Investigation of the Effect of Tensile Strength of Steel Fibers on the Shear Capacity and Crack Widths of Hybrid Steel Fiber Reinforced Concrete (SFRC) Beams

FINAL YEAR PROJECT UG-2018

By

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This is to certify that

The Final Year Project Titled

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CIVIL ENGINEERING

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DEDICATION

CREDIT GOES TO OUR FAMILY AND TEACHERS, WHO HELPED AND INSPIRED US THROUGHOUT OUR LIFE.

ACKNOWLEDGEMENTS

All praises be to ALMIGHTY ALLAH who made everything possible and easy for us to achieve in our amazing journey of NUST. We are extremely grateful to our parents who sacrificed and prayed for us to make progress in our course and research work.

Special gratitude to the respected advisor and mentor Dr. Azam Khan, whose consistent guidance, motivation and help made it possible for the team to fulfill their final year requisites. Special mention to the cooperative staff who assisted dutifully in our experimental works and lab engineer of NICE structural lab for being a great guider in our lab works and research.

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1 Introduction

Steel fiber reinforced concrete is a hybrid product that contains fibers that are scattered uniformly in a random manner in minor percentages, ranging from 0.3 to 2.5 percent by volume in the normal concrete mixture. Steel fibers are added to the concrete materials in the blender and then green concrete is poured into molds to make SFRC products. After that, the product is crushed and cured using traditional procedures. Steel fibers are used to increase the structural qualities of concrete, especially flexural and tensile strength. The degree to which SFRC improves mechanical qualities over plain concrete is determined by various criteria, including the form, length, quantity, frequency, and dispersion of fibers [14].

In an effort to push the frontiers of high-end structural applications, the usage of Steel Fiber Reinforced Concrete (SFRC) has gotten a huge boost in recent years. In general, concrete is characterized by brittle fracture, which constrains its implementation. This can be circumvented by incorporating a modest quantity of short randomly dispersed fibers (steel, glass, synthetic, and natural), that could be used to resolve concrete's areas of weakness including such low ductility, high shrinkage cracking, and low durability, among many other things. SFRC possesses outstanding tensile and flexural strength, as well as impact resilience, wear resistance, flexibility, and fracture bridging properties.

As a result, it has been used in a variety of building areas across the world. Steel fiber reinforced concrete (SFRC) is a composite structural compound made up of traditional concrete components supplemented with steel fibers for shear strength. These fibers are discontinuous, fragmentary structures that are randomly dispersed and directed (nominally homogeneously) all through the matrix material. Depending on the requirements, SFRC could be used alone or in combination with a traditional reinforcement bar [1]. Because of the fiber reinforcing mechanisms supplied by fibers crossing the fracture surfaces, SFRCs have a higher post-cracking residual shear capacity [2]. The number of fibers successfully spanning a fracture, their angle of alignment, and the binding strength qualities of the types of fibers utilized all impact post-peak tensile behavior.

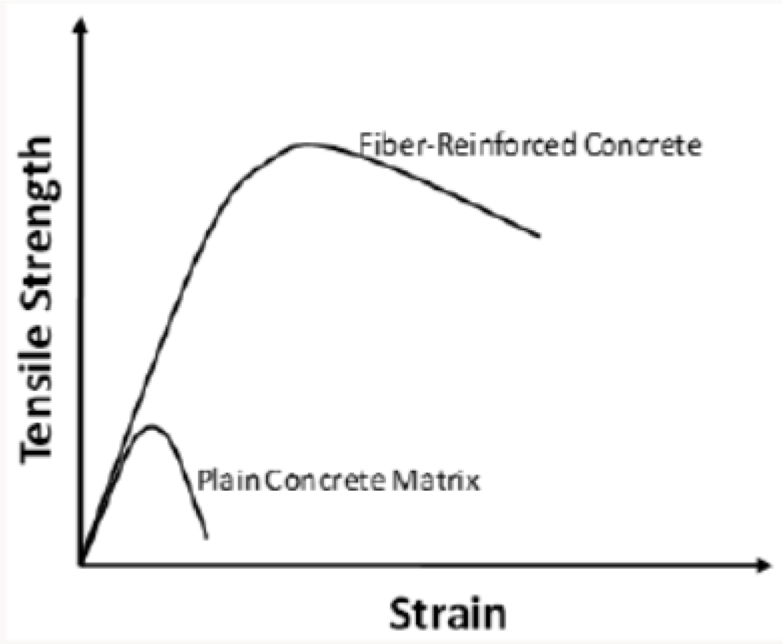


Figure: General Tensile Behavior of Concrete

The purpose of SFRCs is to improve understanding of the material's performance and to offer a foundation for an experimental investigation into the issue of dispersion in post-cracking behaviors. It all originates with the rheological characteristics of SFRC, because workability has a significant impact on numerous phases of the manufacturing process [3], with the biggest impact on the hybrid material's post-cracking behavior. The plain concrete substrate displays a strain-softening behavior with poor tensile and flexural strength when there is no fiber reinforcement added. Because concrete has poor fracture resilience, tensile fractures can quickly form when tension is applied.

The fibers’ strength and stiffness are used to reinforce the brittle matrix through the interfacial connection formed between them and the matrix. The load can still be transmitted across the fracture faces through the steel fibers once the composite cracks. The phenomenon of fiber pullout impacts load-bearing capacity and leads to energy dissipation as the tension on the mixture increases. It has also been proven that utilizing a large volume proportion of fibers with a large specific surface area increases the composite's fracture bridging capability and strength [5,6]. When compared to normal concrete, the flexural behavior of SFRC varies dramatically. Peak load and ductility can both be enhanced depending on the number and kind of fibers employed. The reason that the flexural strength can be raised by adding fibers will be explained, although this is difficult to do with regani to the concrete strength. Even at low fiber volumes, the flexural load-bearing potential may be enhanced in bends as long as the structural strength is maintained.

2 Literature Review

Concrete has long been the primary material for civil and building infrastructure development. But, considering its embrittlement and poor elastic modulus, its uses in constructions exposed to significant dynamic loads such as earthquakes, collisions, and explosions are relatively limited. To address this disadvantage, several studies have included discontinuous fibers in their composition, as steel fibers typically improve the flexural capacity and invoke ductile behavior in concrete [9].

Due to its intrinsic supremacy over simple and reinforced concrete in the following attributes: greater flexural strength, better tensile strength and modulus of rupture, increased shear resilience, elevated shock resistance, improved ductility and fatigue resistance, resistance to cracking, and failure toughness [7], fiber-reinforced material had also uncovered intriguing new applications in the last two decades. Fiber-reinforced concrete has sparked a surge in interest, owing to its use in traditional cementitious materials, which improves various structural characteristics. Diverse fiber kinds, fiber volume proportions, and matrices compositions result in wildly varying composite properties. The mechanical response of the concrete may be altered just by adjusting the fiber content, from practically as brittle and fragile as plain concrete to potentially deflection-hardening compounds.

Fiber-reinforced concrete (FRC) has been in use for years, and even the positive impact of fibers on the behavior of conventional concrete is generally acknowledged in both practice and academics. Fibers are good in preventing diagonally shear-induced fractures from forming. This improves aggregate interlocking across cracks, allowing shear forces to be transferred throughout the crack formation. As a result, introducing fibers to reinforced concrete might greatly enhance its shear capacity. If enough fibers are added to the design mixture, the type of failure for the material can be changed from brittle shearing to ductile or flexible failure [10].

Batson et al. were the first to study fiber-reinforced beams for shearing. They looked at a variety of fiber kinds, geometry, and span-to-depth proportions and their effects on the behavioral properties of the member. Numerous investigations since then have shown that the addition of steel fibers improves the shear properties of concrete members [11].

Micro cracks appear in plain concrete even before it is loaded, owing to drying shrinkage or similar volumetric changes. The early cracks are usually only a few microns across. Whenever those micro cracks are stressed under a load, they propagate and start opening, and new micro cracks emerge as a result of the stress concentration. Tensile deformation in concrete is mostly caused by micro cracks. To address these issues, fiber-reinforced binder and mortar were created. Cracks spread into gradual, regulated development as a result of the inclusion of small discrete fibres. This increases the ductile nature of the cement-based composites, allowing them to overcome their poor tensile strength. Fibers produce a crack-bridging action, resulting in latent tensile strength properties which increase the concrete's endurance and hardness. The usage of fibres is motivated by the need to increase toughness and fracture distribution qualities. This has resulted in an increase in the number of SFRC construction implementations on site [8].

2.1 Reinforcement Mechanisms in Fiber Reinforcements:

When fibers are properly in bound within the hardened concrete state, they entangle with the substrate at the micro cracking scale and appropriately bridge/binds those fractures, formulating a load transference pathway which resists coalescence and unsustainable development. If the fiber volume percentage is in considerably sufficient, the tensile properties of the composite may be increased. Furthermore, a significant improvement in tensile flexural strength beyond the ordinary concrete has been recorded for various high volume concentrations of fiber composites. Fibers, according to their size and binding qualities, continue to constrain shear opening and crack propagation by successfully bridging over macro-cracks until the composite's shear potential is achieved and micro-cracks have coalesced and converted to macro-cracks. In the majority of commercial fiber reinforced concrete mixtures, post-peak macro-crack spanning is the predominant reinforcing method.

2.2 Effect on workability:

To measure the workability and uniformity of concrete mixture, slump tests are performed. The efficacy of all fiber reinforcement is determined by the homogenous distribution of fibers in the mixture, their engagement with the cementitious materials, and the concrete's ability to be poured or sprayed properly. To give any advantage in the concrete, every single fiber must be covered with a cement matrix. Normal users of fiber reinforcement cement will recognize that adding additional fibers to the mixture, especially those with a very minute dimension, has a bigger negative impact on workability and demands mix design revisions. Because of the diverse types of fiber content and shape, the slump varies. The decreased slump is due to the fact that steel fibers may create a framework in cement, preventing segregation and flow. Fibers will absorb more paste for their coverage in cement due to their high content and vast surface area, and the increased viscosity of the mixture will cause slump loss, leading to workability problems.

2.3 Effects on ductility and tensile properties:

Steel fibers added to the concrete mixture can enhance the fracture characteristics of concrete by bridging open fractures and thereby lowering crack widths and improving the ductility and tensile properties of concrete. When compared to concrete lacking fibers, the discharged potential until failure is greater, whereas post-peak elasticity, as well as the pull-out operation, are greatly enhanced. Fibers might marginally raise the maximum values of compressive strength of concrete. Nonetheless, fiber insertion may lower strength properties in specific circumstances. The latter is due to a significant amount of voids and interruptions caused by the dispersion of fibers in the cementitious mixture [12]. While the prices of steel fibers may be significantly higher than those of comparatively inexpensive steel ligatures for transferring stress-strain resultants, there is still the possibility for overall labor cost reductions on the job site. The question of whether fibers may replace traditional longitudinal rebar reinforcements in RC structural members has to be investigated using experimental results and simulation techniques [11].

Initially, fiber reinforced concrete was solely utilized to reduce cracking and increase durability. However, Fibers began to also be addressed in the strength modeling and analysis of the concrete members in the last two decades, notably in terms of twisting and shearing capacities. This development was made possible by the publishing of the very first FRC mechanical behavior regulations and design standards [12].

