrated in Table 6.5. There is a substantial improvement in direct tensile strengthobserved with the fiber hybridization compared with mono ECC and control ECC.

Table6.5Uni-axial tensile strength results of ECC

S. No	Mix designation	Tensile strength (MPa)	Percentage Increase (%)
1	ECC	6.65	-
2	ECC0-2	7.88	18.5
3	ECC2-0	8.2	23.3
4	ECC1-1	8.45	27.1
5	ECC1.5-0.5	9.45	42.1
6	ECC0.5-1.5	8.55	28.6

The maximum strength improvement observed is 18.5% for ECC with mono steel fibers and 23.3% for ECC with mono PVA fibers compared with control ECC. It is also observed that the maximum percentage increase in tensile strength is 42.1% at a hybrid combination of 1.5% of PVA and 0.5% of steel fibers compared with control ECC. Similar observations were made by *Ali et al. (2017)*. The strength improvement in tensile strength with the addition of steel and PVA fibers is manifested as hybridization effect on fracture plane of the cementitious composite, at fracture plane more number of availability of PVA fibers bridge the micro-cracks at lower stress levels, at higher stress levels non-metallic PVA fibers cannot withstand and the stresses are being transferred from non-metallic to metallic fibers, thereafter these metallic fibers come into action to control the formation of macro-cracks.

Figure6.4 shows the tensile stress-strain behavior of ECC. ECC specimens with the addition of fibers exhibited a strain hardening behavior up to failure.

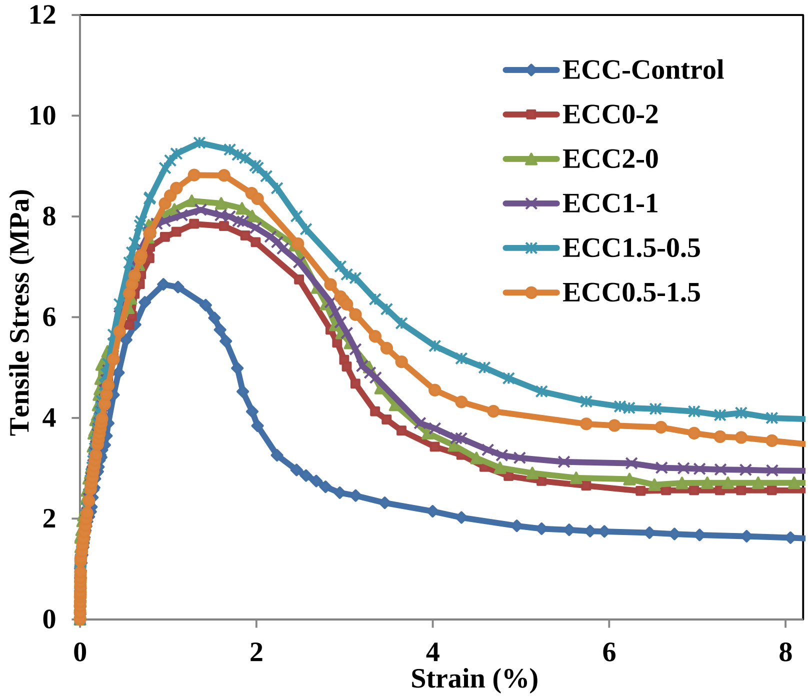


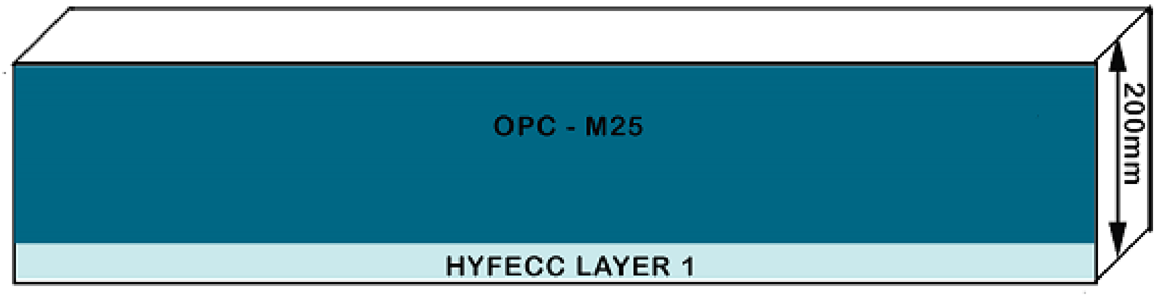
Figure 6.4Tensile stress versus strain of ECC

From the above Figure, it is observed that, ECC specimens with fibers pronounced impact on both pre-peak and post-peak behavior. The combination of both PVA and steel fibers arrest the multi-scale cracks formed at different stress levels in composites. Also, the improved tensile strength of hybrid fiber reinforced ECC can be attributed to increase the fiber-matrix interfacial bond, due to increase in PVA fiber content, which consequently, improving the tensile strength of the composites. Failure pattern of ECC dog-bone specimens are shown in Figure 6.5.

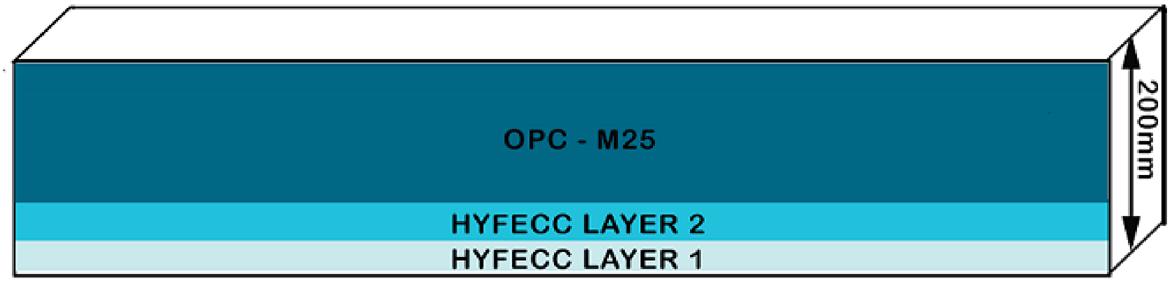
Figure 6.5 Failure patterns of dog-bone specimens of ECC

6.3 Functionally Graded Reinforced Concrete Beams

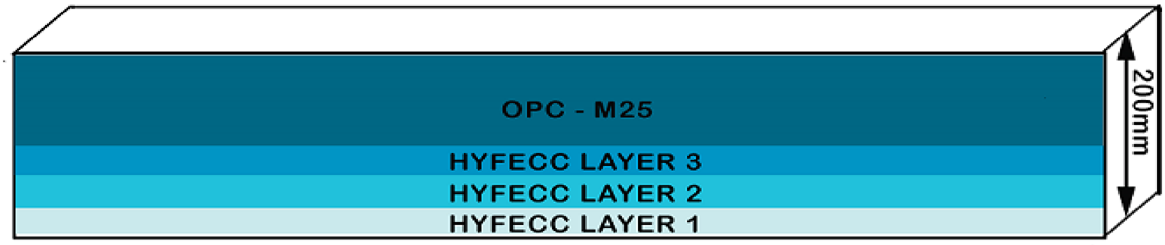
Functionally graded reinforced concrete (FGRC) is a continuously graded material that has different properties in certain directions either in the top or in the bottom portion of the beam. Thissection presents the study ofstatic and dynamic behavior of functionally graded reinforced concrete beams using ECC layers. FGRC beams incorporated with ultra-ductile ECC material in the tension zone in three different layers each layer of thickness 25mm as shown in Figure 6.6.



6.6 (a) FGRC beam with one layer of ECC material



6.6 (b) FGRC beam with two layers of ECC material



6.6 (c) FGRC beam with three layers of ECC material

Figure 6.6 Schematic view of FGRC beams with ECC layers

Total 16 beams were cast and tested, designations and positions of ECC layers in FGRC beams are illustrated in Table 6.6. Two similar beams were tested to assess the static and dynamic behavior of FGRC beams with layered ECC material. The first beam was loaded till ultimate load for obtaining the ultimate static flexural strength and the second beam was tested with different percentage of ultimate load such as 50%, 70% and 90%. After each damage level, beam was unloaded and dynamic testing was carried out to assess the dynamic characteristics. Later the correlation between undamaged and damage states has been assessed through change in dynamic characteristics.

Table 6.6 Designations and positions of ECC layers in FGRC beams

Mixtures	Beam designation	Beam type	No. of ECC layers (25mm thickness)	Type of test
1	M25Control-S	RC	-	Static
2	M25Control-D	RC	-	Dynamic
3	M25ECC1-S	FGRC-175OPC	25	Static
4	M25ECC1-D	FGRC-175OPC	25	Dynamic
5	M25ECC2-S	FGRC-150OPC	50	Static
6	M25ECC2-D	FGRC-150OPC	50	Dynamic
7	M25ECC3-S	FGRC-125OPC	75	Static
8	M25ECC3-D	FGRC-125OPC	75	Dynamic
9	M50Control-S	RC	-	Static
10	M50Control-D	RC	-	Dynamic
11	M50ECC1-S	FGRC-175OPC	25	Static
12	M50ECC1-D	FGRC-175OPC	25	Dynamic
13	M50ECC2-S	FGRC-150OPC	50	Static
14	M50ECC2-D	FGRC-150OPC	50	Dynamic
15	M50ECC3-S	FGRC-125OPC	75	Static
16	M50ECC3-D	FGRC-125OPC	75	Dynamic

6.3.1Static Analysis of RC and FGRC Beams with ECC Layers

Experimental results of static test for both RC beams and FGRC beams are tabulated in Table 6.7 for M25 and M50 grades of concrete. Load versus mid-span deflection plot is shown in Figure 6.7. From the static test results, it is observed that the maximum percentage improvement in FGRC beams is 15.91%, 25.71% and 35.91% for ECC 1 layer, 2 layers and 3 layers respectively for M25 grade concrete compared with control RC beams. Similarly for the FGRC beams strengthened with ECC 1 layer, 2 layers and 3 layers, the maximum percentage strength was increased by about 18.22%, 27.09% and 36.45% respectively for M50 grade concretecompared with control RC beams.

Table 6.7a Static test results of RC and FGRC beams for M25 concrete

Beam designation	Ultimate load (kN)	% Increase of load	Maximum deflection
M25Control-S	122.5	-	48
M25ECC1-S	142	15.91	54
M25ECC2-S	154	25.71	56
M25ECC3-S	166.5	35.91	58

Table 6.7b Static test results of RC and FGRC beams for M50 concrete

Beam designation	Ultimate load (kN)	% Increase of load	Maximum deflection
M50Control-S	208.5	-	46
M50ECC1-S	246.5	18.22	55
M50ECC2-S	265	27.09	56
M50ECC3-S	284.5	36.45	57

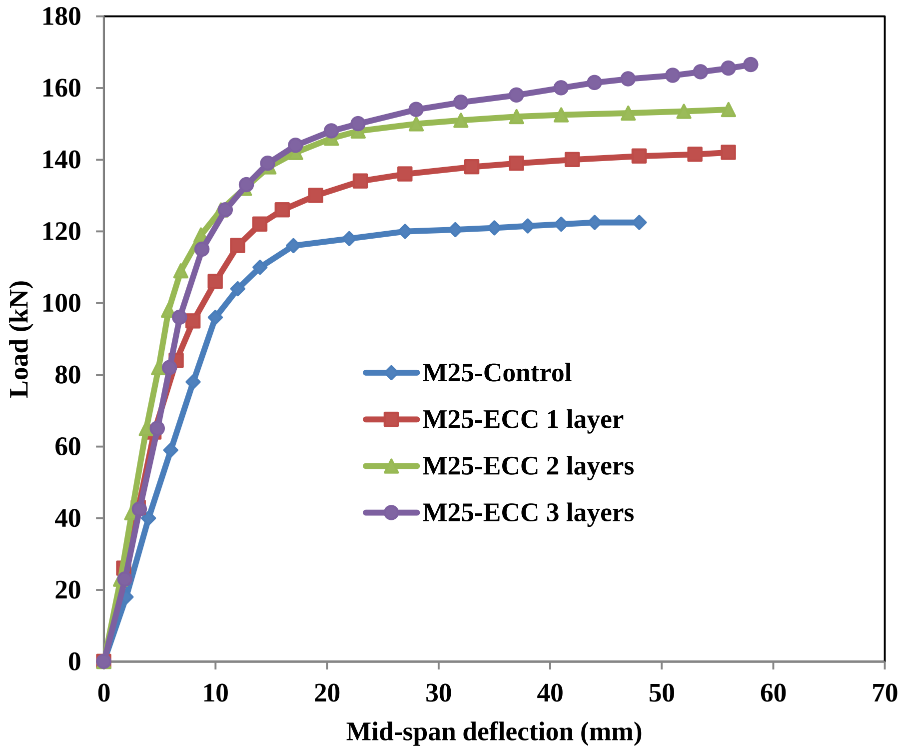


Figure 6.7a Load versus deflection of RC and FGRC beams for M25 concrete

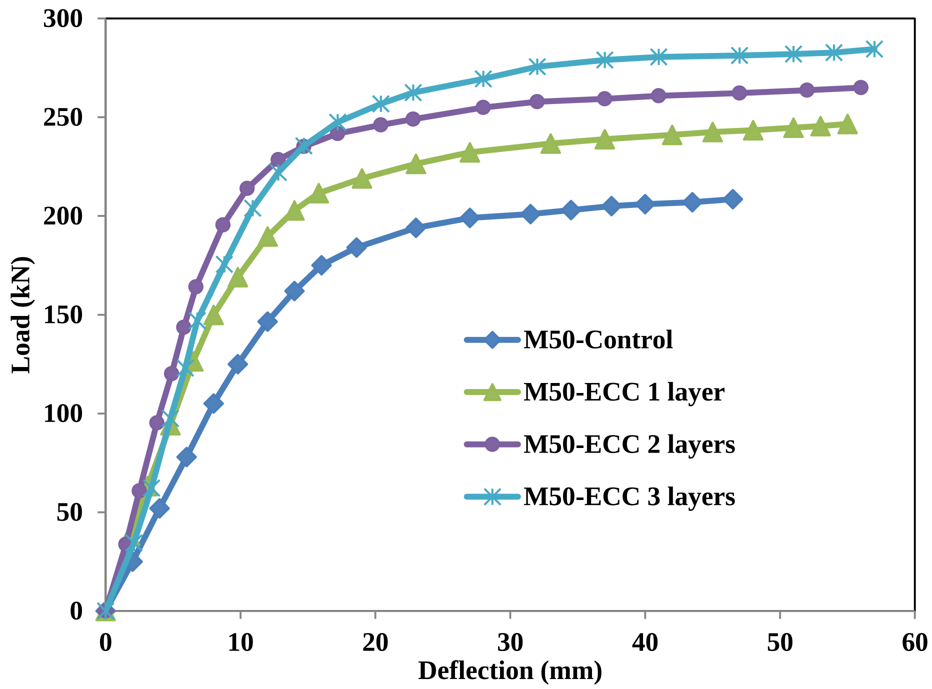
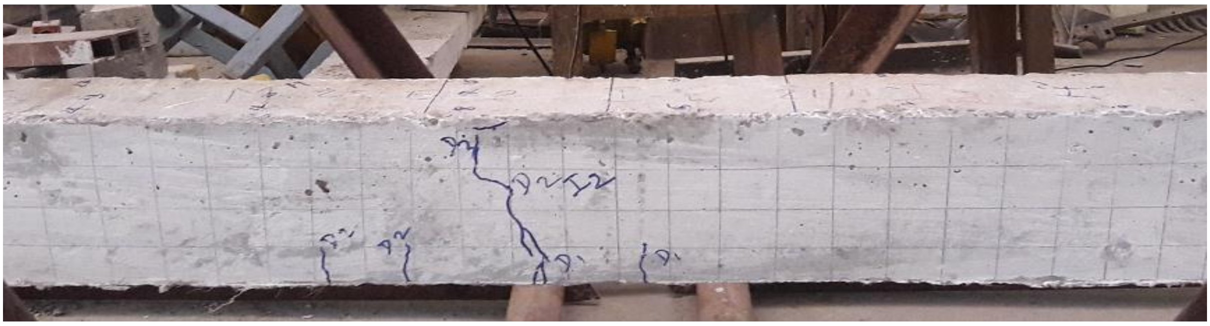


Figure 6.7b Load versus deflection of RC and FGRC beams for M50 concrete

The reason is due toapart from longitudinal and transverse reinforcement in the beams, ECC ductile material in the form of layers have also been added in the tension zone which enhances the flexural strength.Flexural cracks in the tension zone arrested by ductile ECC material. Formation of cracks is very less for FGRC beams with ECC material compared to that of control RC beams as shown in Figure 6.8. From the static test results, it is also observed that the load carrying capacity of FGRC beams increases with the increase of ECC layers. ECC layers are abundantly effective even after the formation of cracks and further it redistributes the flexural stresses after the formation of flexural cracks in the bottom zone. Figure6.8 shows the failure patterns of control RC and FGRC beams under monotonic loading condition. Similar experimental results were observed by *Maalej et al. (2010)*.