Fibers are commonly utilized in conjunction with traditional reinforcement in buildings such as beams and raised slabs. In this regard, the ACI committee 544 is quite cautious. It indicates that throughout the case of dominating bending or directly applied tension forces, traditional reinforcements should be capable of absorbing the complete tensile stresses, whereas fibers should only help to prevent cracks and enhance concrete's dynamical or impact behavior. As a result, the issue of whether it is conceivable to decrease or eliminate reinforcing bars when there are no significant tensile strains remains unanswered. As a result, the impact of varied fiber types and quantities on the mechanical behavior of FRC real-scale beams and raised slabs is still a hot issue in the current study [12].

There have also been attempts to formulate a forecasting model for the shear capacity of the members flexural reinforced with ordinary steel bars or tendons. If the fiber pullout fundamental law is properly analyzed, the model might be applied for cement-based materials reinforced using various fiber types. The prototype consisted of three major parts: a fiber orientation description for calculating the number of fibers passing through the cross-section in discrete time intervals of fiber direction; a fiber pull-out foundational law based upon that unified varying mentoring program, which takes into account the relevant phenomena affecting the fiber placement methodologies; and an adapted compression field theory for predicting the crack propagation and width upon the critical shearing stage of failure.

During the last three decades, several experimental and numerical studies on shear issues of different fibrous RC structural members without transverse reinforcement have been carried out. According to these experiments, introducing fibers to beams boosts their flexural resistance dramatically. Several researchers have suggested algorithms to estimate the ultimate shear strengths of SFRC beams based on the experimental data. The concept that fibers and cement contribute equally towards the shearing strength of steel fiber reinforced concrete (SFRC) members is still widespread in current designs. Other research, on the other hand, claims that the contributions of fibers and concrete to shear strength are correlated [13]. Fiber reinforcement offers two advantages: not only does it increase physical attributes like durability and hardness, but it also opens up new opportunities for material adaptation for specific designs.

3 Aim

The **current study aimed** to check the effects of steel fibers on the shear capacity of the concrete. This would be confirmed by conducting experiments using varied volumes (i.e. 1%, 2%, 3%, 5%, etc.) of the steel fibers of 50mm length with a diameter of 0.9mm and 60mm length with a diameter of 1.1mm incorporated in our design mix to observe the impacts on the development of shear cracks and failure modes of the beams cast. The research examines the impact of steel fibers on various shear transfer processes and studies the factors that influence SFRC shear capacity.

4 Research methodology and testing

4.1 Introduction

In this chapter, we will discuss the methodology applied to achieve our required conditions, casting and testing procedures, material procurement, preparation of the testing samples i.e. 6 feet long beams, 750 mm long small beams, and 4in x 8in cylinders, and the complete process of testing and how the data has been acquired. Our test is performed using four kinds of specimen- control; beams fiber reinforced with low strength steel fibers; beams fiber reinforced with medium strength steel fibers; beams fiber reinforced with high strength steel fibers. Every type of specimen has 2 further different types with one having 0.75% of Vc fiber reinforcement and the other with 1% of Vc of fiber reinforcement. This study included the observation of the crack width propagation due to increased fiber strength and content and it also dealt with the changes in shear strength of the beams. This chapter also explains the testing equipment being used, the process of material procurement, and the other variables and methods inculcated to perform the tests and achieve our desired results.

4.1.1 Naming convention:

L, M, and H represent fiber strength.

SFRC means Steel Fibre Reinforced Concrete

1 represents 0.75% volume fraction of steel fibers

2 represent 1% volume fraction of steel fibers

e.g. LSFRC1: SFRC beam reinforced with L type fiber

4.2 Research Methodology

Steel fiber was procured from the local market in wire form. Later these wires were cut into smaller square pieces of steel fibers with appropriate length and diameter, to keep the aspect ratio the same. Steel wires were procured from City Saddar Road, Nanakpura, and Rawalpindi. These materials were brought to the laboratory of the School of Chemical and Material Engineering, (SCME) and tests were performed in order to measure the tensile result of the wires. After that, the steel wires were taken to a welding shop in G-11, Islamabad, for cutting into smaller pieces. These steel fibers acquired from cutting steel wires were then used in the mix design of concrete and beams were fiber reinforced with it.

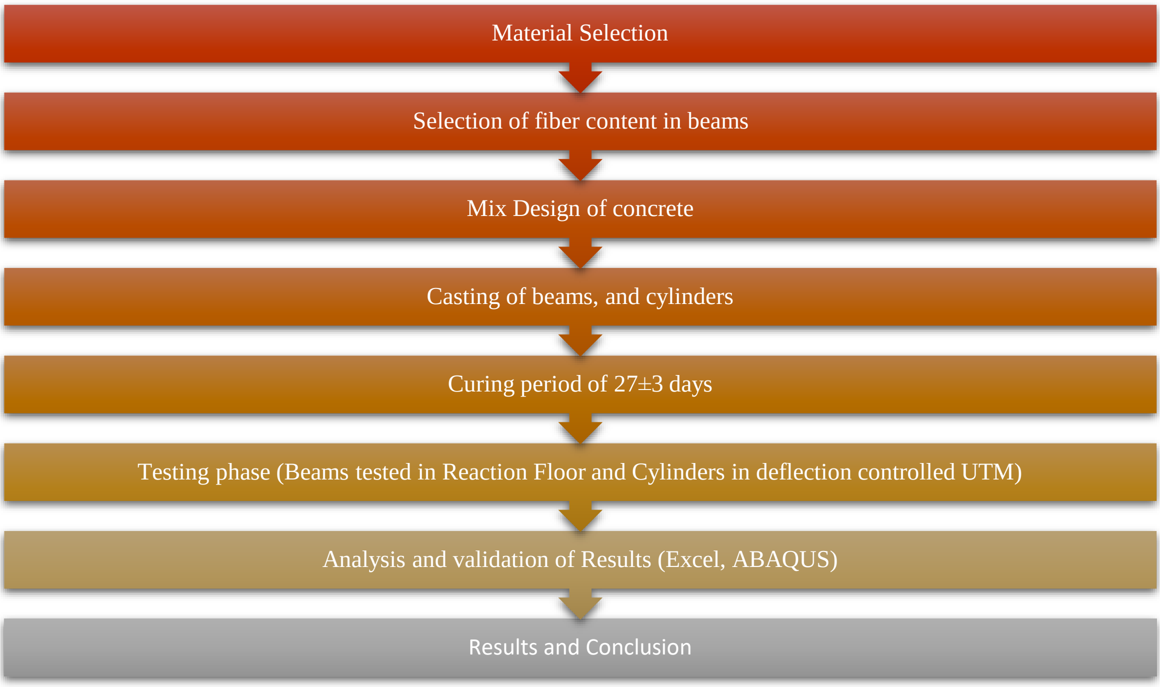


Fig 1.1 (Research Methodology)

4.3 Material Characterization

4.3.1 *Tensile Strength Tests*

After procurement of steel wires, their strength in tensile was to be determined. So they were then tested in an Ultimate Testing Machine at the School of Chemical and Material Engineering, NUST.

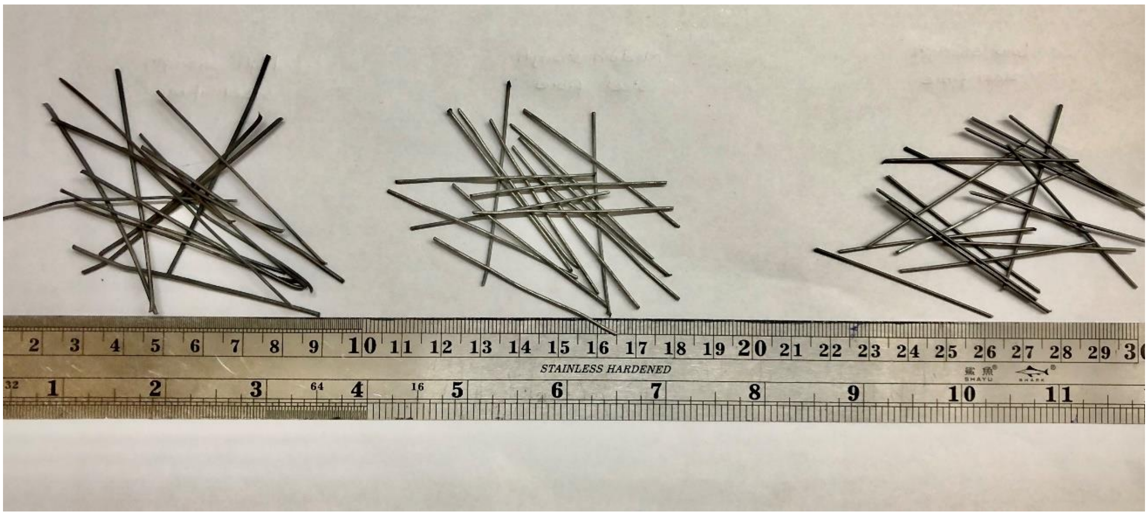


Fig. Steel Fibers

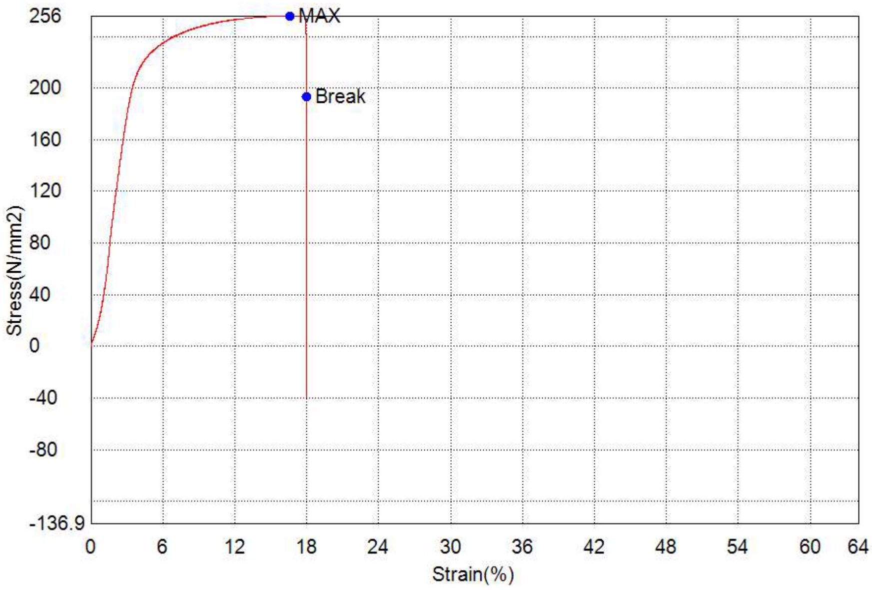


Fig 1.2.1 High Strength Steel Wire (0.8mm)

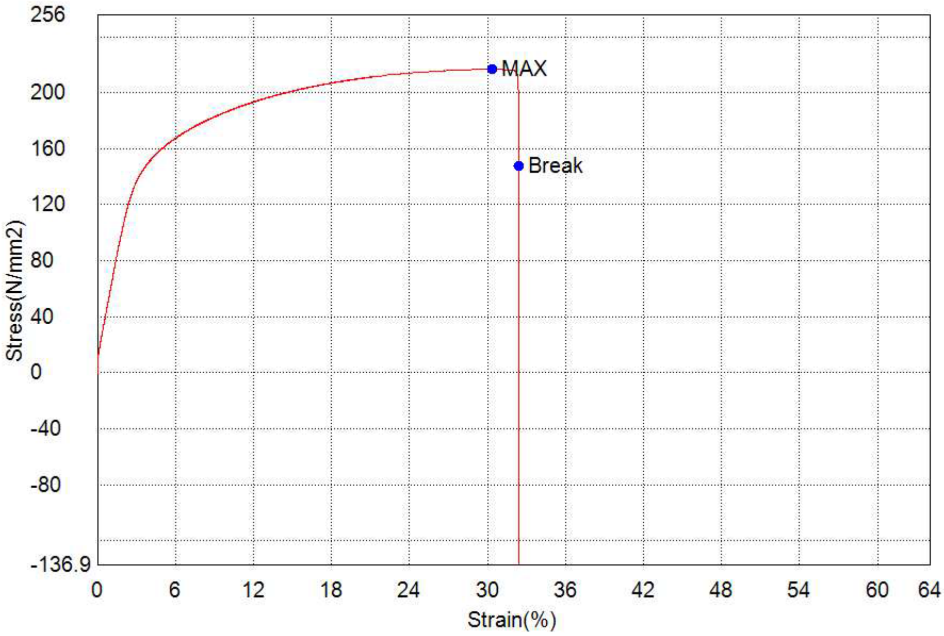


Fig 1.2.2 Medium Strength Steel Wire (0.9mm)

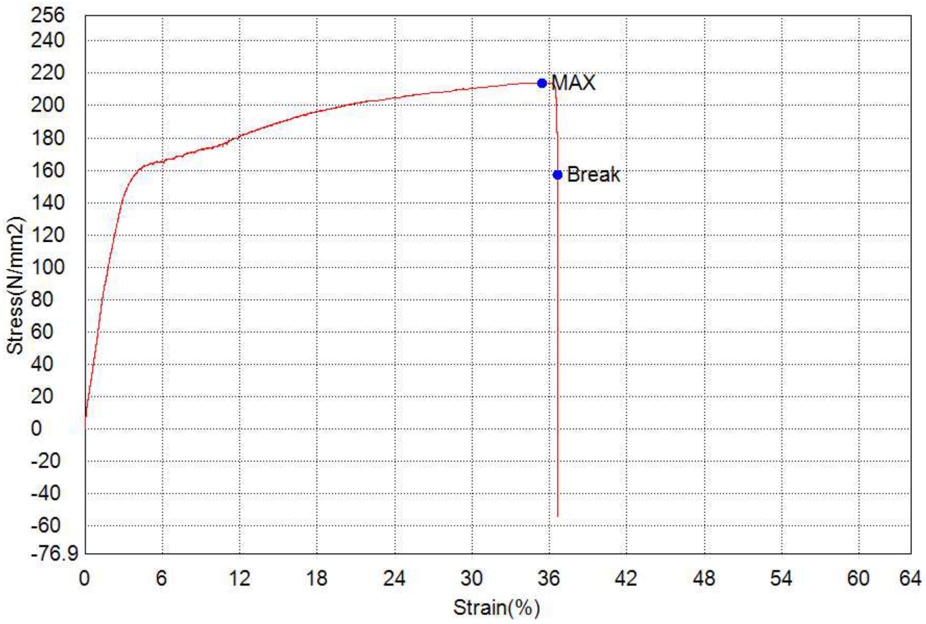


Fig 1.2.3 Low Strength Steel Wire (1.1mm)

4.3.2 Cement, Aggregate, and reinforcement selection for the casting

Normal aggregate retaining on 3/4in the sieve was selected. Max aggregate size was kept at 1". No. 5 steel rebars of Grade 60 were used for the longitudinal reinforcement of beams. Clear span of 2" was provided from the bottom, 1.5" from the sides, and 2.5" from the ends of beam's formwork. Bestway company's cement was used during the casting and it was procured right before the mixing.

4.3.3 Formwork for beam casting

Wooden formwork was acquired for the casting of 6ft long beams. It was tightened using screws and could be opened after each casting for taking out the beam. On the top, wooden bars stopped the beam from expanding, and along with that other solid objects were also placed on each side of the beam while casting to avoid any unnecessary expansion of the beam.

4.4 Casting

Three different types of samples were casted for the testing and analysis of the steel fiber effect:

4.4.1 *Beam for crack measurement*

- 8 no of 6-feet long beams with cross-section 12in deep and 6in wide, reinforced with longitudinal steel bars
    - 2 control samples with no fiber content
    - 6 beams with steel fibers (2 of each type of fiber and further divided into):
        - 3 beams with 0.75% fiber content
        - 3 beams with 1% fiber content

Fig. 6 feet long beam

4.4.2 *Beam for flexural testing*

- 0.75m long beams for flexural testing
    - 1 beam for each of the 8 longer beams
    - Fiber content was 0.75% for 4 beams and 1% for the other 4.

Fig. 0.75m long beam

4.4.3 *Cylinders*

- Cylinders with 4in diameter and 8in height
    - 10 cylinders cast for each beam
        - 5 cylinders with 0.75% fiber content
        - 5 cylinders with 1% fiber content
    - Total 80 cylinders

Fig. Cylinders

4.4.4 Preparation of concrete mix

With the help of the mixture, concrete constituents were then mixed properly for 1 min in the mixer, and then the mixture was poured into the formworks of beams and cylinders.

Mix Type	Fine Aggregate	Coarse Aggregate	Cement	Water	Fiber Volume	W/C Ratio
PCC	458.26	617.24	206.86	144.87	-	0.55
FRC	458.26	567.24	206.86	144.87	0.75% or 1% of Vc	0.55

Table. Mass Proportions (kg) for 1 cubic meter of concrete mixture

4.4.5 Slump values

As the fiber content increased, the value of the slump decreased and the concrete mix became less workable relative to the less fiber content one.

Cylinder Type	Slump Value (in)
CS1	2
CS2	1
LSFRC1	1.7
LSFRC2	1.2
MSFRC1	1.5
MSFRC2	1
HSFRC1	1
HSFRC2	0.5

4.4.6 Curing period

A curing period of 27±3 days was set for the beams and cylinders to achieve maximum strength. Beams and cylinders were cured with water on a regular basis. Woolen bags were also used to cover the specimens and were kept wet so the specimens could stay damp for a longer period of time.

5 Experimental Setup

6 feet Beams were loaded under 4-point loading tests. The reaction Floor at NUST Institute of Civil Engineering was occupied for the said tests. Beams were simply supported. 2 LVDTs were also used to measure the deflection of beams under mid-point and loading points. An illustrative representation of the experimental setup is as below:

Fig. 6 feet beam testing

5.1 Cylinder testing

In order to obtain the overall stress-strain curve, cylinders were to be tested in a strain-controlled ultimate testing machine. To do this, we had to transport our cylinders to the Military College of Engineering at Risalpur, where the machine was available.

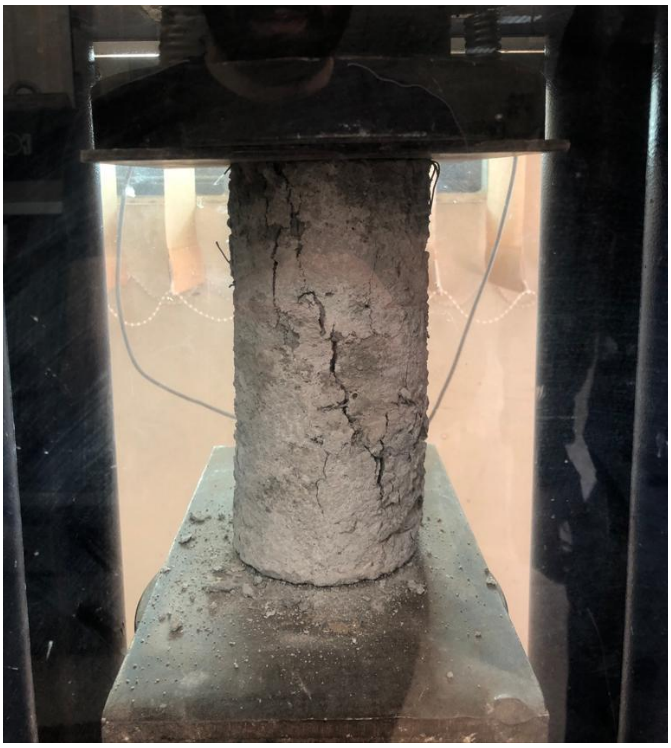


Fig. Cylinder Testing

5.2 Crack width and propagation measurement

In order to measure the crack width and its propagation, the microscope was used and with the help of external light, we were able to measure the width properly.

The microscope had the least count of 0.02mm which was 1 division on the scale.

Fig. Crack width measurement

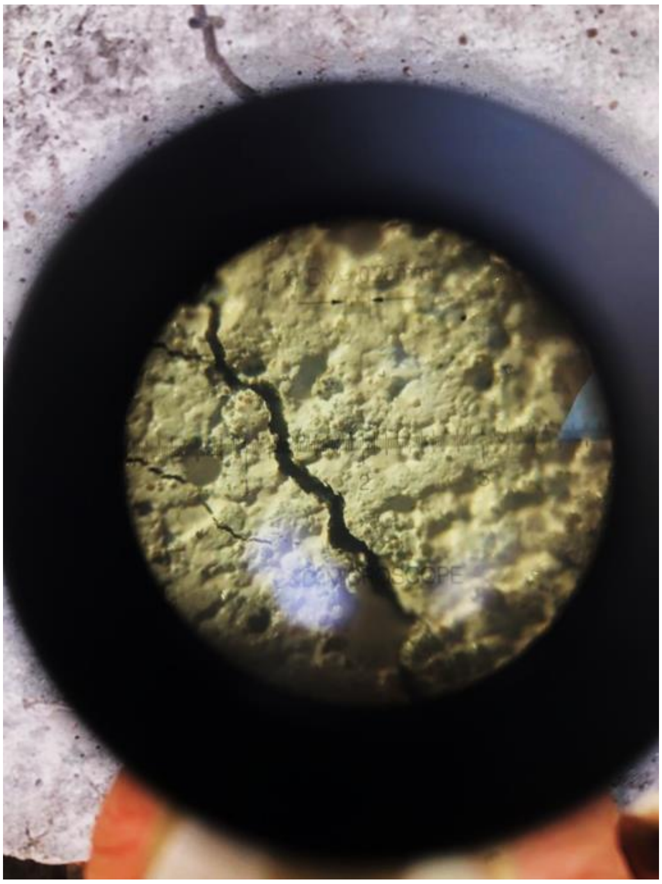


Fig. Divisions shown in the microscope (1 division = 0.02mm)

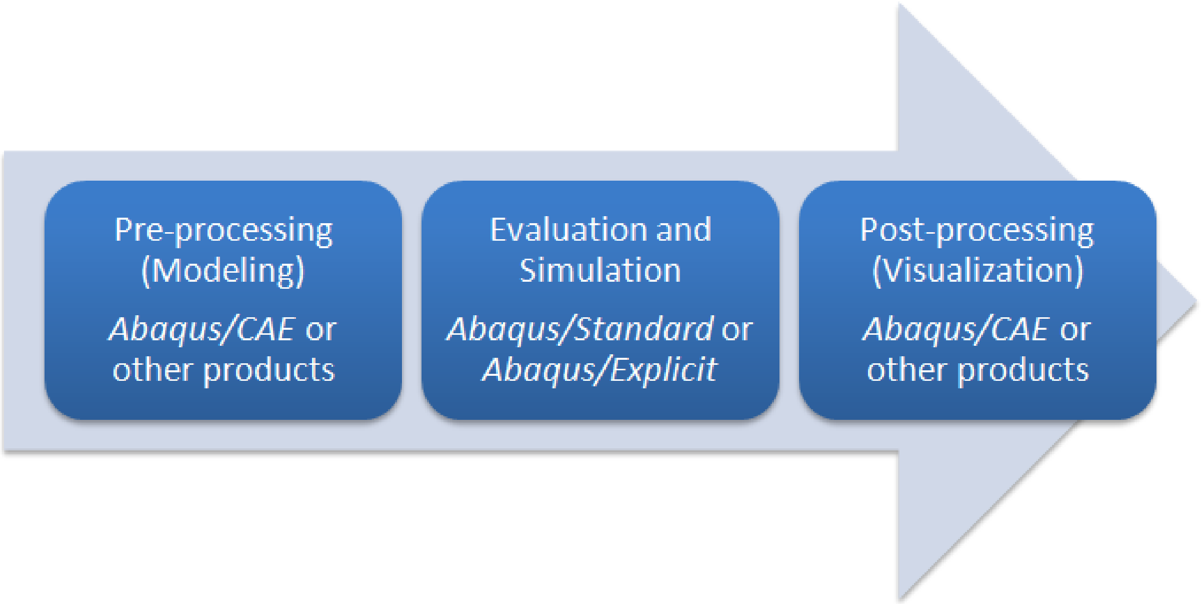
6 4-Point Loading Tests on Beams in ABAQUS

6.1 Introduction:

ABAQUS is a very useful software that can be used to run various engineering simulations. Not only does it have an extensive collection of every possible geometry, but it can also be used to study the behaviors of various kinds of materials for modeling like metals, polymers, concrete, etc. Users can input various materials in several geometries with great ease.