6.8 (a) Control RC beam after complete failure

6.8 (b) FGRC beam with one layer of ECC material after complete failure



6.8 (c) FGRC beam with two layers of ECC material after complete failure

6.8 (d) FGRC beam with three layers of ECC material after complete failure

Figure 6.8 Failure patterns of RC and FGRC beams

6.3.2Dynamic Analysis of RC and FGRC Beams with ECC Layers

Dynamic assessment of RC and FGRC beams have been carried out at each damage degree as discussed in section 5.4.2. Natural frequency and damping ratio values from undamaged to final damage level of FGRC beams with one layer, two layers and three layers of ECC material for both M25 and M50 grade of concrete are tabulated in Table 6.8a, 6.8b, 6.9a, 6.9b, 6.10a, 6.10b, 6.11a, 6.11b, 6.12a, 6.12b, 6.13a and 6.13b respectively. From the dynamic test results it is observed that the natural frequency decreases with the increase of damage whereas damping ratio increases with the increase of damage.

Table 6.8a Experimental natural frequency values of FGRC-ECC1 beam-M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	218.5	0.0	580.2	0.0	1065	0.0	1625	0.0	2284	0.0	2828	0.0
D_1	71	200.3	8.3	538.1	7.3	999.6	6.1	1529	5.9	2091	8.5	2683	5.1
D_2	99.4	184.2	15.7	519.3	10.5	981.6	7.8	1459	10.2	1974	13.6	2548	9.9
D_3	127.8	176.1	19.4	503.4	13.2	936.4	12.1	1393	14.3	1865	18.3	2384	15.7

Table 6.8b Experimental damping ratio values of FGRC-ECC1 beam-M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.95	0.0	0.68	0.0	0.56	0.0	0.53	0.0	0.48	0.0	0.39	0.0
D_1	71	0.98	3.2	0.71	4.4	0.59	5.4	0.56	5.7	0.51	6.3	0.41	5.1
D_2	99.4	1.01	6.3	0.73	7.4	0.63	12.5	0.59	11.3	0.53	10.4	0.43	10.3
D_3	127.8	1.08	13.7	0.75	10.3	0.64	14.3	0.61	15.1	0.56	16.7	0.46	17.9

Table 6.9a Experimental natural frequency values of FGRC-ECC1 beam-M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	241	0.0	625.3	0.0	1151	0.0	1745	0.0	2384	0.0	3125	0.0
D_1	123.25	214.7	10.9	590.1	5.6	1048	9.0	1599	8.4	2254	5.5	2878	7.9
D_2	172.55	203.6	15.5	566.9	9.3	1006	12.6	1542	11.6	2135	10.4	2776	11.2
D_3	221.85	197.1	18.2	548.1	12.3	947	17.7	1459	16.4	2011	15.6	2681	14.2

Table 6.9b Experimental damping ratio values of FGRC-ECC1 beam-M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.77	0.0	0.56	0.0	0.51	0.0	0.44	0.0	0.4	0.0	0.39	0.0
D_1	123.2	0.81	5.2	0.58	3.6	0.54	5.9	0.47	6.8	0.43	7.5	0.42	7.7
D_2	172.5	0.83	7.8	0.61	8.9	0.57	11.8	0.49	11.4	0.45	12.5	0.44	12.8
D_3	221.8	0.86	11.7	0.63	12.5	0.6	17.6	0.51	15.9	0.48	20.0	0.47	20.5

Table 6.10a Experimental natural frequency values of FGRC-ECC2 beam-M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	229.5	0.0	605.8	0.0	1084	0.0	1684	0.0	2248	0.0	2848	0.0
D_1	77	212.8	7.3	565.3	6.7	1035	4.5	1602	4.9	2089	7.1	2731	4.1
D_2	107.8	196.1	14.6	548.6	9.4	1013	6.5	1538	8.7	1964	12.6	2596	8.8
D_3	138.6	189.8	17.3	532.1	12.2	969	10.6	1463	13.1	1863	17.1	2439	14.4

Table 6.10b Experimental damping ratio values of FGRC-ECC2 beam-M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.95	0.0	0.89	0.0	0.77	0.0	0.63	0.0	0.55	0.0	0.41	0.0
D_1	77	0.97	2.1	0.92	3.4	0.79	2.6	0.66	4.8	0.57	3.6	0.42	2.4
D_2	107.8	0.98	3.2	0.94	5.6	0.81	5.2	0.69	9.5	0.59	7.3	0.44	7.3
D_3	138.6	1.06	11.6	0.97	9.0	0.84	9.1	0.72	14.3	0.62	12.7	0.47	14.6

Table 6.11a Experimental natural frequency values of FGRC-ECC2 beam-M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	245.8	0.0	652.3	0.0	1190	0.0	1752	0.0	2351	0.0	2958	0.0
D_1	132.5	221.5	9.9	625.1	4.2	1098	7.7	1645	6.1	2253	4.2	2767	6.5
D_2	185.5	211.3	14.0	594.4	8.9	1056	11.3	1562	10.8	2125	9.6	2673	9.6
D_3	238.5	205.2	16.5	575.8	11.7	1023	14.0	1493	14.8	2007	14.6	2592	12.4

Table 6.11b Experimental damping ratio values of FGRC-ECC2 beam-M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	0.9	0.0	0.77	0.0	0.67	0.0	0.52	0.0	0.46	0.0	0.42	0.0
D_1	132.5	0.93	3.3	0.79	2.6	0.7	4.5	0.54	3.8	0.49	6.5	0.44	4.8
D_2	185.5	0.97	7.8	0.82	6.5	0.72	7.5	0.57	9.6	0.51	10.9	0.47	11.9
D_3	238.5	1.02	13.3	0.85	10.4	0.76	13.4	0.59	13.5	0.53	15.2	0.49	16.7

Table 6.12a Experimental natural frequency values of FGRC-ECC3 beam-M25 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	232.6	0.0	615.5	0.0	1145	0.0	1706	0.0	2239	0.0	2984	0.0
D_1	83.25	218.1	6.2	576.8	6.3	1113	2.8	1656	2.9	2098	6.3	2893	3.0
D_2	116.55	203.4	12.6	562.2	8.7	1074	6.2	1583	7.2	1986	11.3	2755	7.7
D_3	149.85	195.1	16.1	543.8	11.6	1035	9.6	1512	11.4	1886	15.8	2581	13.5

Table 6.12b Experimental damping ratio values of FGRC-ECC3 beam-M25 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	1.03	0.0	0.78	0.0	0.7	0.0	0.61	0.0	0.56	0.0	0.54	0.0
D_1	83.25	1.04	1.0	0.79	1.3	0.71	1.4	0.62	1.6	0.57	1.8	0.56	3.7
D_2	116.55	1.05	1.9	0.81	3.8	0.72	2.9	0.65	6.6	0.59	5.4	0.57	5.6
D_3	149.85	1.07	3.9	0.82	5.1	0.73	4.3	0.66	8.2	0.61	8.9	0.6	11.1

Table 6.13a Experimental natural frequency values of FGRC-ECC3 beam-M50 concrete

Damage degree	Load (kN)	f_1 (Hz)	$\Delta f_1/f_1$ (%)	f_2 (Hz)	$\Delta f_2/f_2$ (%)	f_3 (Hz)	$\Delta f_3/f_3$ (%)	f_4 (Hz)	$\Delta f_4/f_4$ (%)	f_5 (Hz)	$\Delta f_5/f_5$ (%)	f_6 (Hz)	$\Delta f_6/f_6$ (%)
D_0	0	248.7	0.0	625.9	0.0	1190	0.0	1756	0.0	2364	0.0	3125	0.0
D_1	142.25	232.6	6.5	605.8	3.2	1105	7.1	1671	4.8	2279	3.6	2973	4.9
D_2	199.15	215.8	13.2	581.2	7.1	1074	9.8	1594	9.2	2164	8.5	2859	8.5
D_3	256.05	207.7	16.5	555.8	11.2	1035	13.1	1519	13.5	2036	13.9	2776	11.2

Table 6.13b Experimental damping ratio values of FGRC-ECC3 beam-M50 concrete

Damage degree	Load (kN)	ζ_1	$\Delta\zeta_1/\zeta_1$ (%)	ζ_2	$\Delta\zeta_2/\zeta_2$ (%)	ζ_3	$\Delta\zeta_3/\zeta_3$ (%)	ζ_4	$\Delta\zeta_4/\zeta_4$ (%)	ζ_5	$\Delta\zeta_5/\zeta_5$ (%)	ζ_6	$\Delta\zeta_6/\zeta_6$ (%)
D_0	0	1.02	0.0	0.63	0.0	0.59	0.0	0.53	0.0	0.49	0.0	0.46	0.0
D_1	142.25	1.04	2.0	0.64	1.6	0.61	3.4	0.54	1.9	0.51	4.1	0.47	2.2
D_2	199.15	1.07	4.9	0.65	3.2	0.63	6.8	0.56	5.7	0.53	8.2	0.51	10.9
D_3	256.05	1.09	6.9	0.67	6.3	0.64	8.5	0.58	9.4	0.54	10.2	0.52	13.0

From the dynamic test results it is observed that the maximum percentage variation in natural frequency of FGRC beam with one layer of ECC material from undamaged state to final damage state in first mode of vibration is 19.4% for M25 and 18.2% for M50 grade concrete. Similarly the maximum percentage variation in damping ratio of FGRC beam with one layer of ECC material from undamaged state to final damage state in sixth mode of vibration is 17.9% for M25 and 20.5% for M50 grade concrete. Similarly for FGRC beams with two layers of ECC material from undamaged state to final damage state, the maximum percentage variation in natural frequency in first mode of vibration is 17.3% for M25 and 16.5% and M50 grade concrete. The maximum percentage variation in damping ratio of FGRC beam with two layers of ECC material from undamaged state to final damage state in sixth mode of vibration is 14.6% for M25 and 16.7% for M50 grade concrete. For FGRC beams with three layers of ECC material from undamaged state to final damage state, the maximum percentage variation in natural frequency in first mode of vibration is 16.1% for M25 and 16.5% and M50 grade concrete. The maximum percentage variation in damping ratio of FGRC beam with three layers of ECC material from undamaged state to final damage state in sixth mode of vibration is 11.1% for M25 and 13% for M50 grade concrete. It is also observed that the percentage decrease of natural frequency decreases with the increase of ECC layers in the tension zone of the beam whereas the percentage increase of damping ratio decreases with the increase of ECC layers. Similar kind of observation was found by *Capozzuca et al. (2015)*for

RC beams strengthened with CFRP NSM rods. The reason is due to the addition of ultra-ductile ECC material in the tension zone of the beams with the incorporation of steel and PVA fibers which can arrest the micro as well as macro cracks and also preventing from the propagation and formation of cracks further. Figure 6.9a, 6.9b and 6.9c shows the envelope of FRF for different damage levels of FGRC beams with one layer, two layers and three layers of ECC material in the tension zone of the beam. From the FRF diagrams, the peaks in FRF shifted towards the left side which shows the decrease in natural frequency values recorded at undamaged to the final damage degree.

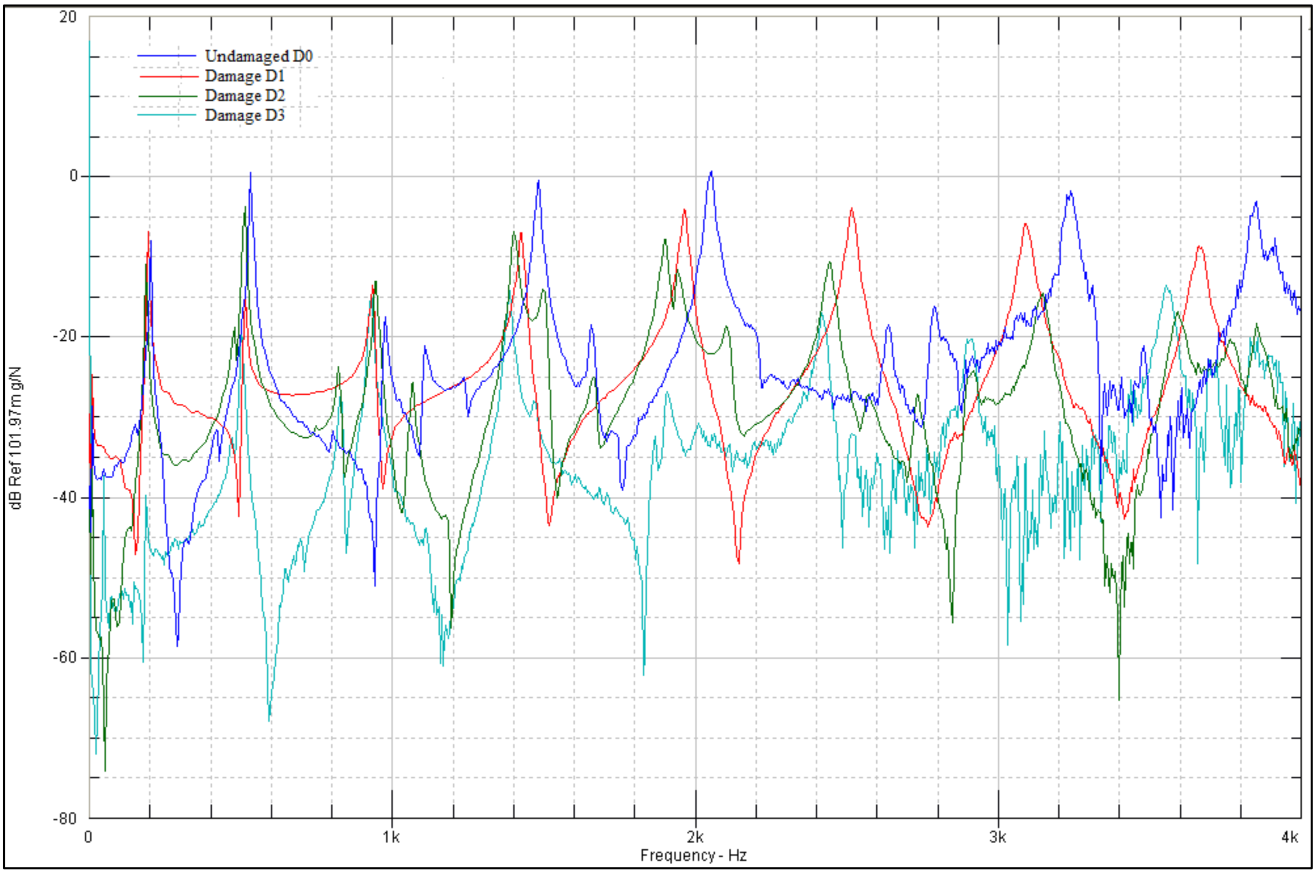


Figure 6.9a Envelope of FRF for different damage levels of FGRC beams with one layer of ECC material

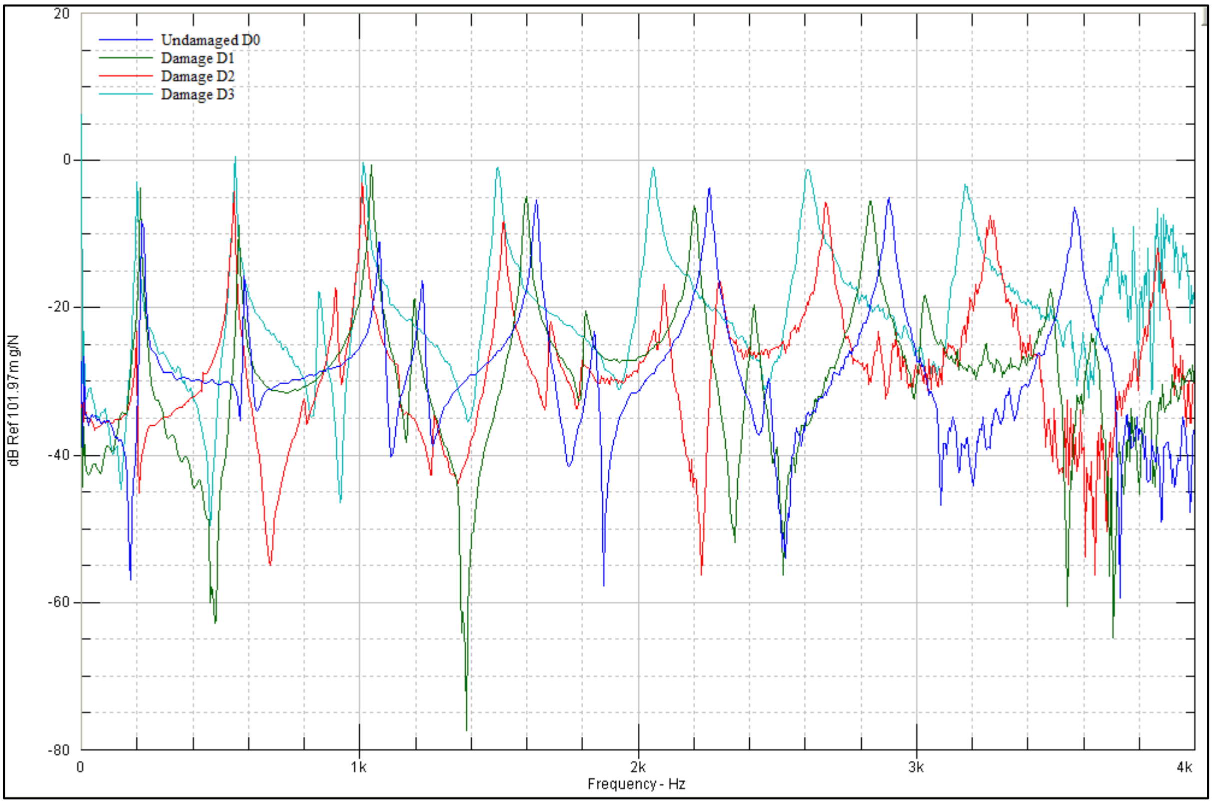


Figure 6.9b Envelope of FRF for different damage levels of FGRC beams with two layers of ECC material

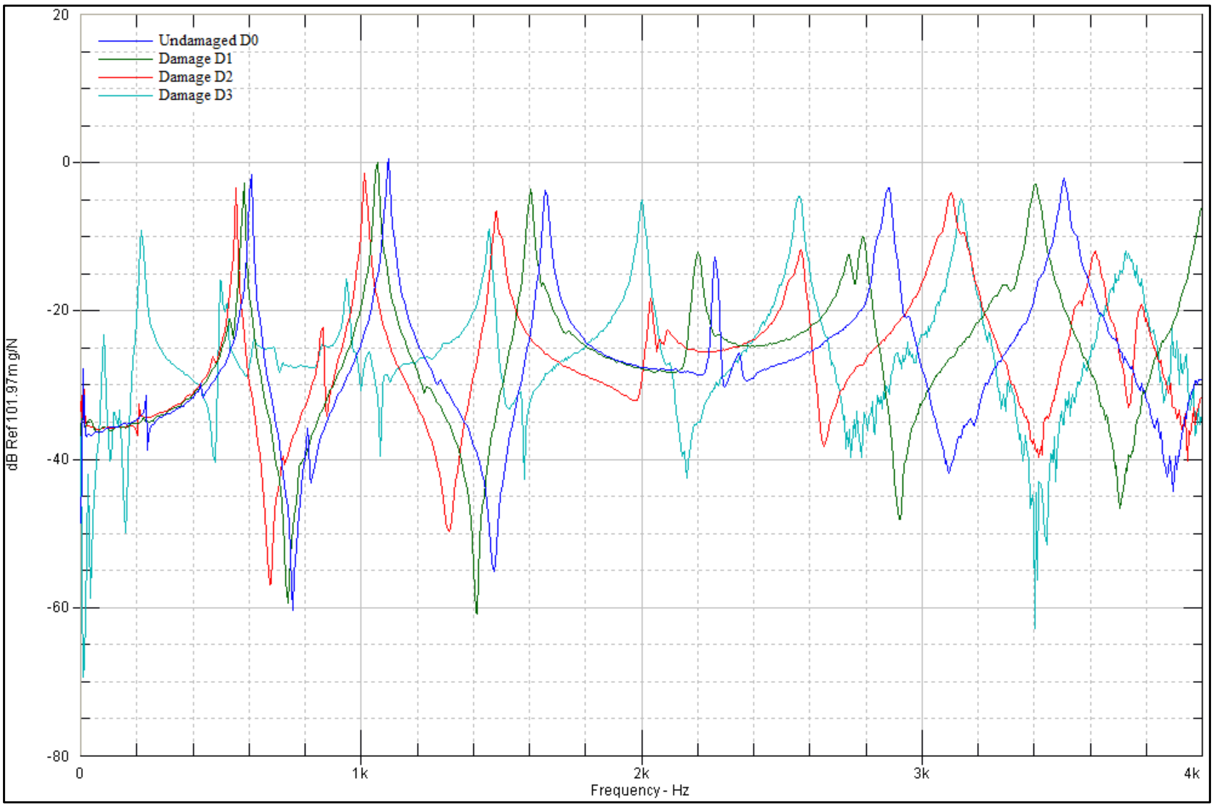


Figure 6.9c Envelope of FRF for different damage levels of FGRC beams with three layers of ECC material

6.3.3 Comparison of Dynamic Behavior on RC and FGRC Beams

Comparison of natural frequency values of control RC and FGRC beams from undamaged level to final damage level for both M25 and M50 grade concrete is shown in Figure 6.10a and Figure 6.10b respectively.

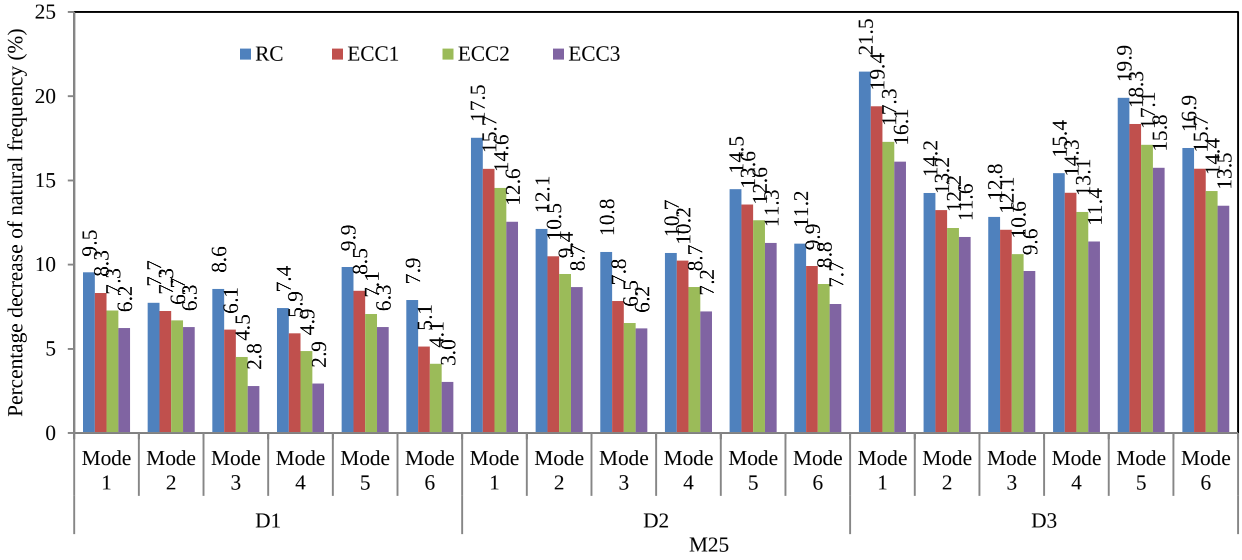


Figure 6.10a Comparison of natural frequency values of control RC and FGRC beams – M25 concrete

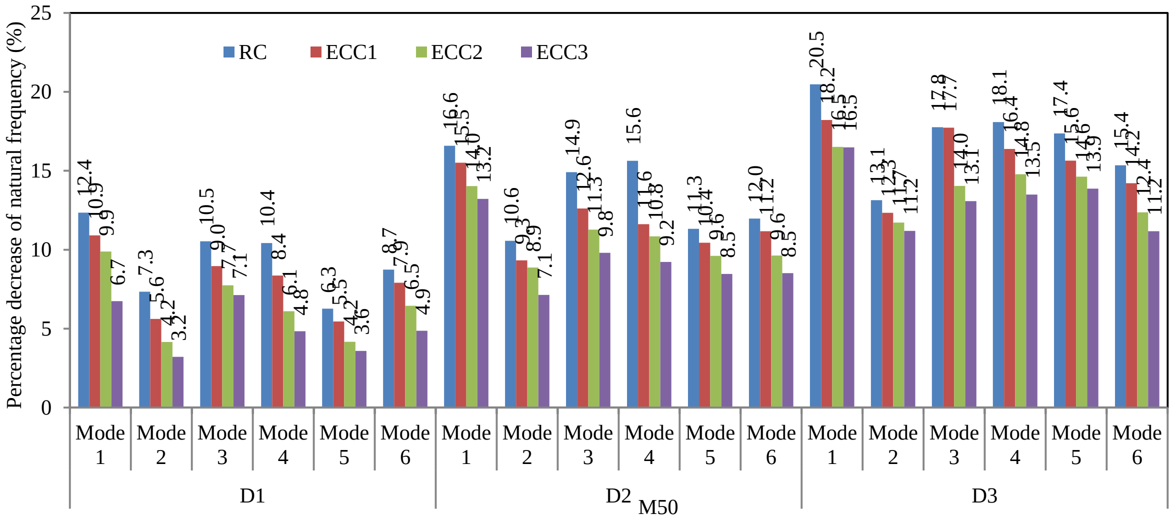


Figure 6.10b Comparison of natural frequency values of RC and FGRC beams – M50 concrete

From the Figure, it is observed that the maximum percentage variation in natural frequency is very less for FGRC beam with three layers of ECC material compared with RC beams with control RC beams. Percentage variation of FGRC beam with three layers of ECC material in first mode of vibration is 16.1% for M25 and 16.5% for M50 grade concrete from undamaged to final damage state which is lesser than FGRC beams with one and two layers of ECC material as well as control RC beams.

Comparison of damping ratio values of control RC and FGRC beams from undamaged level to final damage level for M25 and M50 grade concrete is shown in Figure 6.11a and Figure 6.11b respectively. From the Figure, it is observed that the maximum percentage variation in damping ratio is very less for FGRC beam with three layers of ECC material compared with control RC beams. The maximum percentage variation of FGRC beam with three layers of ECC material in sixth mode of vibration is 11.1% for M25 and 13% for M50 grade concrete from undamaged to final damage state which is lesser than FGRC beams with one and two layers of ECC material as well as control RC beams.