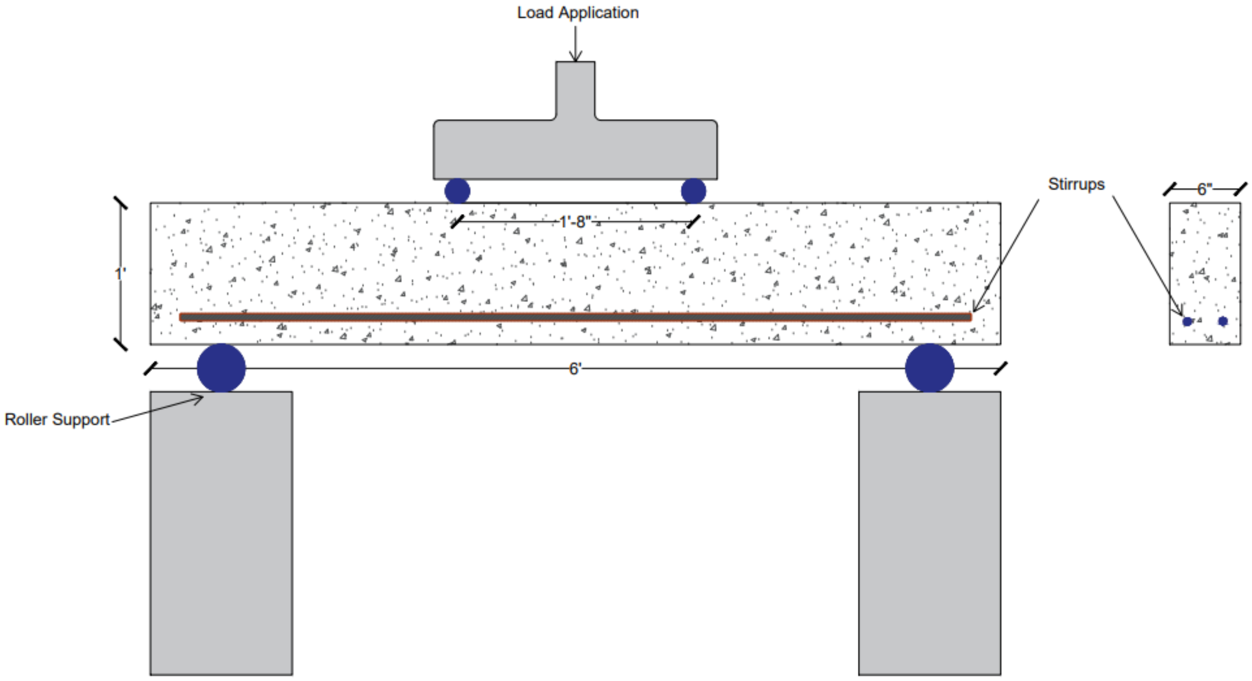
A complete ABAQUS analysis consists of three vital parts.

1. **Pre-processing:** This is the modeling stage. An input file is generated
2. **Processing:** A visual output file is produced at this stage.
3. **Post-processing:** In this step, the visual output file is rendered or used to generate a report.



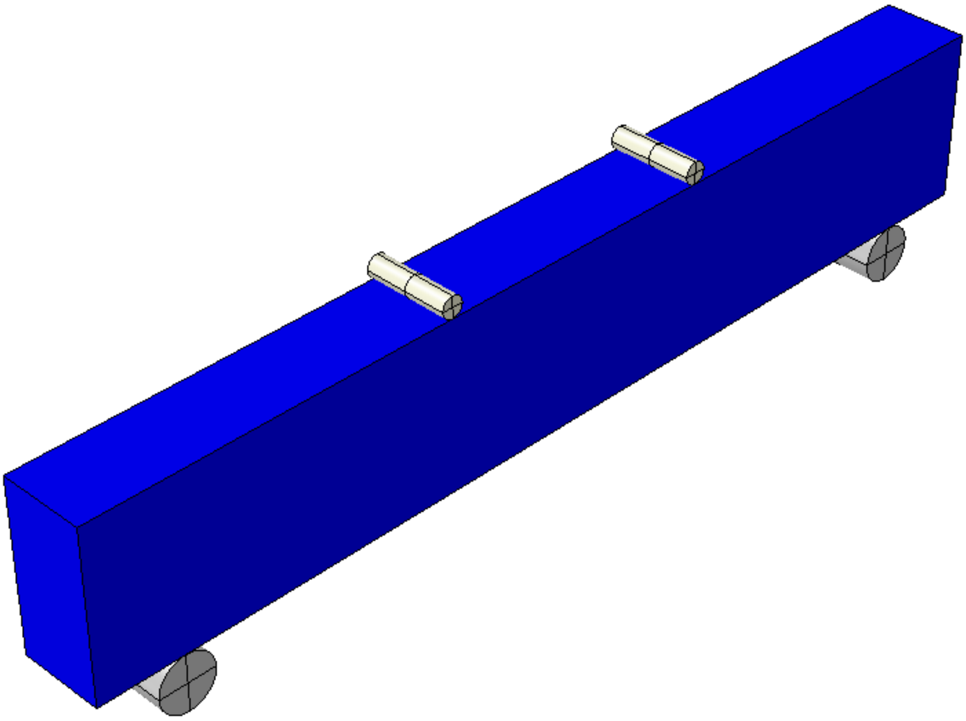
ABAQUS is divided into multiple units that indicate the type of input, called **modules.** Each **module** consists of useful tools that are exclusive to that certain modeling task. For example, the **Mesh module** contains only the tools needed to create finite element meshes. A completed model contains everything that ABAQUS needs to start the analysis. ABAQUS/CAE uses a model database to store your models.

6.2 Worked example: Simply Supported Beam



6.3 Modelling in ABAQUS:

The concrete beam and steel rollers were modelled as C3D8R elements which means 8 node 3 dimensional linear brick elements with reduced integration. The steel rebars were modelled as wires and the element type was T3D2 which means 2 node 3 dimensional truss elements.



The concrete damaged Plasticity (CDP) model was used to model the control concrete beams and steel fibre reinforced concrete beams. The concrete damage plasticity model was used because of its accuracy in predicting results. For computing compression damages, stress strain curves were obtained by conducting displacement controlled compression tests on concrete cylinders. For formulating CDP in tension, the stress strain curve in tension was obtained by using Lok and Xiao tensile relationship. This model was selected because of:

1. Its simplicity and
2. Higher accuracy in predicting desired results

All the parameters required to generate the stress strain curve were either known or tests were conducted to find them out.

7 RESULTS AND ANALYSIS

This study is based on incorporating steel fibers in the concrete mix as a replacement for the stirrups in RCC (Reinforced cement concrete) and is called Steel fiber reinforced concrete (SFRC). 3 Steel fibers of varying tensile strength were procured locally.

In this chapter, results are shown and analyzed for tests i.e., 4-point loading test, Finite Element Analysis (FEA) simulation results, uniaxial compression test, and split tensile test of concrete cylinders. A total of 8 beams were tested under a 4-point loading test with a span of 6' and a cross-section of 6" by 12". The cylinders were of the dimension 4" by 8" and were tested under uniaxial displacement controlled compression to get both the compressive strength and the post-peak stress-strain curve, and split tensile test for tensile strength of concrete.

7.1 CONCRETE CYLINDERS TESTS

Results of Concrete Cylinders under uniaxial compression and split tensile test and the corresponding elastic modulus are tabulated below:

Cylinder Type	**Compressive Strength (MPa)**	**Split Tensile Strength (MPa)**	**Elastic Modulus (MPa)**	**Slump Value(in)**
CS1	24.87	2.31	21025.2	2
CS2	28.81	2.4	20855.14	1
LSFRC1	27.55	2.61	24664.93	1.7
LSFRC2	24.6	3.04	20855.5	1.2
MSFRC1	25.47	2.71	23010.52	1.5
MSFRC2	27.79	2.8	23717.87	1
HSFRC1	28.88	3.55	26966.22	1
HSFRC2	28.01	4.03	27962.16	0.5

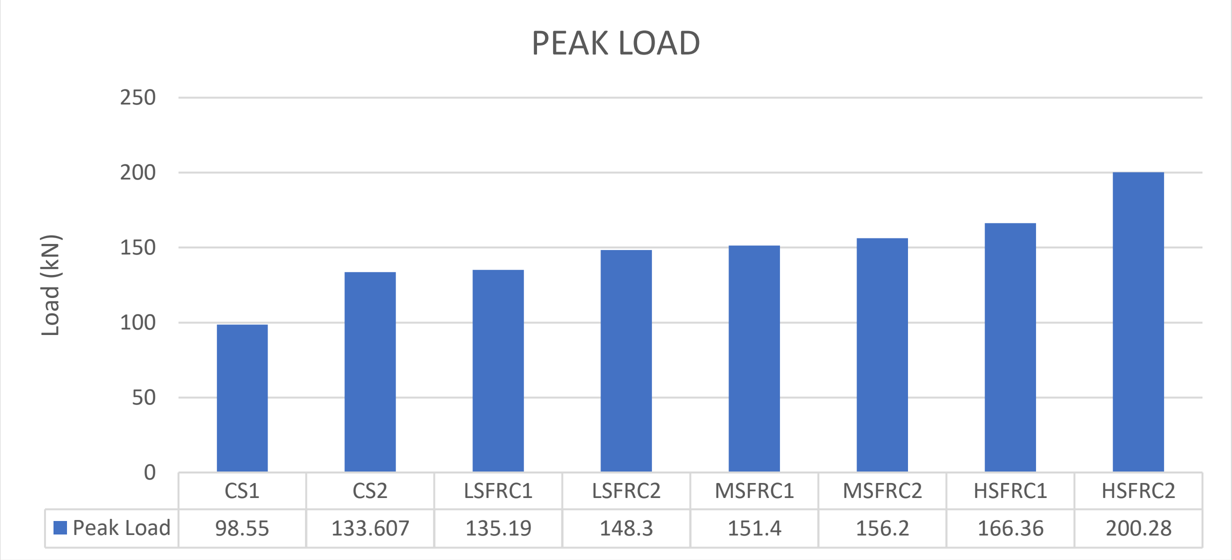
There is a clear trend being followed that the greater the tensile strength of the fibers greater the compressive strength, split tensile strength, and likewise elastic modulus. This can be attributed to the fiber bridging effect in the concrete matrix i.e., holding the shape intact. The compressive strength of the concrete is increasing from CS1 to HSFRC2, CS1 the control sample that had no fibers had the lowest strength and as the strength of fiber is increasing the compressive strength, split tensile strength and Elastic modulus is increasing. The increase in strength is due to the fiber bridging effect, holding the concrete matrix intact. Cylinders with same fiber strength have greater strength for the one with greater fiber volume fraction. The slump values are lower for concrete with the fibers because there is loss of workability as fibers are incorporated in the mix.