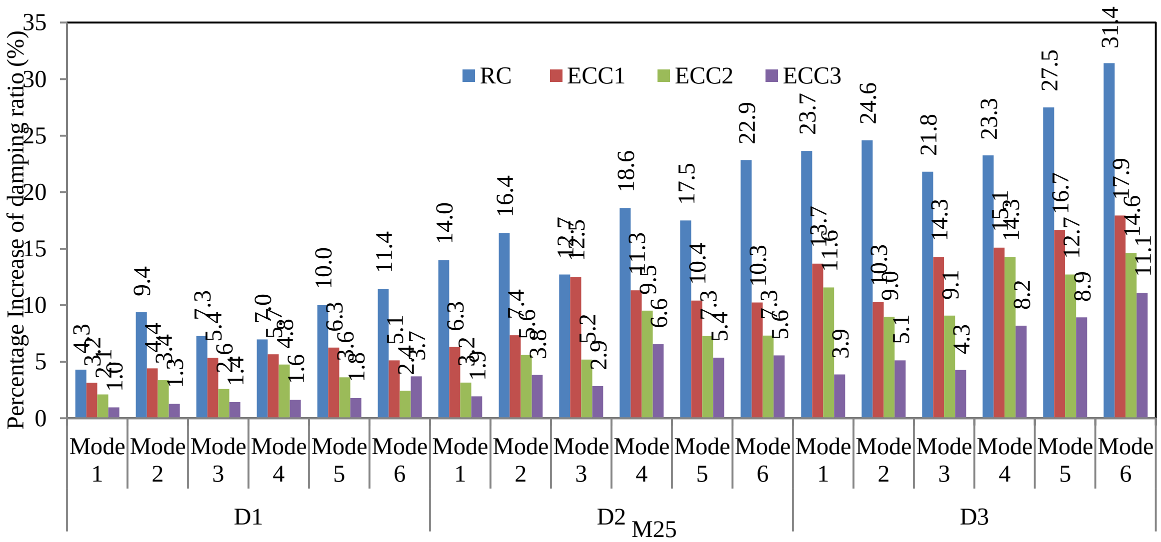


Figure 6.11a Comparison of damping ratio values of control RC and FGRC – M25 concrete

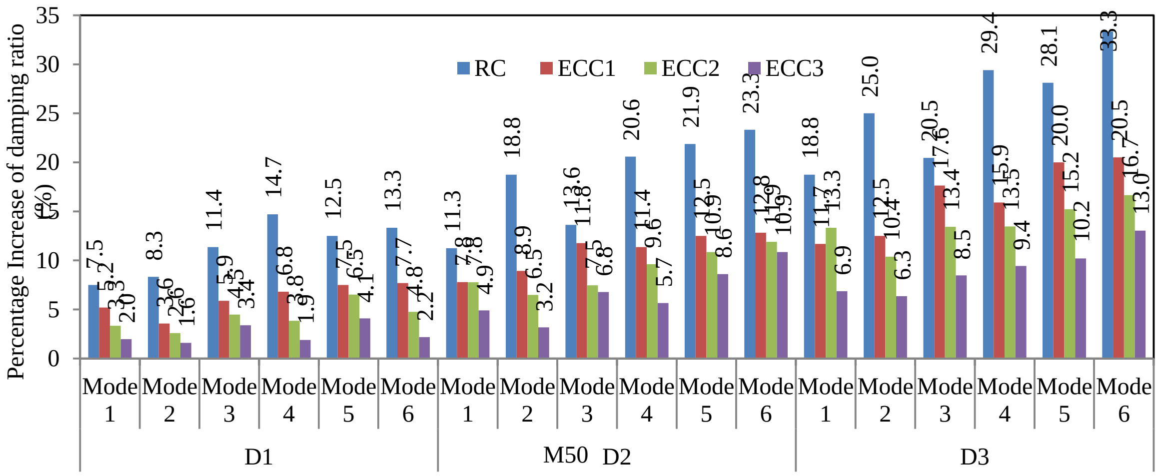
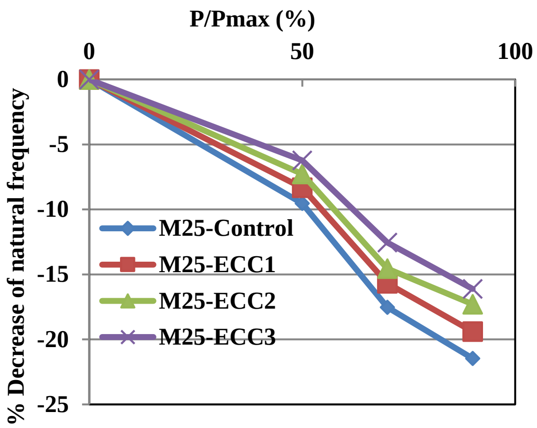
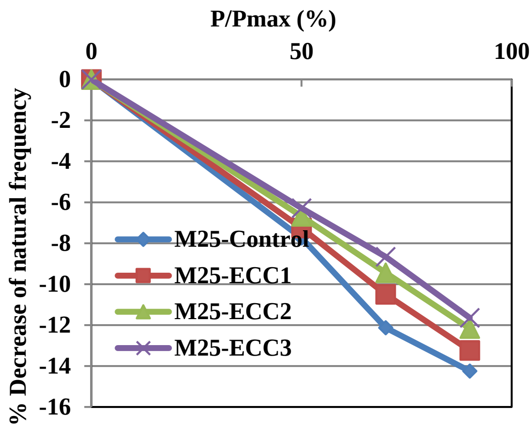


Figure 6.11b Comparison of damping ratio values of control RC and FGRC – M25 concrete

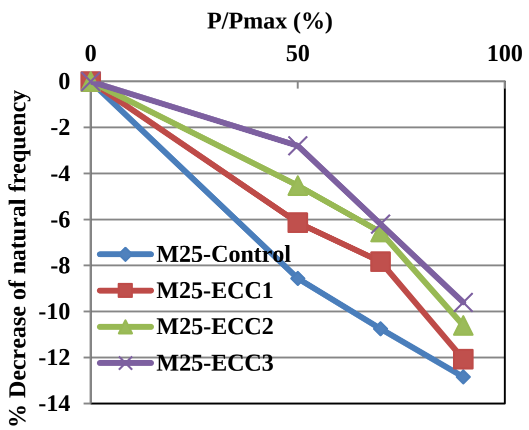
In order to observe the effectiveness of ECC material with three different layers in the tension zone of the beam with the incorporation of steel and PVA fibers against different damage levels, P/Pmax ratio versus frequency ratioofRC and FGRC beamsat each damage levelforsix different modes of vibration are plottedas shown in Figure 6.12a and Figure 6.12b for M25 and M50 grades of concrete respectively. From the Figure, it can be observed that up to first damage level (50% of ultimate load) the change in stiffness of the FGRC beam with ECC layers is not significantly reduced than the control RC beams. The reason is within the serviceable limit the flexural cracks formed in the FGRC beams has been arrested by the steel and PVA fibers. If the applied load is beyond 50% of ultimate load i.e. D_2 and D_3 damage level, more stiffness degradation perceived which is observed by more drop in natural frequency values in all types of beams. Even in damage levelD_2 and D_3, ECC material with hybrid fibers in the tension zone of the beam is more pronounced in restricting the cracks as shown in Figure 6.12.P/Pmax ratio versus damping ratio of RC and FGRC beamsat each damage level for six different modes of vibration are plotted as shown in Figure 6.13a and 6.13b for M25 and M50 grades of concrete respectively. The high ductile ECC material makes the FGRC beam more damage tolerance is evident and hence FGRC beams with three layers of ECC material has pronounced to be effective against damage induced.



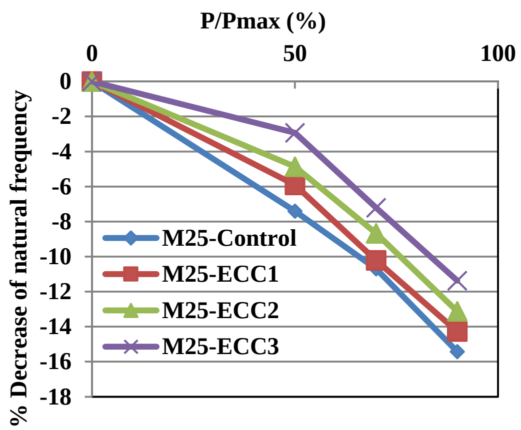
(a) First vibration mode



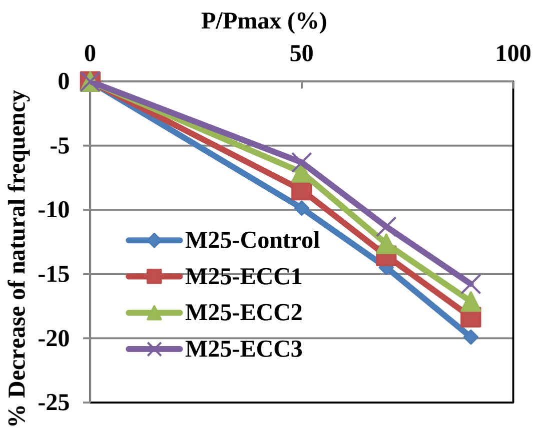
(b) Second vibration mode



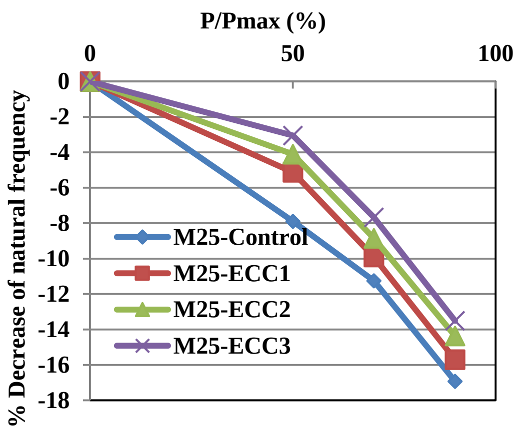
(c) Third vibration mode



(d) Fourth vibration mode

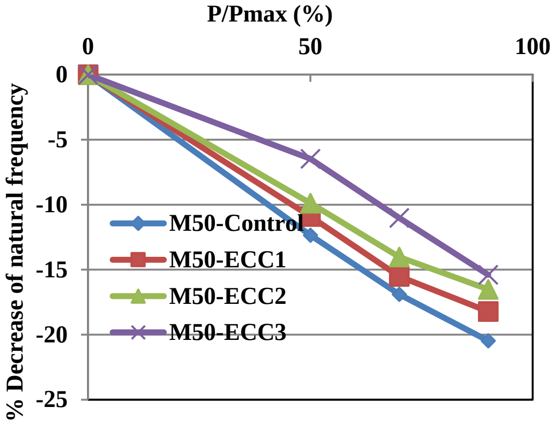


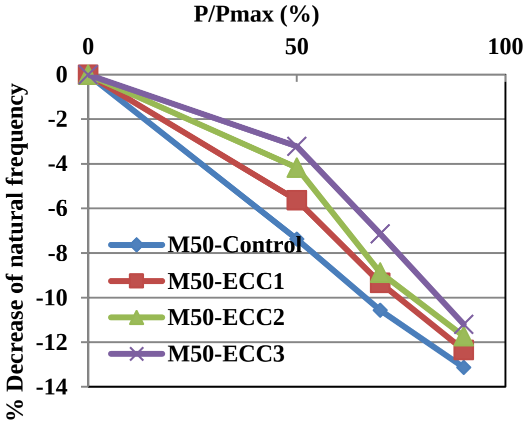
(e) Fifth vibration mode



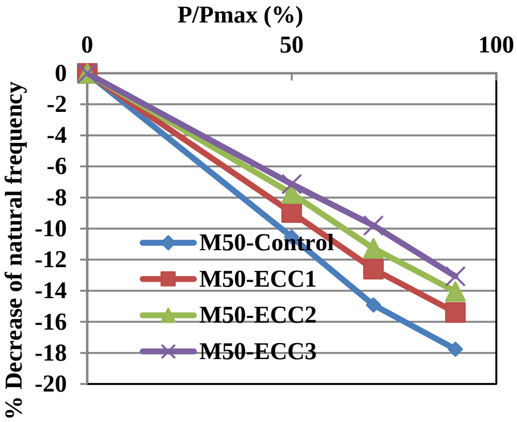
(f) Sixth vibration mode

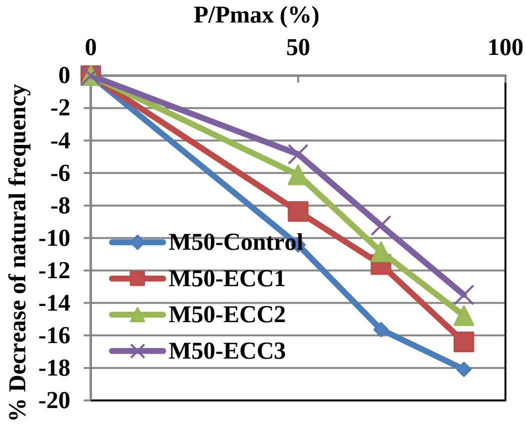
Figure 6.12a Comparison of P/Pmax ratioversus frequency variation ratio for RC and FGRC beams for M25 concrete



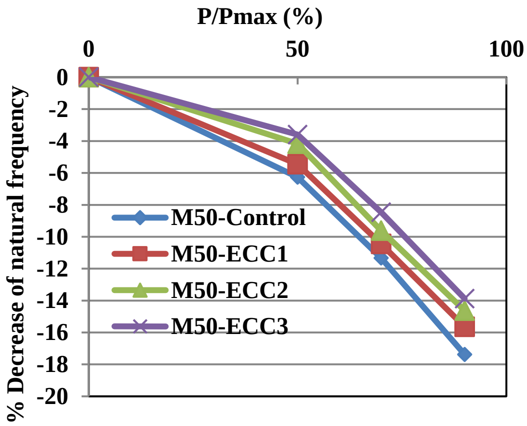


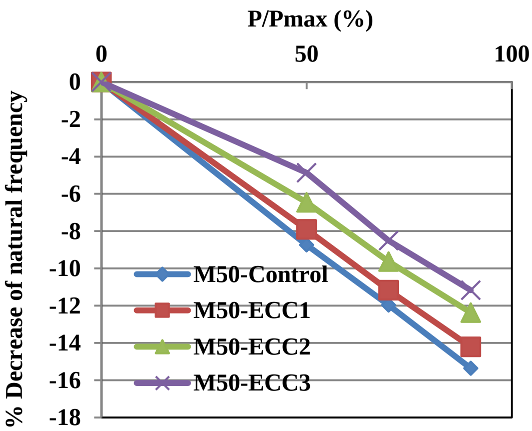
(a) First vibration mode(b) Second vibration mode





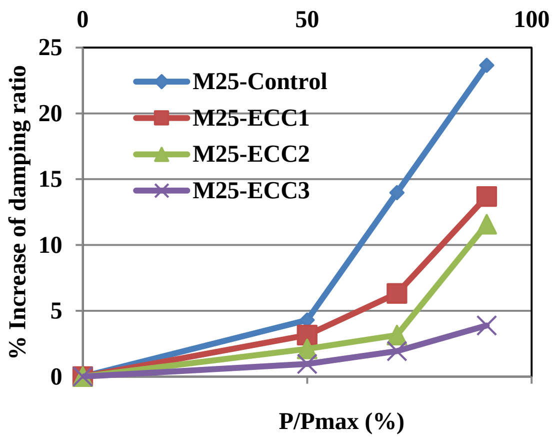
(c) Third vibration mode (d) Fourth vibration mode



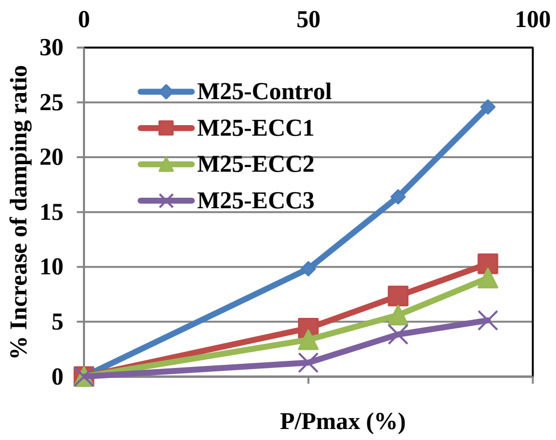


(e) Fifth vibration mode (f) Sixth vibration mode

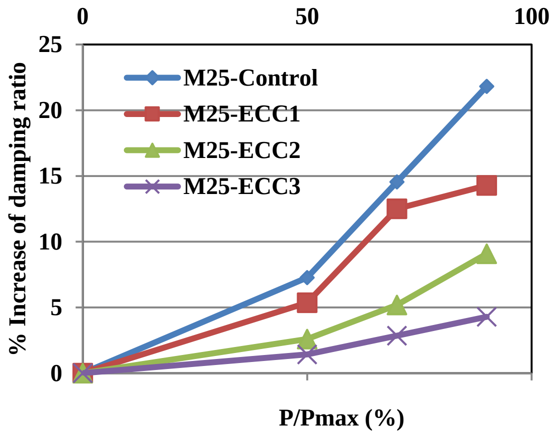
Figure 6.12b Comparison of P/Pmax ratioversus frequency variation ratio for RC and FGRC beams for M50 concrete