7.2 4-POINT LOADING TEST RESULTS

4-point loading tests were carried out on the Reaction Floor in NICE Structural Lab. It was performed in stress-controlled conditions in which the stress rate was kept constant while the strain increased.

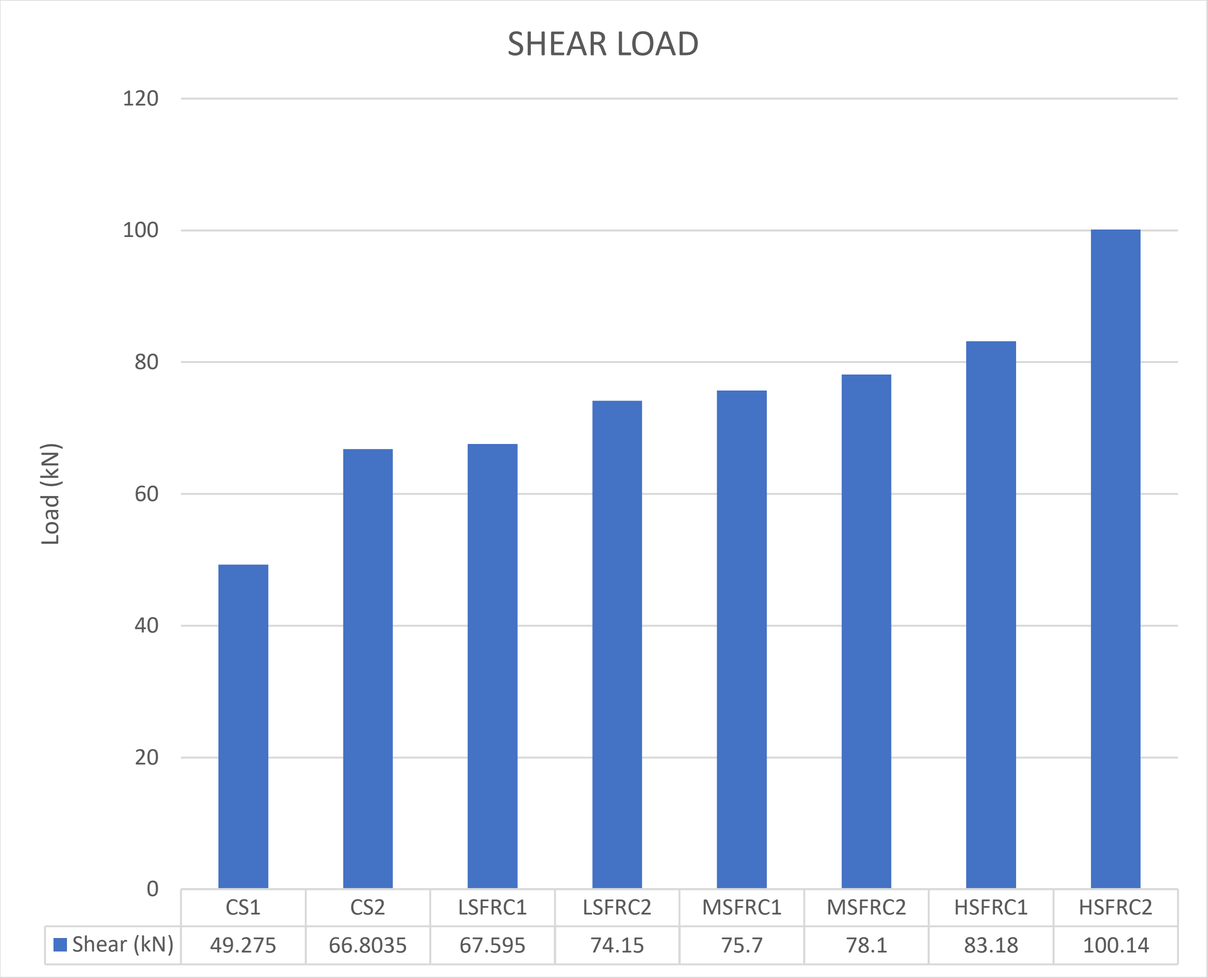
7.2.1 Peak Loads Comparison:

Peak loads at the failure of the beams are shown in the following bar chart:



From the chart, as the tensile strength of fiber increases greater the peak load because of the greater ability to resist the shear forces across the shear cracks. This is evident from the peak load of CS2 of 133.607kN and the peak load of HSFRC2 of 200.28kN. The value of CS1 is discarded because of the considerably low value of peak load. The peak load is also increasing for same fiber strength as the fiber volume fraction is increased. The peak load values increase is caused due to the fibers holding the concrete matrix firm and intact and thus preventing the concrete from breaking by virtue of its fiber strength. The value of CS1 has abnormally low peak load value so that value is considered an outlier.

7.2.2 *Shear Capacity Comparison:*



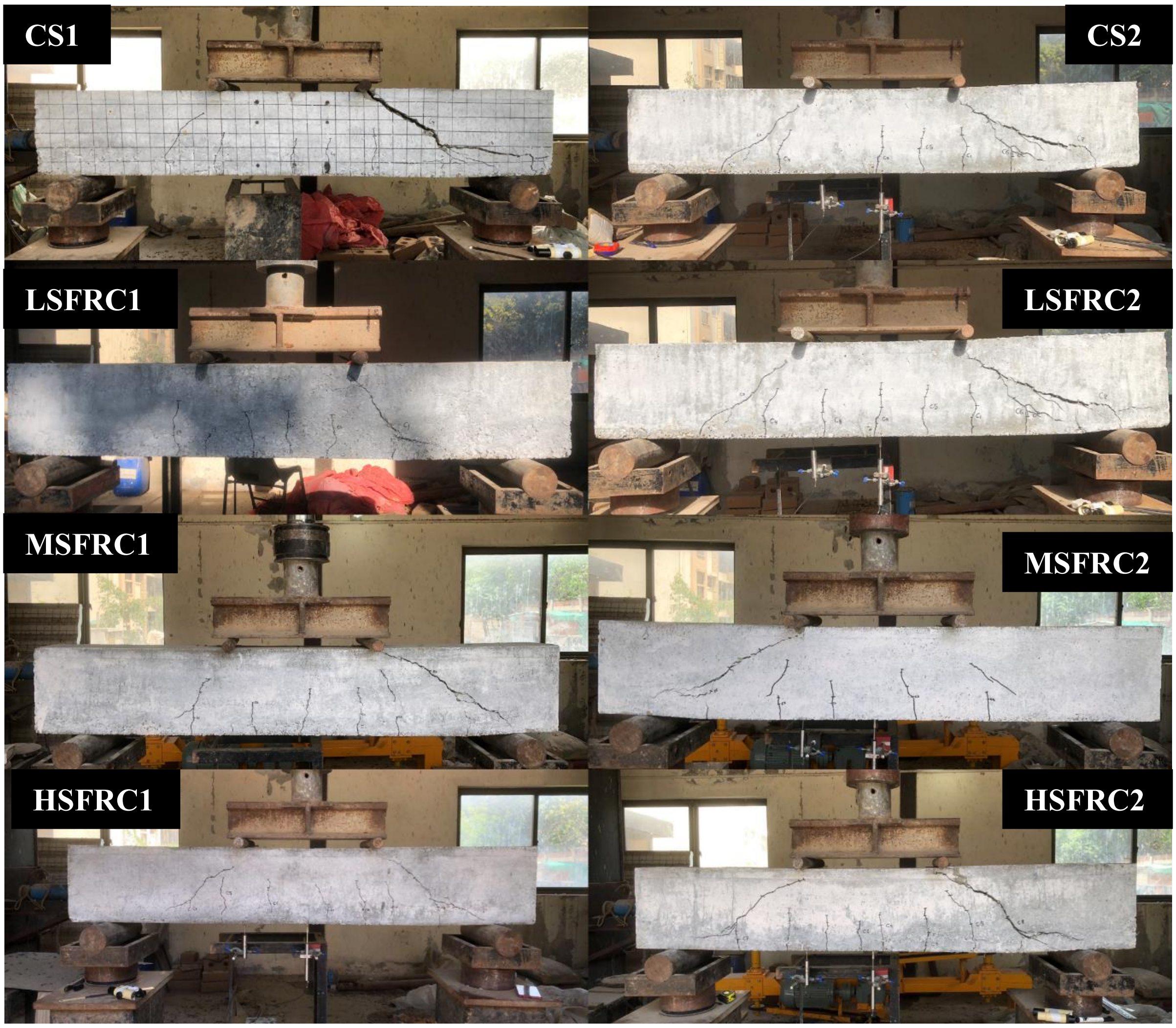
Beam ID	Peak Load(kN)	Shear(kN)	% Increase
CS1	98.55	49.275	-
CS2	133.607	66.8035	CS
LSFRC1	135.19	67.595	1.18481
LSFRC2	148.3	74.15	10.99717
MSFRC1	156.2	78.1	16.91004
HSFRC1	166.36	83.18	24.51443
HSFRC2	200.28	100.14	49.90232