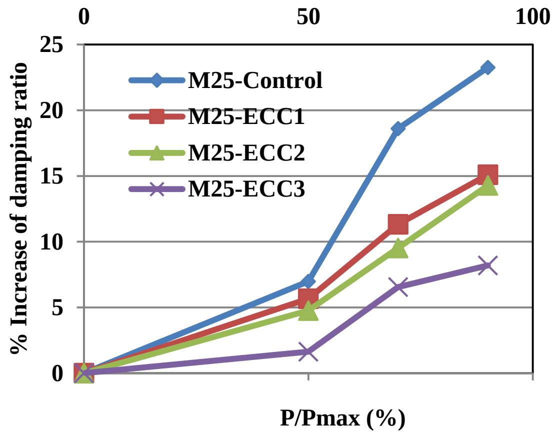
(a) First vibration mode



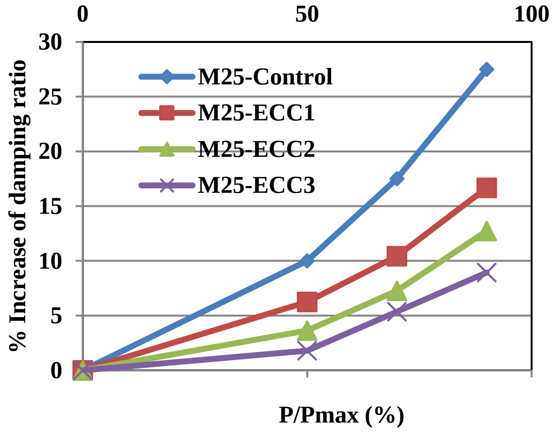
(b) Second vibration mode



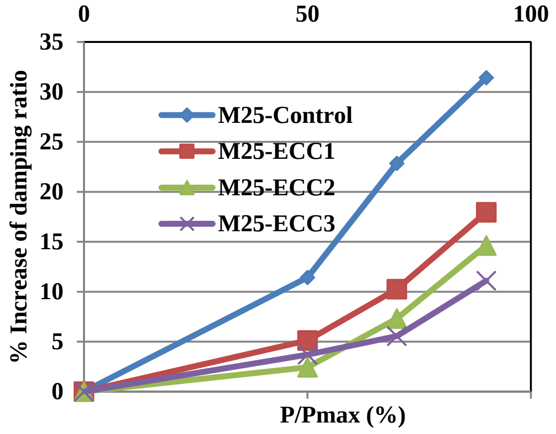
(c) Third vibration mode



(d) Fourth vibration mode

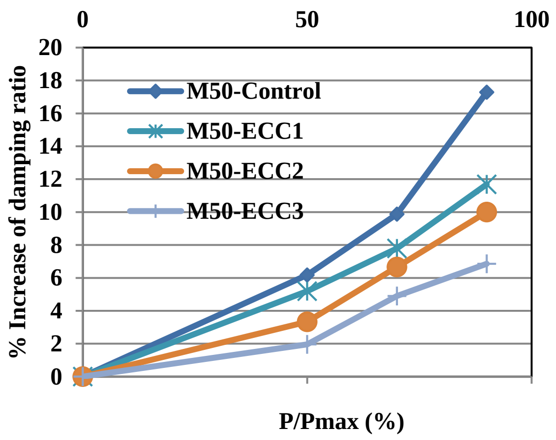


(e) Fifth vibration mode

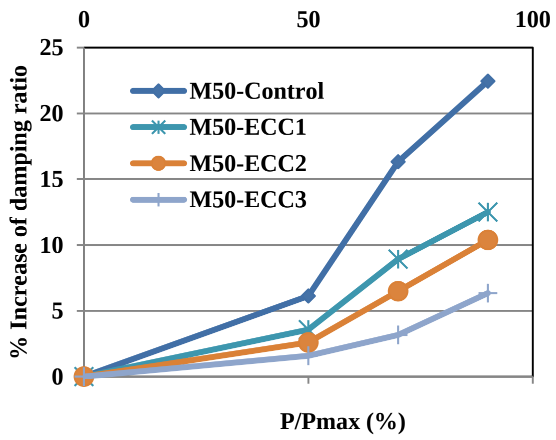


(f) Sixth vibration mode

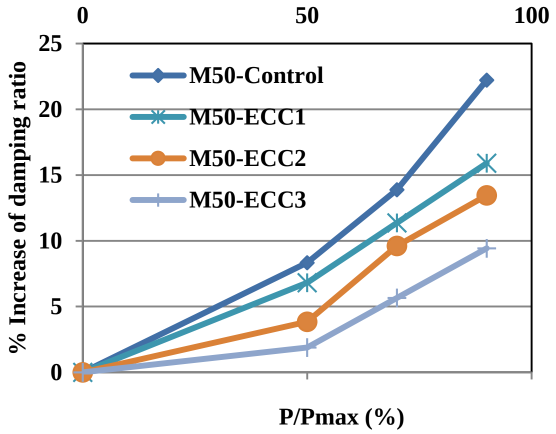
Figure 6.13a P/Pmax ratio versus damping ratios of RC and FGRC beams for M25 concrete



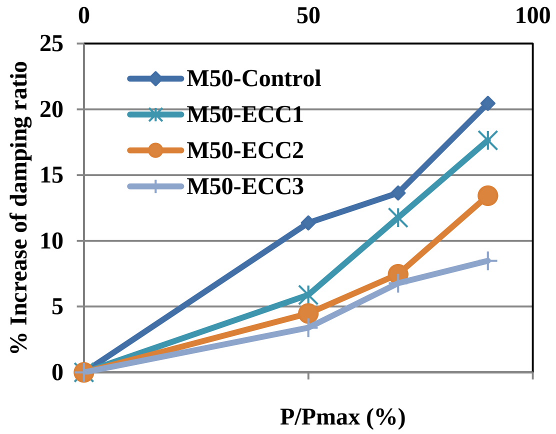
(a) First vibration mode



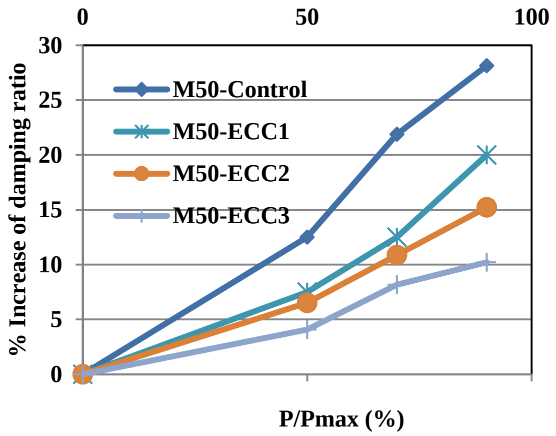
(b) Second vibration mode



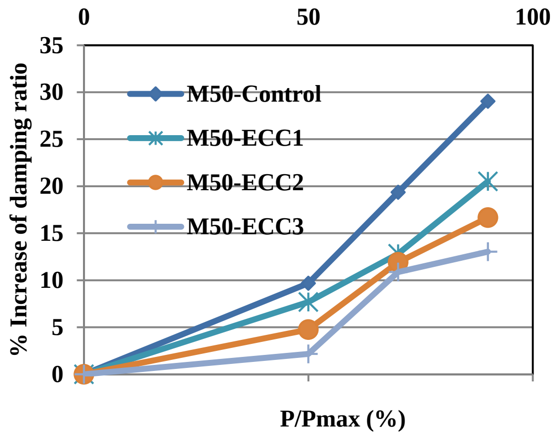
(c) Third vibration mode



(d) Fourth vibration mode



(e) Fifth vibration mode



(f) Sixth vibration mode

Figure 6.13b P/Pmax ratio versus damping ratios of RC and FGRC beams for M50 concrete

6.3.4 Comparison of Static and Dynamic Behavior on RC, HFRC and FGRC with ECC-3

From the overall static test results, it is observed that the load carrying capacity of FGRC beam with three layers of ECC material in the tension zone of the beam showed higher load carrying capacity compared with SFRC, PPFRC, HFRC and FGRC beams with ECC-1 and ECC-2 and control RC beams. Figure 6.14 shows the comparison of static test results of control RC, HFRC and FGRC-ECC-3 beams for both the grades of concrete.

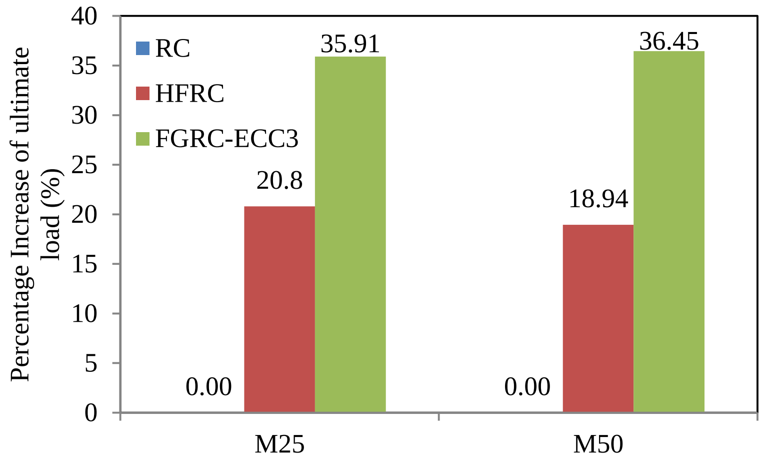


Figure 6.14Comparison of control RC, HFRC and FGRC-ECC3 beams

From the above graph, it is observed that the maximum percentage increase of FGRC beam three layers of ECC material is 35.91% compared to that of control RC beams. The reason is due to incorporation of ECC material (steel and PVA) in the bottom zone of the beam (75 mm thick) which restricts the flexural and flexural-shear at both low and high stress levels with the increase of load. From the overall static test results, FGRC beams with three layers of ECC material performed better for both the grades of concrete.

Comparison of natural frequency and damping ratio values of control RC, HFRC and FGRC-ECC-3 are shown in Figure 6.15 and 6.16. From the dynamic test results, the maximum percentage decrease in natural frequency is very less for RC beams with hybrid fibers compared with FGRC-ECC3 layers and also control RC beams for both the grades of concrete at first mode of vibration.

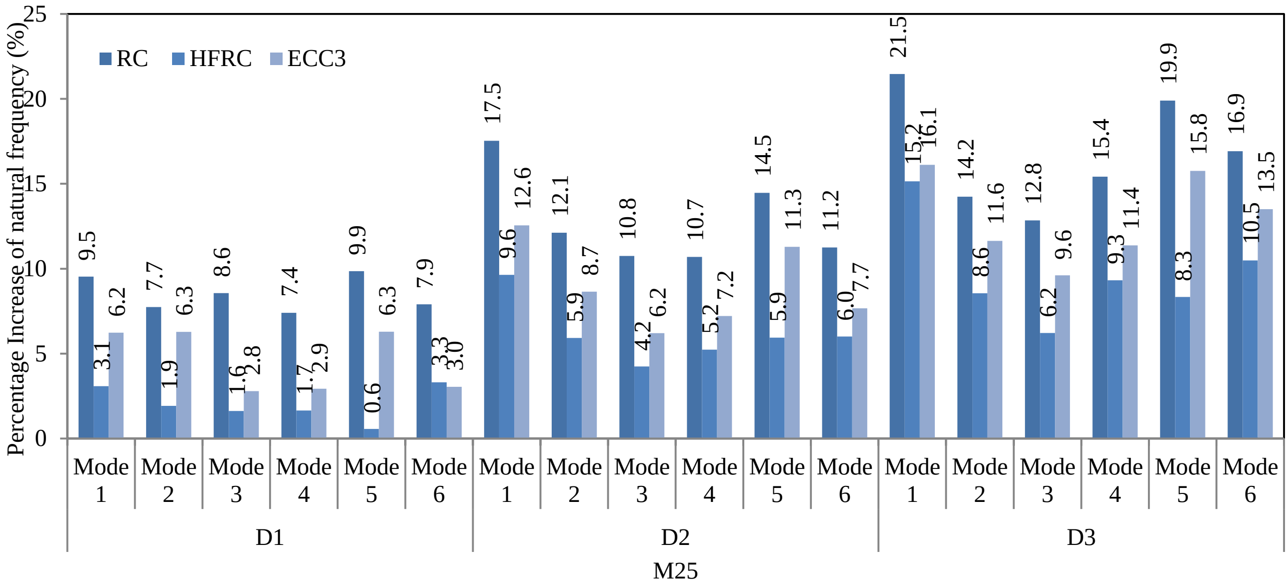


Figure 6.15aComparison of natural frequency values of control RC, HFRC and FGRC-ECC-3 beams – M25 concrete

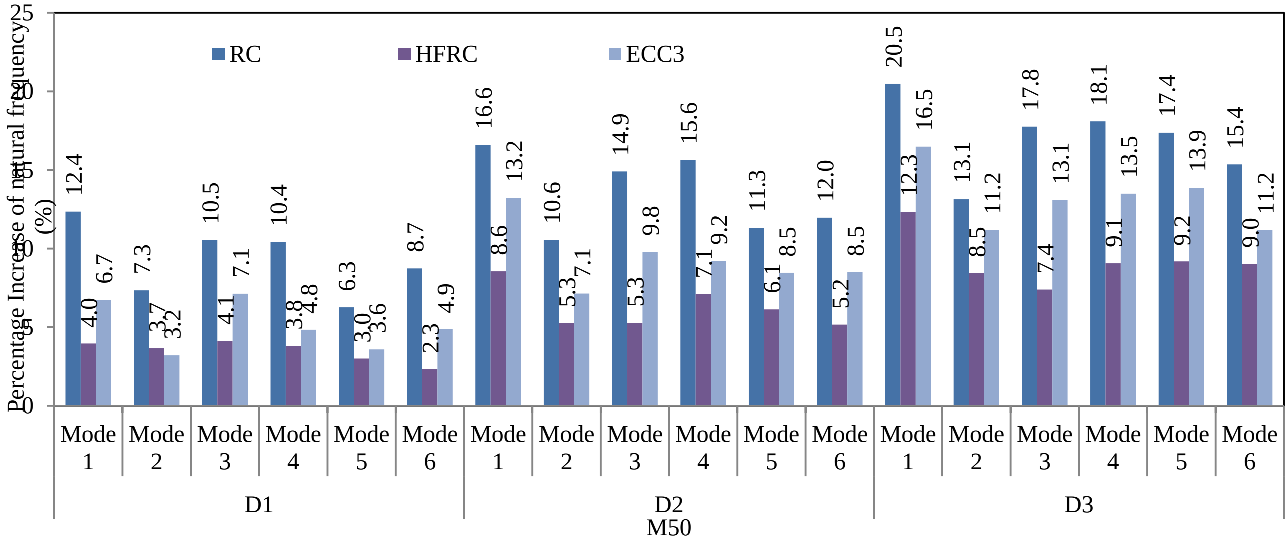


Figure 6.15bComparison of natural frequency values of control RC, HFRC and FGRC-ECC-3 beams – M50 concrete

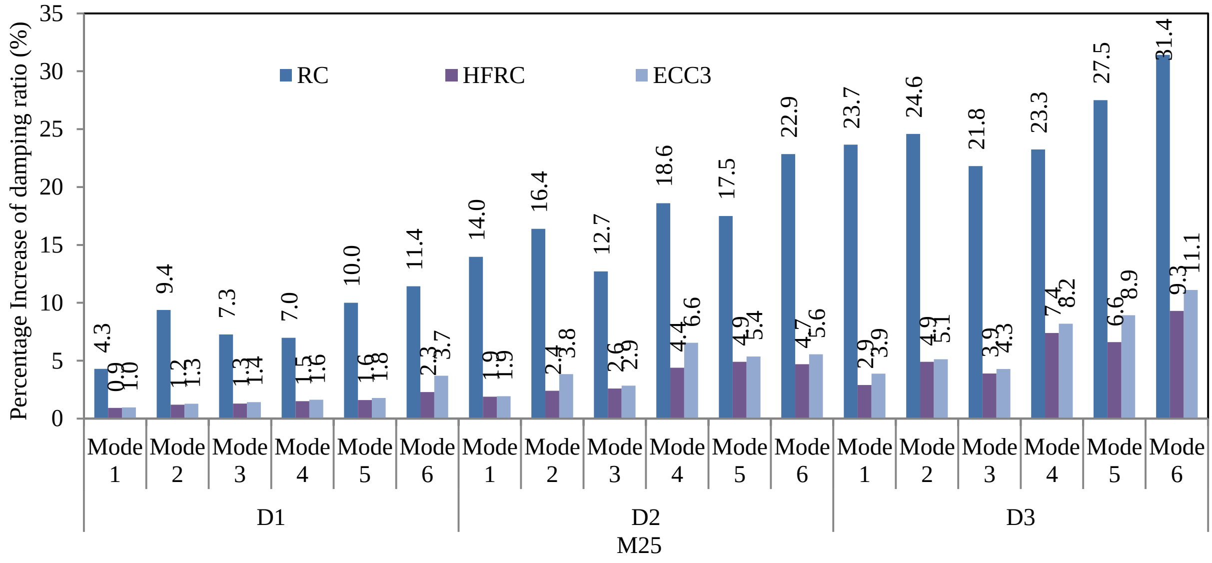


Figure 6.16aComparison of damping ratio values of control RC, HFRC and FGRC-ECC-3 beams – M25 concrete

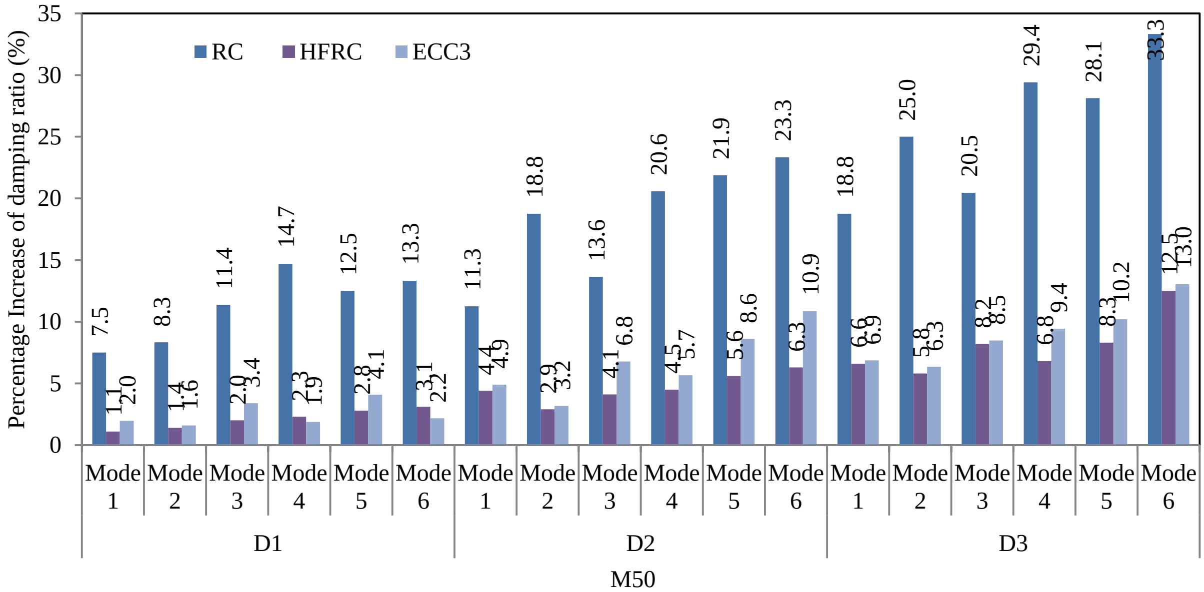


Figure 6.16bComparison of damping ratio values of control RC, HFRC and FGRC-ECC-3 beams – M50 concrete

From the Figures 6.15 and 6.15, it is observed that the maximum percentage increase in damping ratio is very less for RC beams with hybrid fibers compared with FGRC-ECC3 layers and also control RC beams for both the grades of concrete at sixth mode of vibration. The addition of hybrid fibers (steel and PP) in the entire cross-section of the beam restricts the micro as well as macro-cracks in the tension and also in the compression zone, thereby reduces the formation and propagation of cracks further which leads to less occurrence of damage compared to that of control RC, SFRC, PPFRC and FGRC beams with one, two and three layers of ECC material. It can be concluded that the performance of RC beam with hybrid fibers under dynamic behavior is good comparatively.

6.4Concluding Remarks from Phase – II

The main results obtained from phase II experimental program consists of static and dynamic response of functionally graded concrete beams using ECC. Following conclusions are drawn from this phase of investigation.

- Mechanical properties of ECC such as compressive strength, flexural strength and uni-axial tensile strength increased by about 20.8%, 55.5% and 42.1%, respectively for the cementitious composites with the addition of 1.5% of PVA and 0.5% of steel fibers when compared with non-fibrous ECC mixture.
- It is observed that the mechanical properties of hybrid fiber reinforced ECCs improved more when compared with control as well as mono fiber reinforced ECC,because the combination of steel and PVA fibers increases the capability to resist the interaction and propagation of micro as well as macro cracks.
- The addition of ECC layers in tension zone of the beams which led to an increase of ultimate load carrying capacityin flexure is about 15.91%, 25.71% and 35.91% for FGRC beams with one, two and three layered ECC material respectively compared with M25 control RC beams.
- Ultimate load carrying capacity was increased by about 18.22%, 27.09% and 36.45% for FGRC beams with one, two and three layered ECC material, respectively, when compared with M50 control RC beams.
- From the experimental dynamic behavior of RC beams, from undamaged state (D_0) to final damage state(D_3), the natural frequencies of RC, FGRC beams with one, two and three layers of ECC material decreased by about 21.4%, 19.4%, 17.29% and 16.112%, respectively in first mode of vibration for M25 grade of concrete.

- The damping ratioRC, FGRC beams with one, two and three layers of ECC material increased by approximately 31.42%, 17.97%, 14.63% and 11.11% in sixth mode, respectively for M25 grade of concrete.

- The natural frequencies of RC, FGRC beams with one, two and three layers of ECC material decreased by about 20.48%, 18.21%, 16.51% and 16.48%, respectively in first mode of vibration for M50 grade of concrete.

- The damping ratio of RC, FGRC beams with one, two and three layers of ECC material increased by approximately 33.33%, 20.15%, 16.66% and 13.04% in sixth mode, respectively for M50 grade of concrete.

- The percentage decrease in natural frequency and percentage increase in damping ratio of control RC beam were higher when compared with FGRC beams for both grades of concrete. ECC layers were abundantly effective even after the formation of cracks in preventing the propagation of cracks with the increased stress level.

- It is observed from the present investigation, FGRC beams with three layers of ECC material performing better under static flexure, it is evident from the dynamic testing that RC beams strengthened with hybrid fibers experienced less damage compared to all other beams.

CHAPTER 7

PHASE-III: NUMERICAL MODELING OF MONO FRC, HFRC AND FGRC BEAMS

7.1 General

This chapter presents the results obtained through the FEM model of reinforced concrete beam strengthened with mono and hybrid fibers. In addition to that, validation of functionally graded concrete beams using engineered cementitious composites has been modeled for undamaged condition and the results are compared with the experimental values. FEM modeling of RC beams strengthened with fibers and FGRC beams with ECC layers have been done based on the commercially available finite element software package ABAQUS.

7.2Methodology of FEM Modeling

FEM modeling has been done as follows,

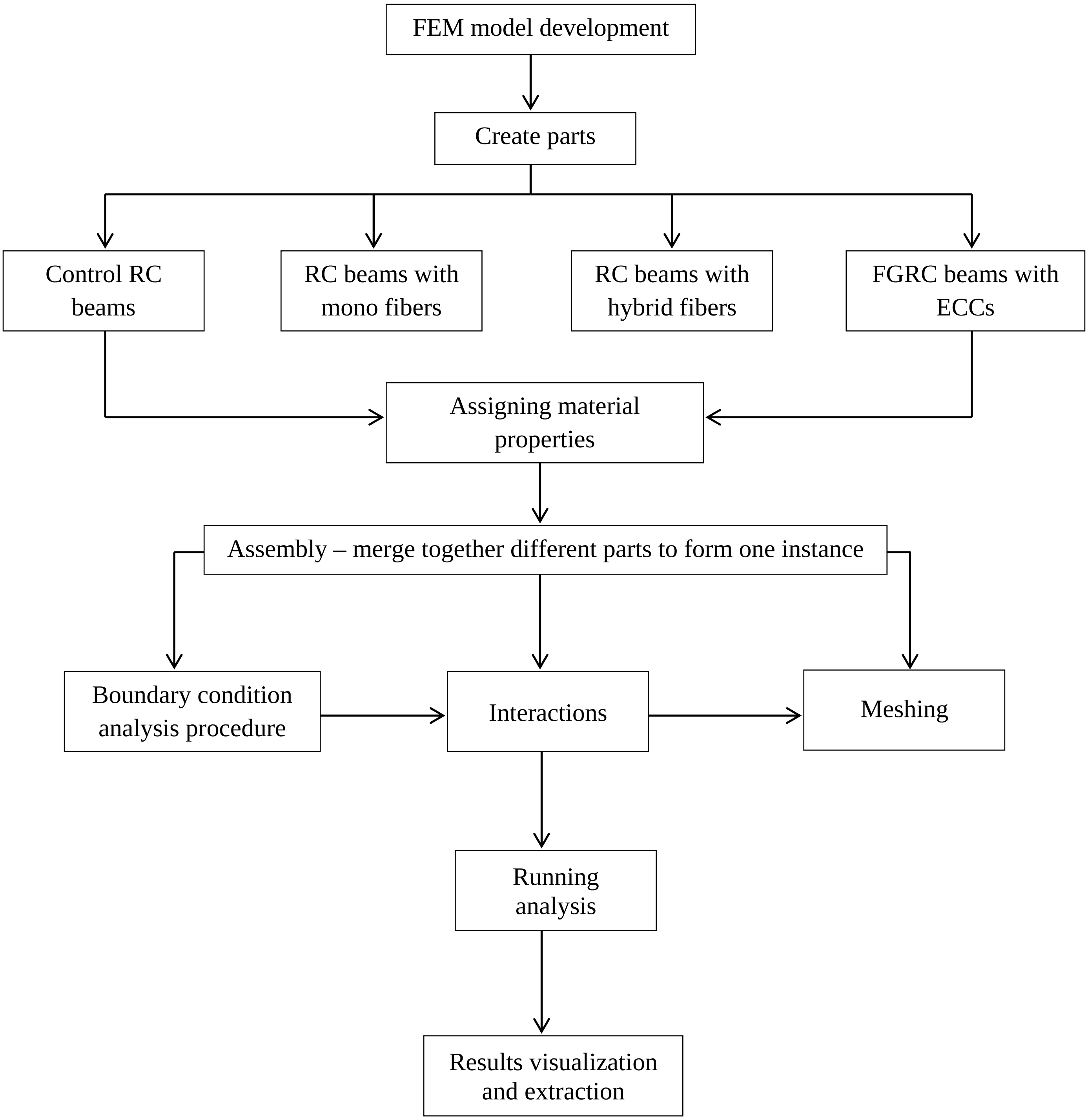
- Modeling of RC beam, RC beams strengthened with mono and hybrids fibers and FGRC beams with ECC layers.
- Performing modal analysis using ABAQUS software for undamaged state.
- Determination of natural frequencies at undamaged level of corresponding modes.
- The experimental results from dynamic analysis have been compared with the values obtained by FEM model.

7.3Material Properties Definition and Assignment

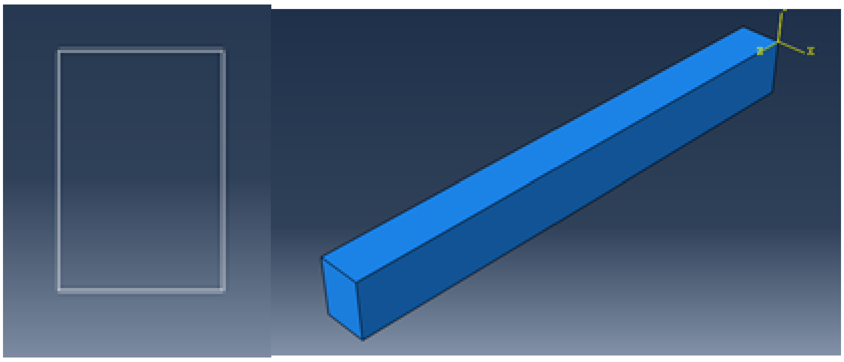
Finite element modeling of RC beams strengthened with mono fibers, hybrid fibers and FGRC beams at undamaged condition was carried out using commercially available FEM software (ABAQUS). A 3D Finite Element mesh of a concrete beam block, stirrups, and reinforcement bars are constructed employing ABAQUS/CAE standard explicit structural analysis modeling tool (2004) to execute dynamic analysis of the RC beam. Finite element methods consist of dicretizing the actual geometry of the structure into a collection of finite elements where each finite element represents a discrete portion of the physical structure. For any finite element model, it is necessary to assign material property which has to be predicted as accurate as possible. In the FE analysis modeling, the concrete block of the tested beam is modeled with eight-node solid (brick) elements, which are identified as C3D8R elements in ABAQUS. The longitudinal and transverse reinforcements were modeled as 3D deformable truss element. These all steel elements are merged to form a single truss element embedded into a concrete prism. The mesh of solid beam model strictly followed the geometries of the tested beam. The longitudinal and confinement reinforcement bars were modeled as embedded elements in the concrete block of the beam with 3D beam elements B31. To construct the mesh of the model, moderately fine mesh was used to obtain close responses to the experimental results.