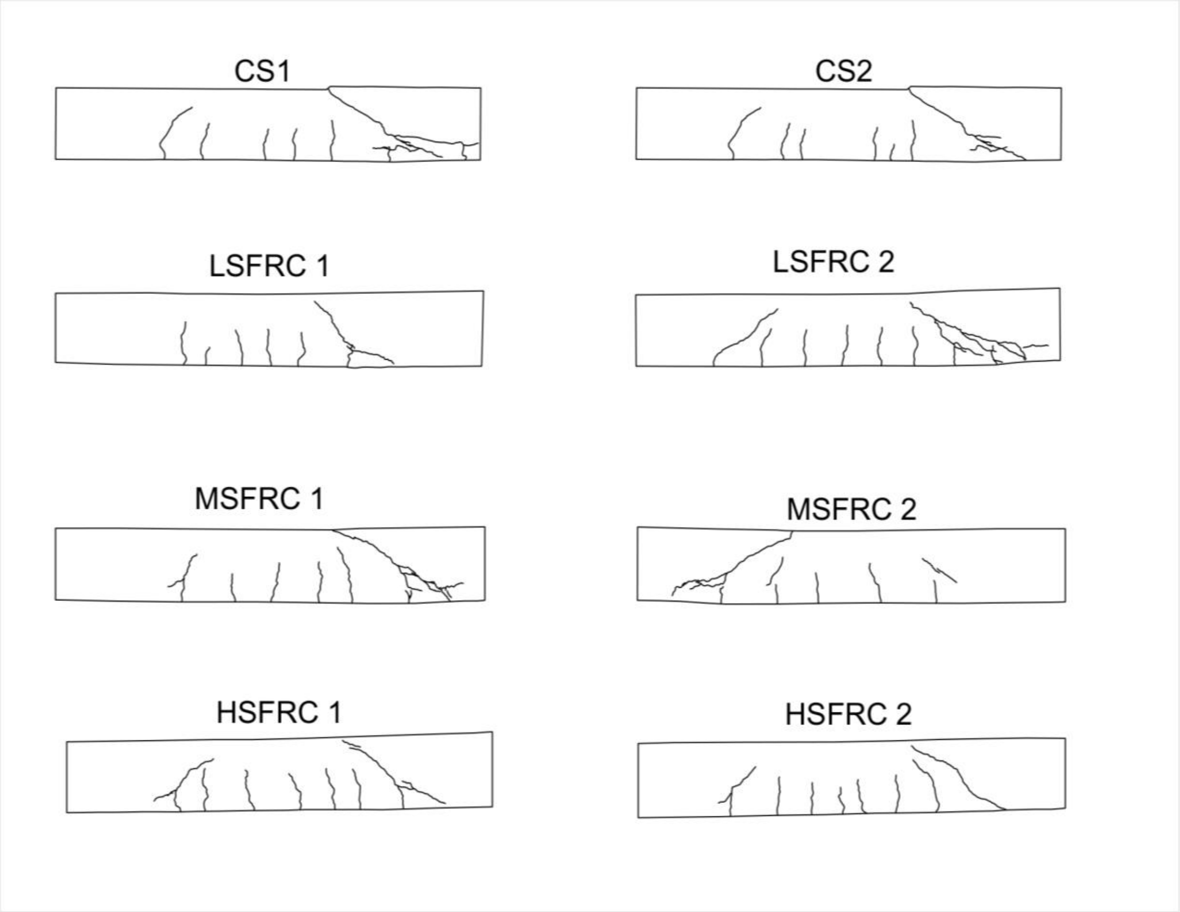
The results of CS1 are discarded because they showed great error and deviation from the common trend formed. The CS2 beam had the lowest shear strength of 66.80 kN and the shear strength is increasing as the fiber strength is increased with the highest value at HSFRC2 with

1% Fiber Volume Fraction and a strength of 100.14 kN. From the above chart and the following table, almost a 50% increase in shear strength was observed when the fibers of the highest tensile strength were used. The strength gain is attributed to the fiber bridging effect of the fibers and as the load is applied the fiber strength is initiated that holds the beam intact and thus increases strength.

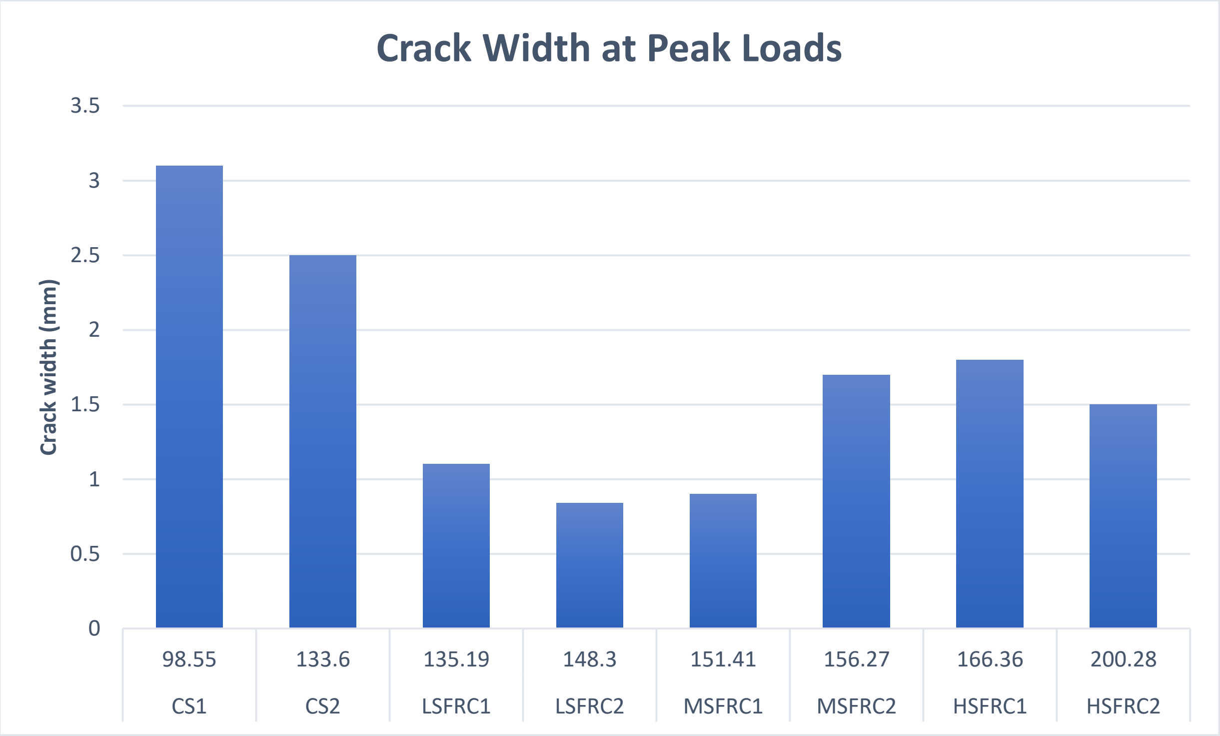
7.2.3 Crack Patterns in beams tested:

The following picture shows the crack patterns in the beams at failure and the same cracks are also depicted in an AutoCAD drawing file for clear visibility.




CS1
CS2
LSFRC 1
LSFRC 2
MSFRC 1
MSFRC 2
HSFRC 1
HSFRC 2

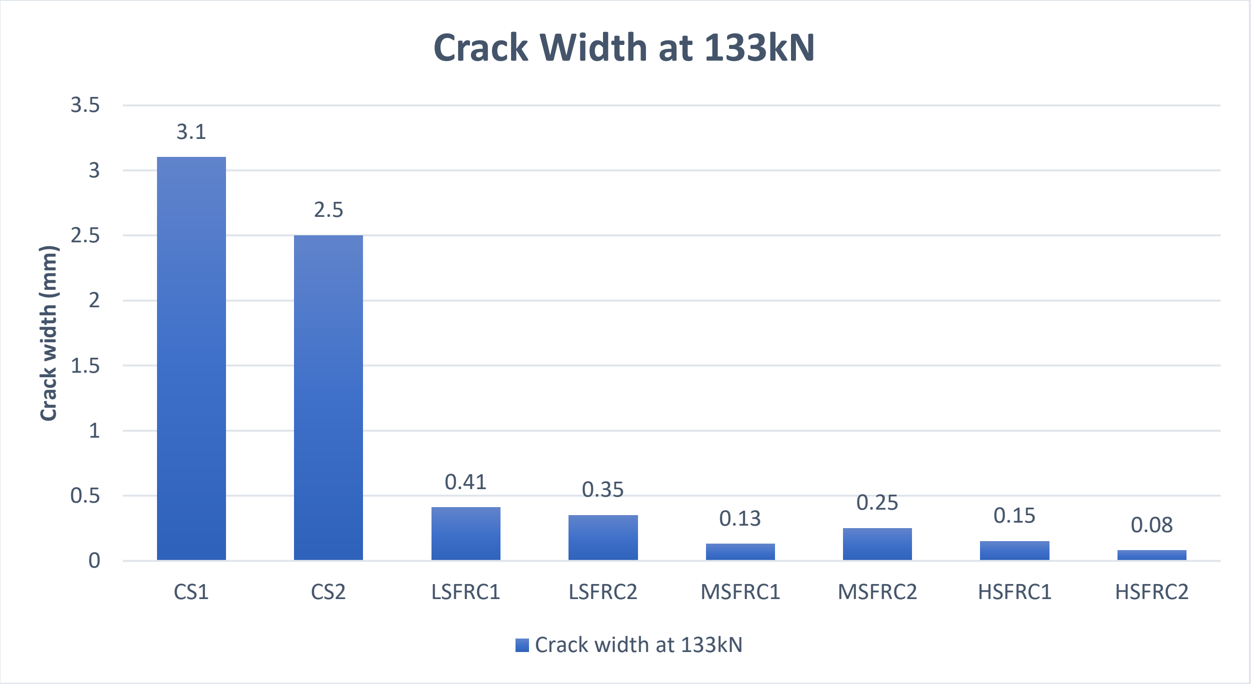
7.2.4.1 Crack Data (Shear Crack):



Beam Type	**Peak Load(kN)**	**Crack Width (mm)**
CS1	**98.55**	**3.1**
CS2	**133.6**	**2.5**
LSFRC1	**135.19**	**1.1**
LSFRC2	**148.3**	**0.84**
MSFRC1	**151.4**	**0.9**
MSFRC2	**156.2**	**1.7**
HSFRC1	**166.36**	**1.8**
HSFRC2	**200.28**	**1.5**

Discarding the CS1 result and comparing the CS2 crack widths with the beams incorporated with fibers showed that the addition of fibers decreased the crack widths at peak loads. CS2 had the shear crack width of 2.5mm at peak loads while the beams with fibers all had widths of less than 1.8mm at peak loads with the lowest width of 0.84 of LSFRC2 at peak load. Keeping in mind that the peak loads of the beams with fibers is also greater while the respective crack widths are lower. Again this result is due to the bridging effect caused by the fibers holding the matrix intact and preventing the cracks from further propagating.

7.2.4.2 Crack Widths (Shear Crack) at failure load of CS2:

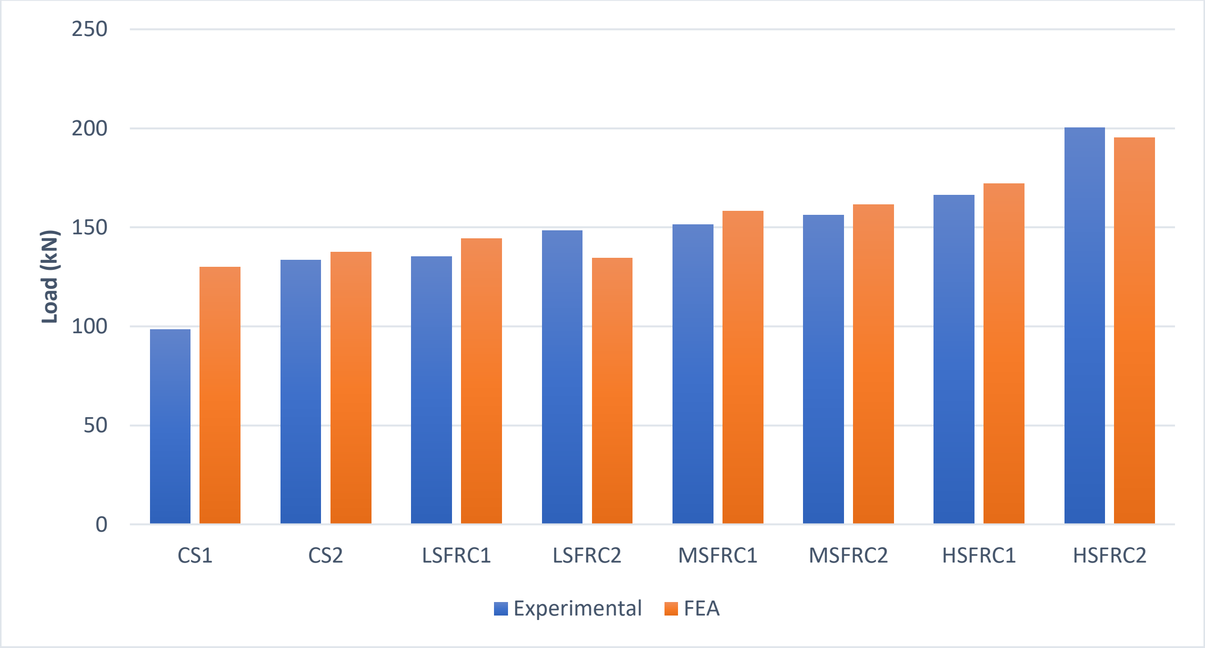


Beam Type	**Peak Load(kN)**	**Crack Width (mm)**
CS1	**133**	**3.1**
CS2	**133**	**2.5**
LSFRC1	**133**	**0.41**
LSFRC2	**133**	**0.35**
MSFRC1	**133**	**0.13**
MSFRC2	**133**	**0.25**
HSFRC1	**133**	**0.15**
HSFRC2	**133**	**0.08**

This chart compares the crack widths(mm) at the peak load of CS2 of 133kN. From the table, it shows that as the fiber strength increases the crack width decreases at a given load value as the beam with the highest strength fiber shows the least crack width of 0.08mm as compared to beam CS2(no fiber) of 2.5mm again due to the fiber bridging effect being more prominent as the strength of the fiber increases. All the SFRC beams had crack widths lower than 0.5mm at 133kN and the lowest crack width was observed in the case of HSFRC2 with 0.08mm only.