7.4Reinforced Concrete Beam Model Creation

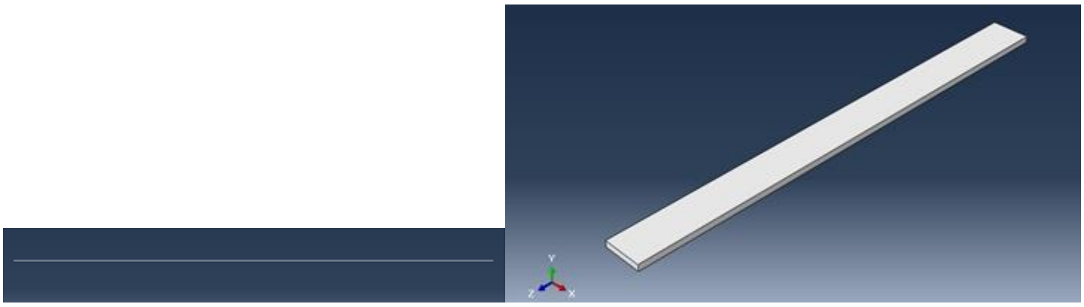
The geometry of the beam for two different grades of concrete has been shown in chapter 4 for which finite element models were developed and it is shown in Figure 7.1. All parts making up the models were created in Abaqus CAE, which is graphical user interface in which we create models, submit jobs, monitor analysis and evaluate the results. Figure 7.2 shows parts created in Abaqus for modeling. Different parts created exist independently of each other in local co-ordinates system even though material properties assigned to them. For complete construction of model, it is necessary to assemble different part instances and it has been done in the assemble module to position and orient different part instances relative to each other in the global co-ordinates system.



7.1 Finite element model development



(a) Rectangular section (b) Concrete



(c) Steel bar (d) ECC layer

Figure7.2 Parts created in Abaqus

Steel reinforcements were embedded into the beam with a cover of 15mm on all sides. Concrete beam, tension steel, compression steel and shear reinforcement part instances were created and assembled in linear pattern option in the assembly module. Figure 7.3 shows the reinforcement assembled in global coordinate system.

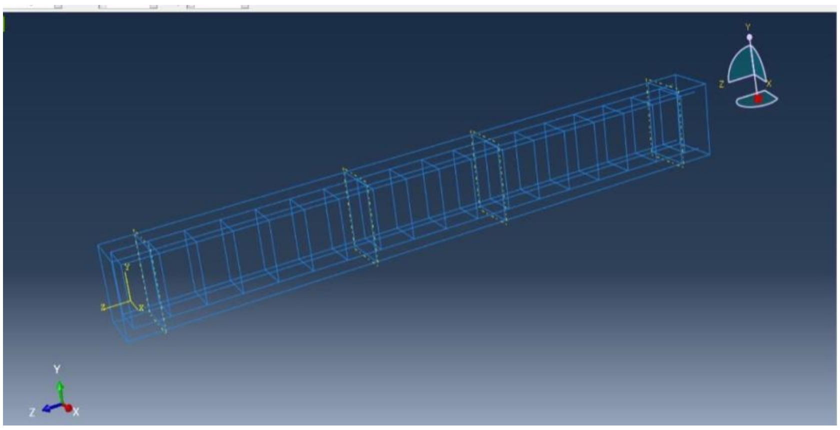


Figure7.3 Reinforcement assembled in global coordinate system

Figure 7.4 displays the reinforcement embedded in concrete. Before the application of loads to the model, boundary conditions have to be assigned. Density of the mesh was given before meshing process in order to seed the edges of the model regions to get accurate solutions which further depend on the number of elements. The mesh size of 10mm was given and hence seeding has been applied uniformly. Figure 7.5 shows the typical view of meshed RC beam. All the beams have been analysed in free-free boundary conditions. Figure 7.6 shows the typical view of FGRC beam with two layers of ECC material model. Figure 7.7 shows the typical view of meshed FGRC beam with two layers of ECC material.

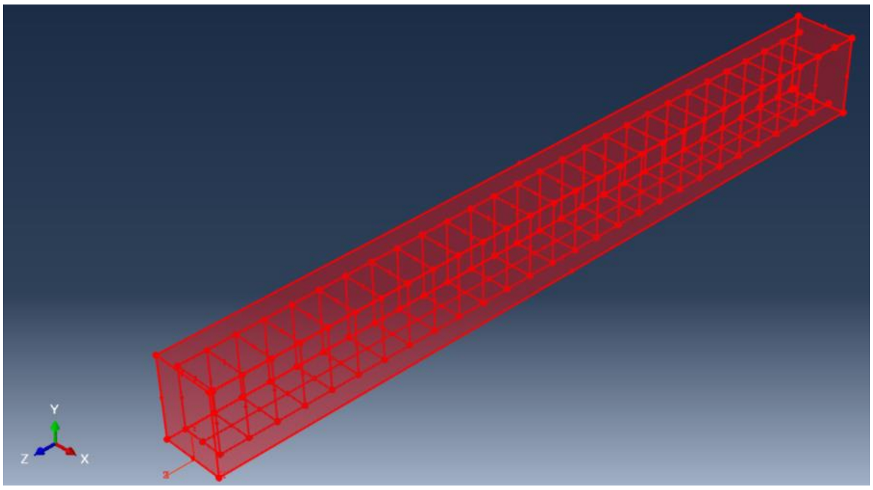


Figure 7.4 Reinforcement embedded inside concrete

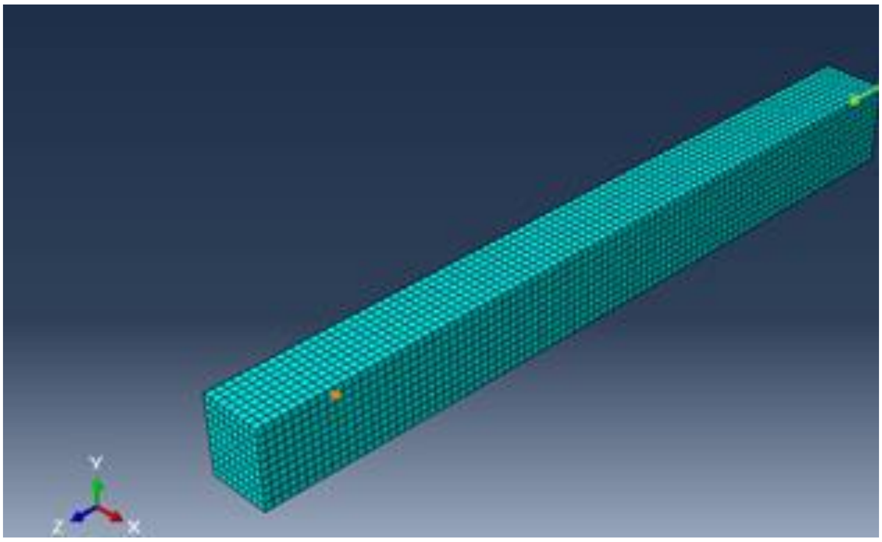


Figure 7.5 Typical view of meshed RC beam

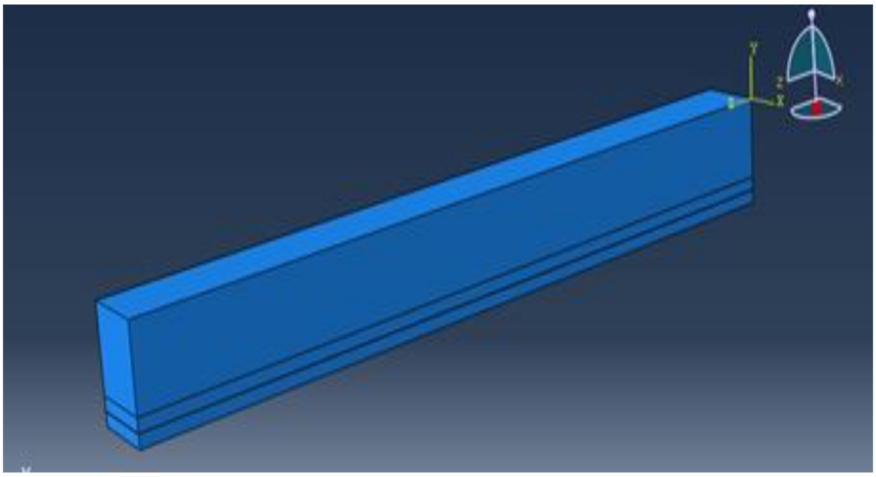


Figure 7.6 Typical view of FGRC beam model with two layers of ECC material

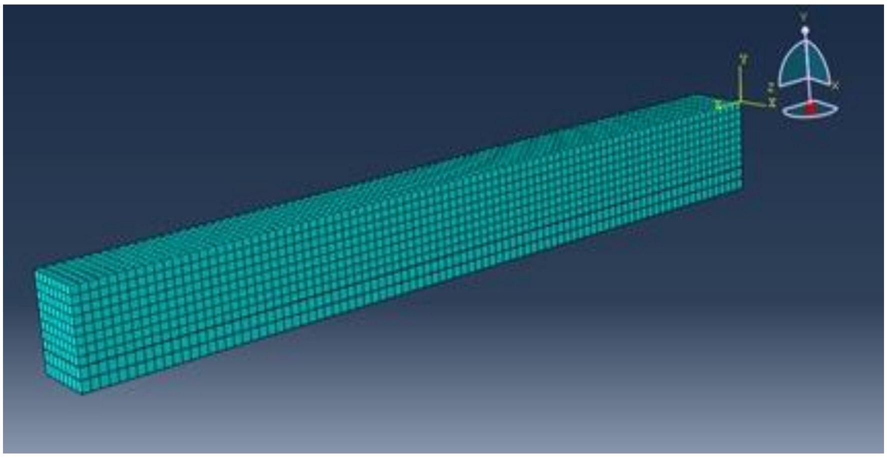


Figure 7.7 Typical view of meshedFGRC beam with two layers of ECC material

7.5Comparison of Numerical Results with Experimental Results

Numerical results and discussion of control RC beam, RC beams strengthened with mono and hybrid fibers and functionally graded beam with ECC layers using finite element modeling software (ABAQUS) have been presented in this section. The primary aim of finite element model updating is to correlate with the results obtained from experiments. This is attained through matching many pairs of analytical and experimental vibration modes with respect to the natural frequencies. As a result, an accurate finite element model is achievable and would facilitate further studies on the behavior of the reinforced concrete beams without carrying out physical tests on the structure. The results from FEM analysis of control RC beam, RC beam strengthened with mono, hybrid fibers and FGRC beams with ECC layers are tabulated in Table 7.1 for M25 grade concrete. Similarly, FEM results of control RC beam, RC beam strengthened with mono, hybrid fibers and FGRC beams with ECC layers are tabulated in Table 7.2 for M50 grade concrete. Structures with free-free boundary conditions illustrate rigid body motion at low frequencies that are close to zero and do not undergo bending or flexure.

Table 7.1a Results of the FEM analysis of control RC, SFRC, PPFRC and HFRC beams-M25 concrete

Mode no	Frequency values for undamaged state in free-free constraints											
	RC beam			SFRC beam			PPFRC beam			HFRC beam		
	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
1	221.3	202	8.72	226	214	5.31	228.4	217	4.99	227	209	7.93
2	579.7	524	9.61	583.6	528	9.53	590.8	528	10.63	608	584	3.95
3	1051	982	6.57	1079	973	9.82	1043	974	6.62	1107	1056	4.61
4	1608	1548	3.73	1681	1542	8.27	1615	1532	5.14	1694	1623	4.19
5	2211	2271	-2.71	2271	2154	5.15	2225	2173	2.34	2294	2217	3.36
6	2836	2718	4.16	2897	2719	6.14	2845	2884	-1.37	3029	2941	2.91

Table 7.1bResults of the FEM analysis of control RC and FGRC beams with ECCs - M25 concrete

Mode no	Frequency values for undamaged state in free-free constraints											
	RC beam			FGRC-ECC1			FGRC-ECC2			FGRC-ECC3		
	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
1	221.3	202	8.72	218.5	204	6.64	229.5	214	6.75	232.6	221	4.99
2	579.7	524	9.61	580.2	513	11.58	605.8	553	8.72	615.5	573	6.90
3	1051	982	6.57	1065	1095	-2.82	1084	1021	5.81	1145	1084	5.33
4	1608	1548	3.73	1625	1548	4.74	1684	1723	-2.32	1706	1642	3.75
5	2211	2271	-2.71	2284	2352	-2.98	2248	2154	4.18	2239	2146	4.15
6	2836	2718	4.16	2828	2715	4.00	2848	2743	3.69	2984	3045	-2.04

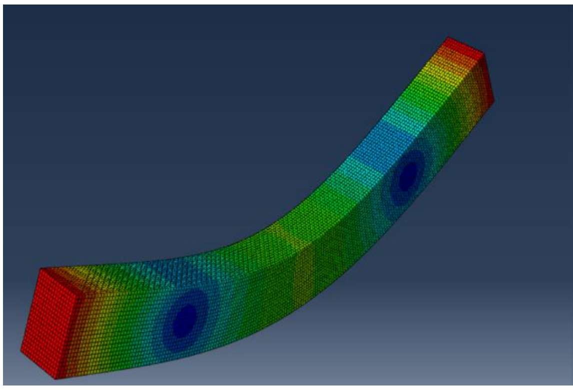
Table7.2a Results of the FEM analysis of control RCand FGRC beams with ECCs-M25 concrete

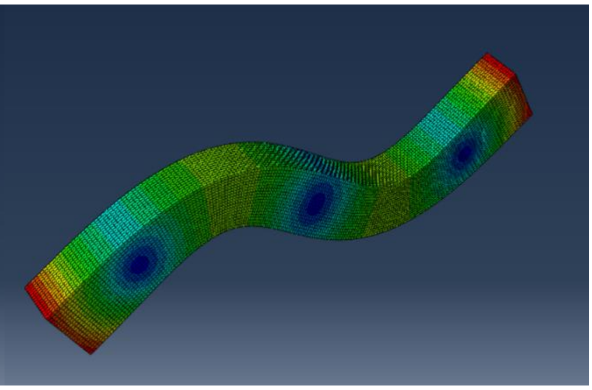
Mode no	Frequency values for undamaged state in free-free constraints											
	RC beam			SFRC beam			PPFRC beam			HFRC beam		
	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
1	236.6	218	7.86	245.2	236	3.75	243.4	229	5.92	239.5	242	-1.04
2	614.3	584	4.93	639	609	4.69	633.3	619	2.26	627	608	3.03
3	1120	1071	4.38	1160	1189	-2.50	1147	1174	-2.35	1136	1098	3.35
4	1708	1643	3.81	1755	1698	3.25	1745	1694	2.92	1732	1782	-2.89
5	2348	2396	-2.04	2397	2295	4.26	2380	2296	3.53	2363	2284	3.34
6	3008	3059	-1.70	3066	3147	-2.64	3059	3115	-1.83	3036	2941	3.13

Table7.2b Results of the FEM analysis of control RC and FGRC beams with ECCs-M50 concrete

Mode no	Frequency values for undamaged state in free-free constraints											
	RC beam			FGRC-ECC1			FGRC-ECC2			FGRC-ECC3		
	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
1	236.6	218	7.86	241	237	1.66	245.8	239	2.77	248.7	245	1.49
2	614.3	584	4.93	625.3	593	5.17	652.3	659	-1.03	625.9	618	1.26
3	1120	1071	4.38	1151.2	1097	4.71	1190.2	1164	2.20	1190.7	1123	5.69
4	1708	1643	3.81	1745	1682	3.61	1752	1683	3.94	1756	1684	4.10
5	2348	2396	-2.04	2384	2314	2.94	2351	2254	4.13	2364	2315	2.07
6	3008	3059	-1.70	3125	3024	3.23	2958	2846	3.79	3125	3184	-1.89

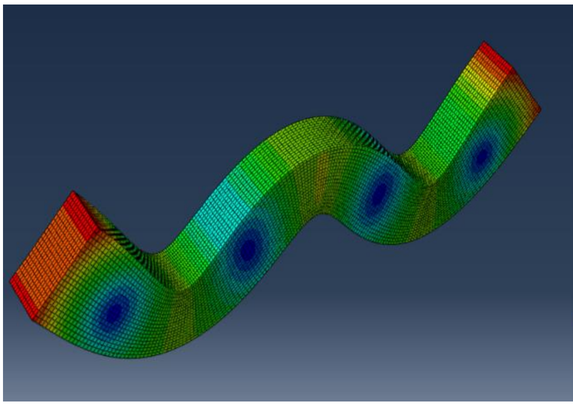
The overall frequencies obtained from the FEM modeling were just lower the experimental natural frequencies. From the FEM model results, the maximum difference in natural frequency values was less than 15%. Similar results were observed by *Allahyari et al. (2018)*. Figure 7.8 shows the typical mode shapes which were obtained from finite element model of RC beam.