7.3 COMPARISON BETWEEN EXPERIMENTAL AND FINITE ELEMENT ANALYSIS (FEA)

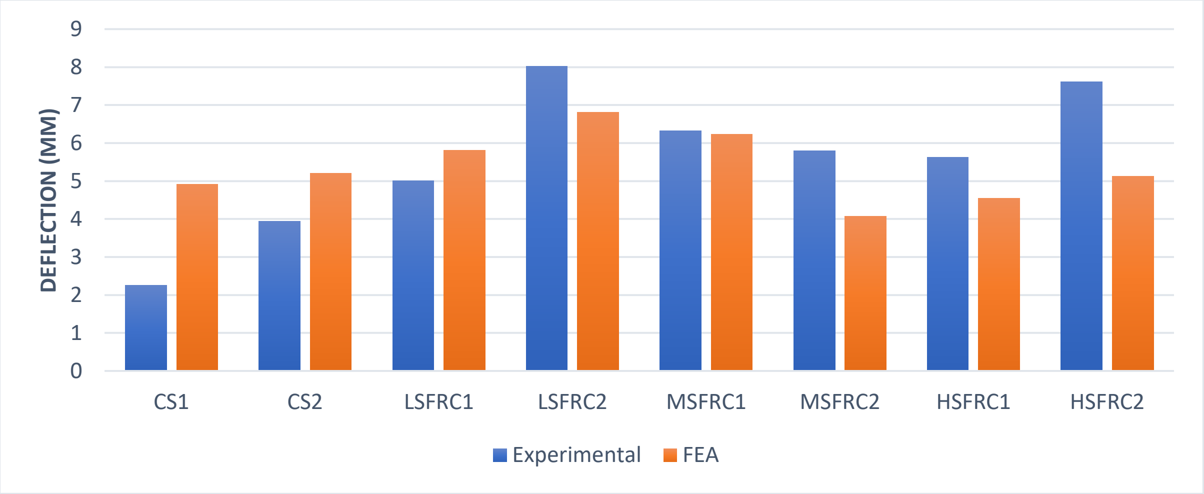
7.3.1 Comparison of peak loads (Experimental and FEA):



Beam ID	**Peak Load(kN)**		**Error %**
	Experimental	**FEA**	
CS1	**98.55**	**130.11**	**32.02435**
CS2	**133.607**	**137.5**	**2.91376**
LSFRC1	**135.19**	**144.18**	**6.64990**
LSFRC2	**148.3**	**134.34**	**9.41335**
MSFRC1	**151.4**	**158.08**	**4.41215**
MSFRC2	**156.2**	**161.6**	**3.45710**
HSFRC1	**166.36**	**172.17**	**3.49242**
HSFRC2	**200.28**	**195.28**	**2.49650**

From the table above, apart from CS1 whose values show great abnormality, the experimental peak loads obtained from 4-point loading test and obtained from FEA simulation showed that the highest %error of 9.41% occurred in LSFRC2 while the lowest error occurred in HSFRC2 of 2.49%. The difference in peak loads is less than 10% in experimental and FEA results. The model shows great promise. Also, the trend shows that the difference reduces when greater peak load values are obtained i.e. when greater tensile strength fibers are used.

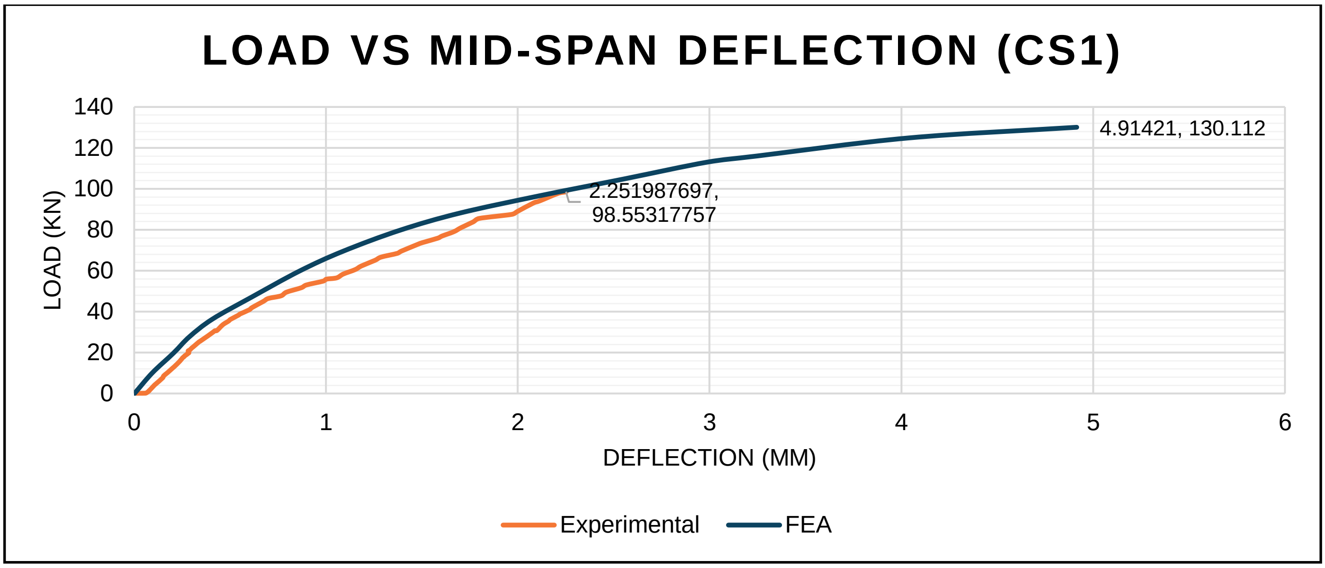
7.3.2 Comparison of Mid-Span Deflections (Experimental and FEA):



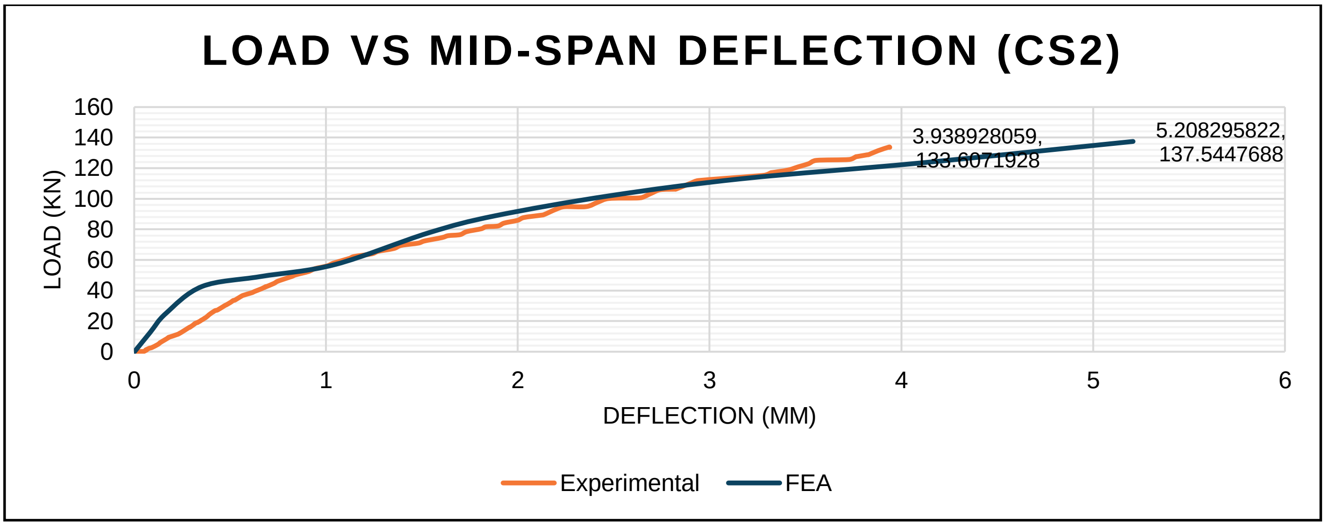
Beam ID	**Mid-span Deflection(mm)**		**Error %**
	Experimental	**FEA**	
CS1	**2.25**	**4.91**	**118.22222**
CS2	**3.938**	**5.208**	**32.24987**
LSFRC1	**5.01**	**5.81**	**15.96806**
LSFRC2	**8.02**	**6.81**	**15.08728**
MSFRC1	**6.32**	**6.24**	**1.26582**
MSFRC2	**5.799**	**4.08**	**26.64304**
HSFRC1	**5.63**	**4.55**	**19.18295**
HSFRC2	**7.609**	**5.12**	**32.71126**

The mid-span deflections of CS2 for experimental and FEA is 3.938mm and 5.208mm respectively, a difference of 32.24% while for HSFRC2 it is 7.606mm and 5.12mm respectively, a 32.711% difference. For MSFRC1 it has least percentage error of 1.26 with 6.32mm experimental and 6.24mm from the FEA Model. Apart from MSFRC1 where the % error was the least, there is a considerable difference in deflections in experimental and FEA, this might be due to the quality and calibration error in the LVDTs used for measuring experimental deflections.