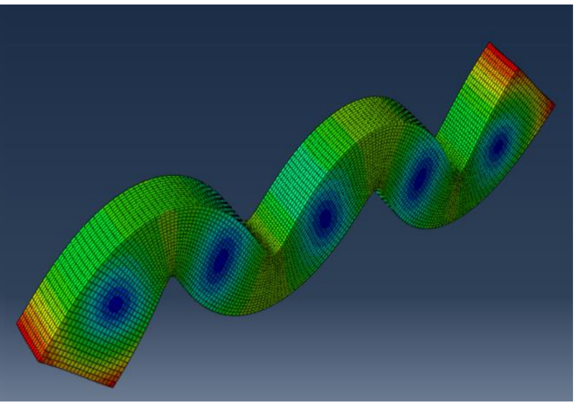




7.8 (a) First mode of vibration

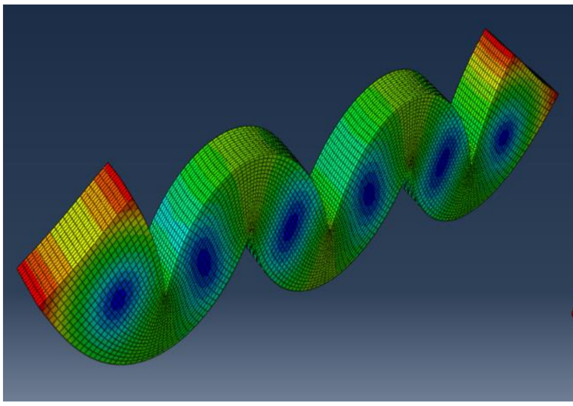
7.8 (b) Second mode of vibration

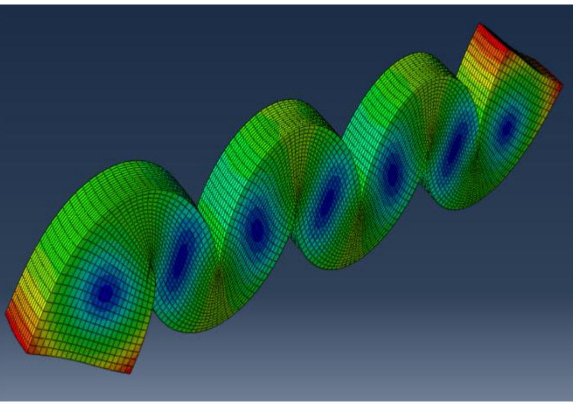




7.8 (c) Third mode of vibration

7.8 (d) Fourth mode of vibration





7.8 (e) Fifth mode of vibration

7.8 (f) Sixth mode of vibration

Figure 7.8 Mode shapes obtained from finite element model of RC beam

7.6Concluding Remarks from Phase – III

In this section, fourteen RC beams were modeled and analyzed using FEM software in order to compare analytical and experimental results. From the resultsobtained, the following conclusions have been drawn,

- Experimental results at optimized fiber volume fractions in mono steel, mono PP FRC, HFRC (steel and PP) and FGRC with ECC layers compared with the results obtained from numerical analysis are in good agreement with the values obtained from the FEM model.
- The maximum difference in natural frequency between the experimental and FEM model was less than 15%.

CHAPTER 8

OVERALL CONCLUSIONS

8.1 General

This section presents the overall conclusions of the present investigation which is aimed to evaluate the static and dynamic assessment of mono fiber reinforced concrete, hybrid fiber reinforced concrete and functionally graded reinforced concrete beams using engineered cementitious composite material. In addition to that, FEM modeling has been done for reinforced concrete beams strengthened with mono and hybrid fibers and functionally graded concrete beams. The following conclusions have been drawn from the present research work.

8.2Conclusions on Static and Dynamic Behavior of Mono and Hybrid FRC

- Optimum dosage of mono steel and PP fibers achieved at 1% and 0.3% of total fiber volume fraction. Thereafter there is decrease in strength characteristics observed in both M25 and M50 grade concrete mix. The reason may be due to more number of fibers replaced the cement matrix.
- Addition of steel fibers to concrete marginally improves the compressive strength whereas split tensile strength and flexural strength improved up to 33.6% and 42.6%, respectively for M25 composite and 29.4% and 39.1%, respectively for M50 composite at 1% of fiber volume fraction compared with non-fibrous concrete.
- The addition of polypropylene fibers to concrete marginally improves the compressive strength whereas split tensile strength and flexural strength improved up to 24.1% and 28.1%, respectively for M25 composite and 22.9% and 33.5%, respectively for M50 composite at 0.3% volume fraction compared with non-fibrous concrete.

- The mechanical properties of steel fiber reinforced concrete improved when compared with control as well as polypropylene fiber reinforced concrete. Higher tensile strength and modulus of elasticity of steel fibers are the two main factors that contribute towards the better performance of concrete reinforced with steel fibers.
- The hybrid combination at 0.5% total fiber volume fraction with 75% steel and 25% PP considered to be best proportion in the composite in all the strength parameters, among all the fiber volume fractions considered.
- The addition of hybrid fibers to concrete slightly improves the compressive strength, whereas split tensile strength and flexural strength increased by about 51% and 56.8%, respectively for M25 composite50% and 55.9%, respectively for M50compositeat a total fiber volume fraction of 0.5% compared with non-fibrous concrete.
- The hybrid fibers consists of steel and polypropylene in M25 and M50 concrete mixtures, resulted an enhanced behavior in terms of compressive, splitting tensile and flexural strength compared with mono FRC and control concrete. This may be due to the synergic effect from the combination of high elastic modulus steel fiber and low elastic modulus polypropylene fibers.
- The natural frequency of SFRC specimen with the addition of 0.5% of steel fiber was increased by about 3.6% and 1.57% for first and second mode, respectively for M25 concrete and 4.04% and 2%respectively for M50 concrete compared with control concrete.
- Similarly, the natural frequency of PPFRC specimen with the addition of 0.1% of PP fiber was increased significantly about 2.43% and 1.7% for the first two modes of vibrationrespectively for M25 concrete and 4.11% and 1.9%respectively for M50 concrete compared with control concrete.

- Damping ratio of SFRC specimen with the addition of 1.25% of steel fiber was increased by about 29.16% and 35.29% for first and second mode, respectively for M25 concrete and 19.64% and 28.5%respectively for M50 concrete when compared with non-fibrous concrete.
- Damping ratio of PPFRC specimen with the addition of 0.4% of PP fiber was increased by about 22.19% and 32.35% for first and second mode, respectively for M25 concrete and 19% and 28.7%respectively for M50 concrete compared with non-fibrous concrete.
- The natural frequency of HFRC specimens with the addition of 0.25% of total fiber volume fraction containing 25% of steel and 75% of PP fibers was increased by about 4.5% and 2.2% for first and second mode, respectively for M25 concrete and 4.65% and 2.77%respectively for M50 concrete compared with non-fibrous concrete.
- Damping ratio of HFRC specimen with the addition of 0.75% of total fiber volume fraction containing 75% of steel and 25% of PP fibers was increased by about 35.41% and 52.95% for the first and second mode of vibrations, respectively for M25 concrete and 44.65% and 52.4%respectively for M50 concrete when compared with non-fibrous concrete.
- Regarding static behavior of RC beams, the addition of mono steel and PP fibers were led to an increase in ultimate strength about 18.36% and 8.1% respectively for RC beams strengthened with steel and polypropylene fibersat its optimum fiber volume fraction when compared with control RC beams of M25 concrete.
- Ultimate strength of RC beams with the addition of steel and PP fibers were increased by about 16.54% and 12% respectively for RC beams strengthened with steel and polypropylene fibers at its optimum fiber volume fraction when compared with

control RC beams of M50 concrete. The reason is due to the confinement effect provided by the fibersat all stress levels in concrete.

- Ultimate load carrying capacity of RC beams improved up to 20.80% and 18.94% respectively for M25 and M50 grade concrete with the addition of hybrid fibers at 0.5% total fiber volume fraction (75% steel and 25% PP) when compared with control RC beams. This is due to the ability of fibers to restrain the extension of cracks, reduce the extent of stress concentration and delayed the growth of cracks.
- From the experimental dynamic behavior of RC beams, from undamaged state (D_0) to final damage state (D_3), the natural frequencies of RC, SFRC, PFRC and HFRC beams decreased by about 21.4%, 19.38%, 17.51% and 15.15%, respectively in first mode of vibration where more drop in natural frequency is observed in corresponding beam for M25 grade of concrete.
- The damping ratio of RC, SFRC, PPFRC and HFRC beams increased by 31.42%, 17.94%, 14.63% and 12.12% at sixth mode, respectively for M25 grade of concrete.
- The natural frequencies of RC, SFRC, PFRC and HFRC beams decreased by about 20.48%, 17.82%, 13.96% and 12.31%, respectively in first mode of vibrationfor M50 grade of concrete.The decrease in natural frequency attributed to the decrease in stiffness of RC beams with the damage induced.
- The damping ratioof RC, SFRC,PPFRC and HFRC beams increased by approximately 33.33%, 25.81%, 20% and 16.12% at sixth mode, respectively for M50 grade of concrete. Damping is increased due to the damage induced; the reason is due to internal slippage or sliding during vibration.
- It is observed that the natural frequency decreases with the increase of damage level, whereas damping ratio increases with the increase of structural damage for all beams. The decrease in natural frequency attributed to the decrease in stiffness of RC beams

with the damage induced. Damping is increased due to the damage induced, the reason is due to internal slippage or sliding during vibration. Flexure or shear cracks that accompanied with the yielding of the reinforcements were able to be detected based on the reduction of natural frequency.

- The percentage decrease in natural frequency and the percentage increase in damping ratio for RC beam strengthened with mono steel and PP fiber is more compared with beams strengthened with hybrid fibers. The intensity and the occurrence of damage is very less for the beams strengthened with hybrid fibersfrom undamaged state to final damage state. This clearly indicates the effectiveness of hybrid fibers in preventing the damage.

8.3 Conclusions on Static and Dynamic Behavior of FGRC

- Mechanical properties of ECC such as compressive strength, flexural strength and uni-axial tensile strength increased by about 20.8%, 55.5% and 42.1%, respectively for the cementitious composites with the addition of 1.5% of PVA and 0.5% of steel fibers when compared with non-fibrous ECC mixture.
- It is observed that the mechanical properties of hybrid fiber reinforced ECCs improved more when compared with control as well as mono fiber reinforced ECC,because the combination of steel and PVA fibers increases the capability to resist the interaction and propagation of micro as well as macro cracks.
- The addition of ECC layers in tension zone of the beams which led to an increase of ultimate load carrying capacityin flexure is about 15.91%, 25.71% and 35.91% for FGRC beams with one, two and three layered ECC material respectively compared with M25 control RC beams.

- Ultimate load carrying capacity was increased by about 18.22%, 27.09% and 36.45% for FGRC beams with one, two and three layered ECC material, respectively, when compared with M50 control RC beams.
- From the experimental dynamic behavior of RC beams, from undamaged state (D_0) to final damage state(D_3), the natural frequencies of RC, FGRC beams with one, two and three layers of ECC material decreased by about 21.4%, 19.4%, 17.29% and 16.112%, respectively in first mode of vibration for M25 grade of concrete.
- The damping ratioRC, FGRC beams with one, two and three layers of ECC material increased by approximately 31.42%, 17.97%, 14.63% and 11.11% in sixth mode, respectively for M25 grade of concrete.
- The natural frequencies of RC, FGRC beams with one, two and three layers of ECC material decreased by about 20.48%, 18.21%, 16.51% and 16.48%, respectively in first mode of vibration for M50 grade of concrete.
- The damping ratio of RC, FGRC beams with one, two and three layers of ECC material increased by approximately 33.33%, 20.15%, 16.66% and 13.04% in sixth mode, respectively for M50 grade of concrete.
- The percentage decrease in natural frequency and percentage increase in damping ratio of control RC beam were higher when compared with FGRC beams for both grades of concrete. ECC layers were abundantly effective even after the formation of cracks in preventing the propagation of cracks with the increased stress level.
- It is observed from the present investigation, FGRC beams with three layers of ECC material performing better under static flexure, it is evident from the dynamic testing

that RC beams strengthened with hybrid fibers experienced less damage compared to all other beams.

8.4 Conclusions on Numerical Analysis

- Experimental results at optimized fiber volume fractions in mono steel, mono PP FRC, HFRC (steel and PP) and FGRC with ECC layers compared with the results obtained from numerical analysis are in good agreement with the values obtained from the FEM model.
- The maximum difference in natural frequency between the experimental and FEM model was less than 15%.

8.5 Specific Contributions Made in this Work

1. Mechanical and dynamic properties of mono and hybrid fiber reinforced concrete have been determined.
2. Mechanical properties of engineered cementitious composites with mono and hybrid fibers have been evaluated.
3. Static and dynamic behavior of RC beams strengthened with mono fibers and hybrid fibers have been evaluated.
4. Static and dynamic behavior of functionally graded concrete beams using ECC material have been assessed.
5. Modeling of reinforced concrete beam strengthened with mono fibers, hybrid fibers and FGRC beams with ECC layers using FEM software (ABAQUS) has been done.

8.6 Scope for Future Study

1. Glass, basalt or other type of fibers can be used with different percentage variation of total fiber volume fraction on damage assessment studies.

2. Variation of reinforcement ratio can be considered with the optimized contents of fibers on damage assessment studies.
3. Damage assessment can be done with different boundary conditions experimentally as well as numerically.

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