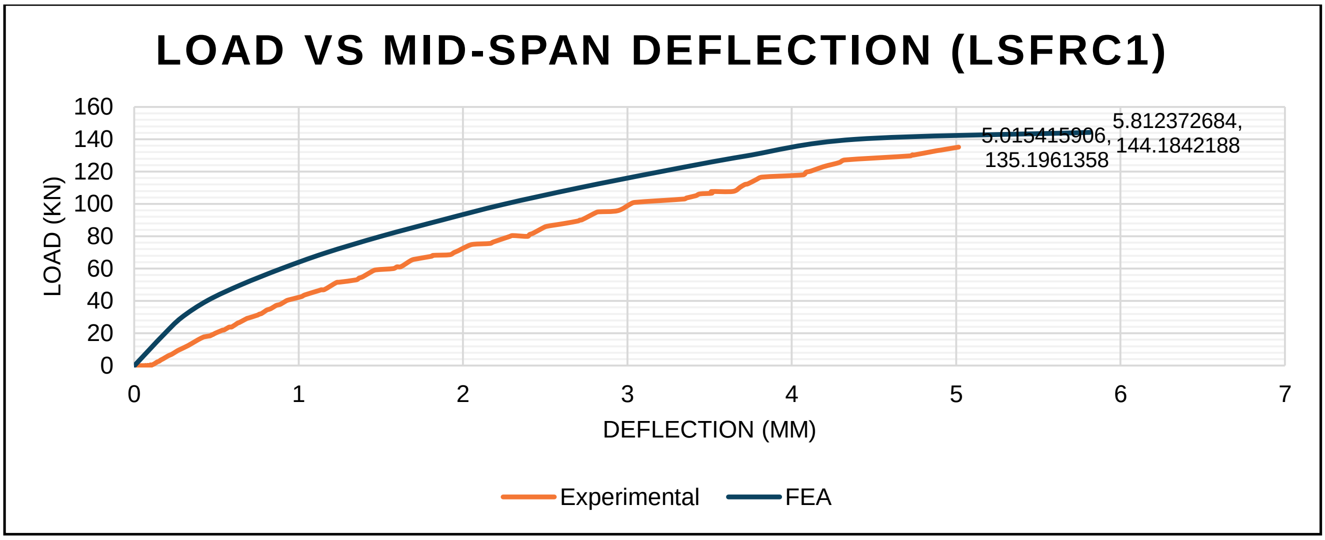
7.3.3 Load vs Mid-Span Deflection in Simple Beams (Experimental vs FEA):



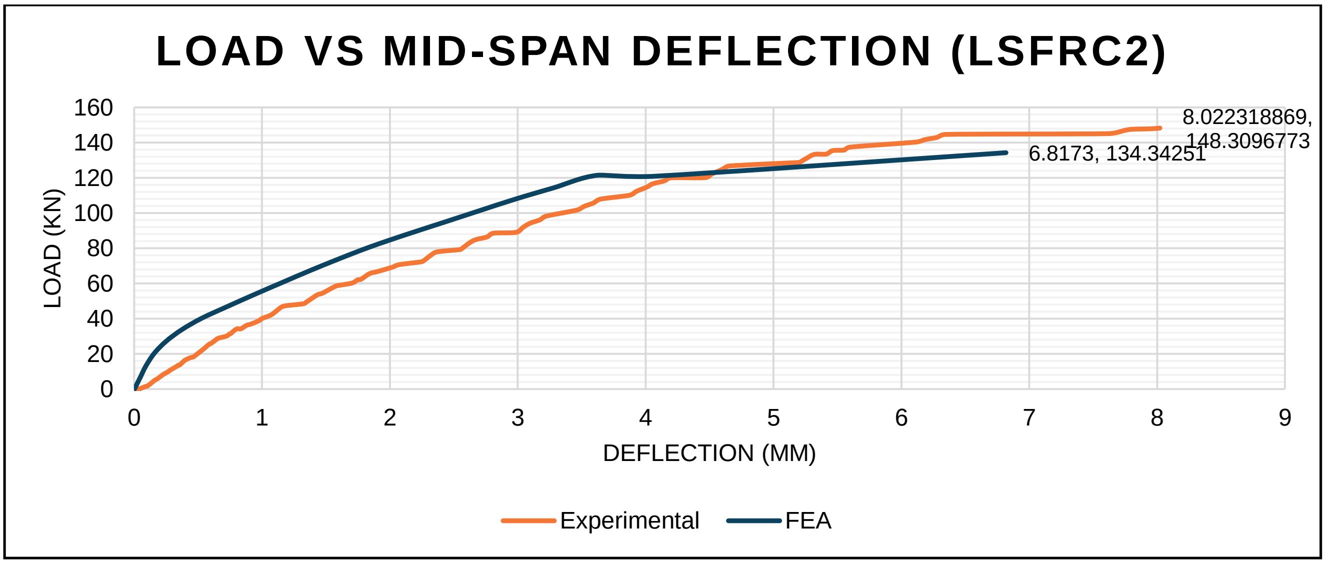
For CS1, the load vs deflection curves both experimentally determined, and FEA are slightly mismatched in 1mm to 2mm region.



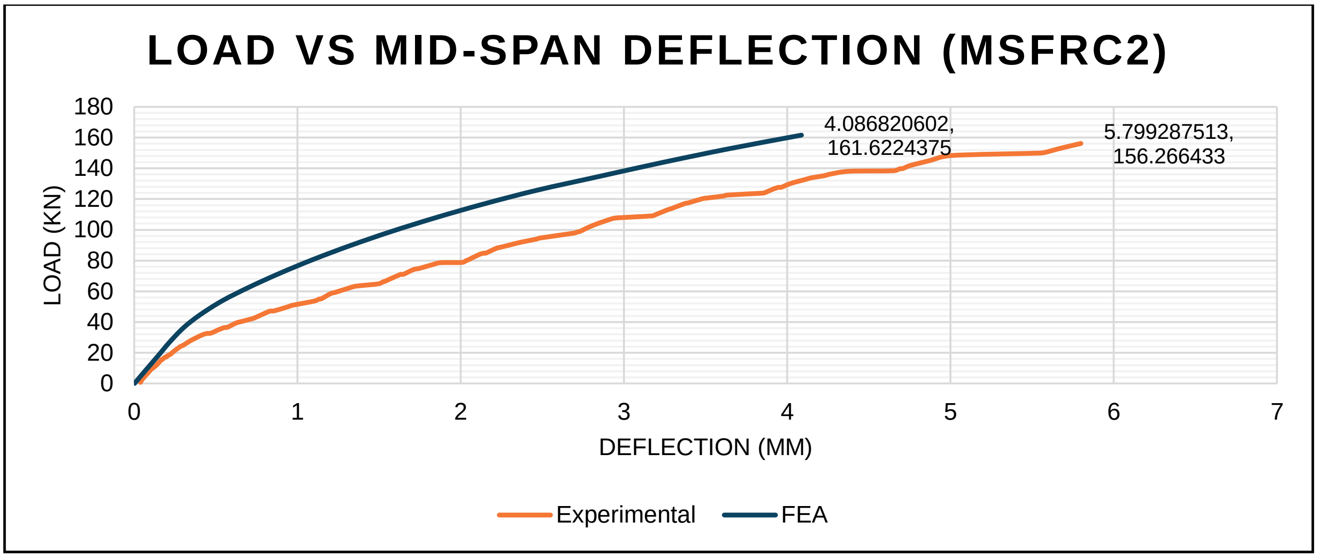
For CS2, the experimentally determined and FEA load-deflection curves show almost identical behavior.



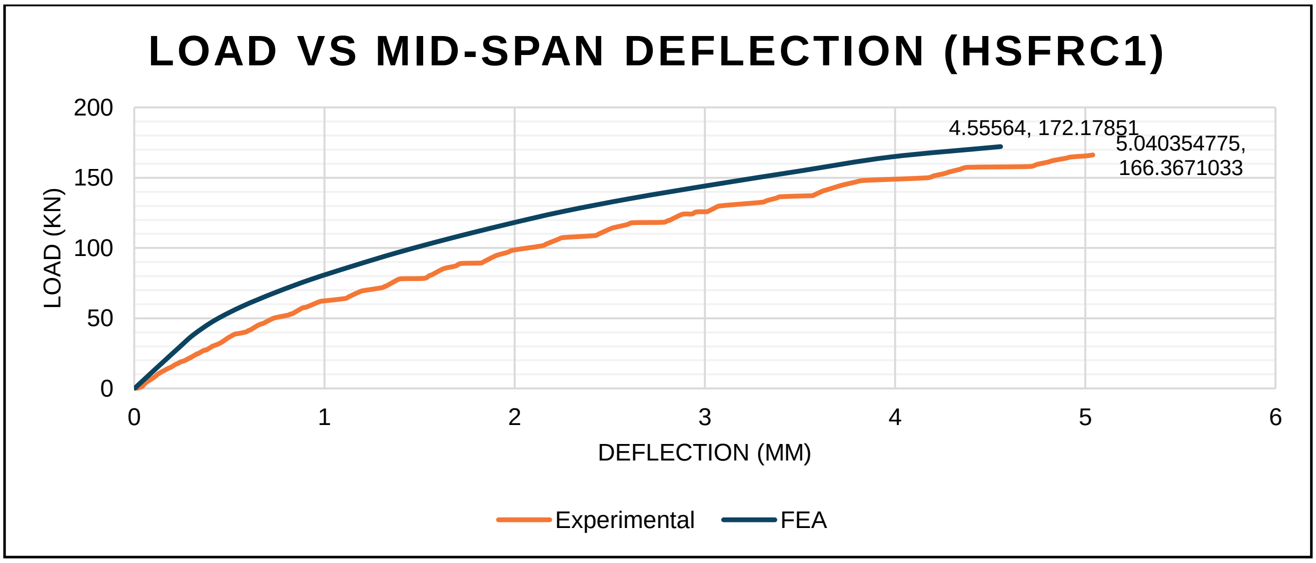
For LSFRC1, both experimentally determined, and FEA load-deflections curves show slight difference in loads at same deflections, but peak loads are almost equal.



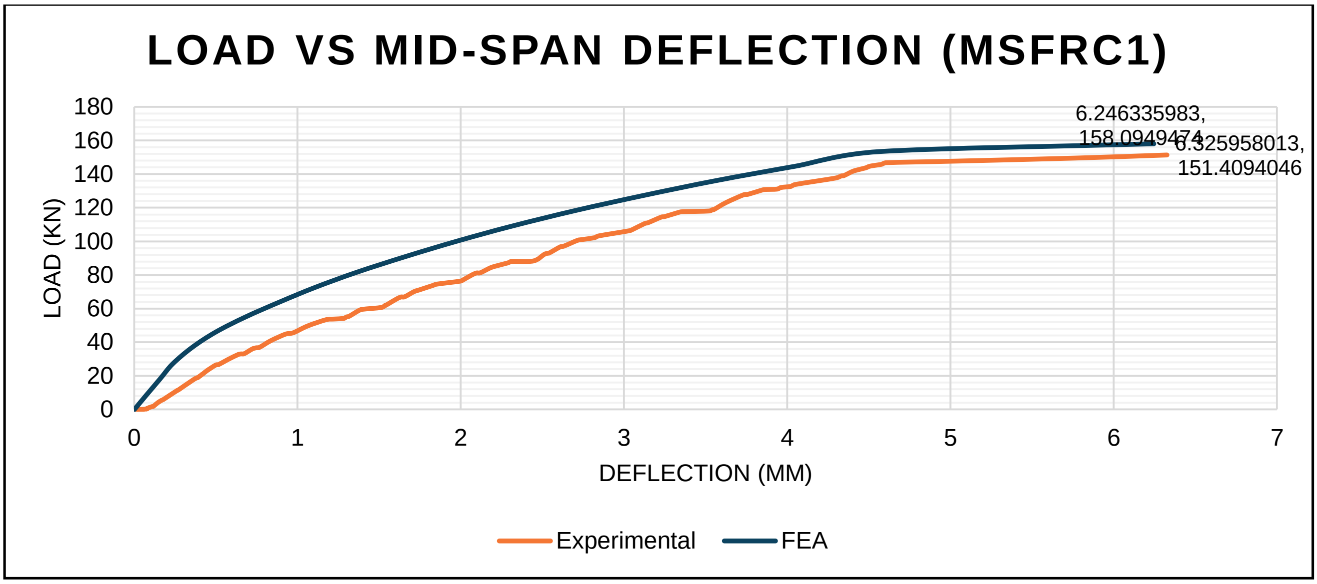
For LSFRC2, both the experimentally determined and FEA load-deflection curves slight deviation in loads at same deflection but there is miniscule difference in peak loads.



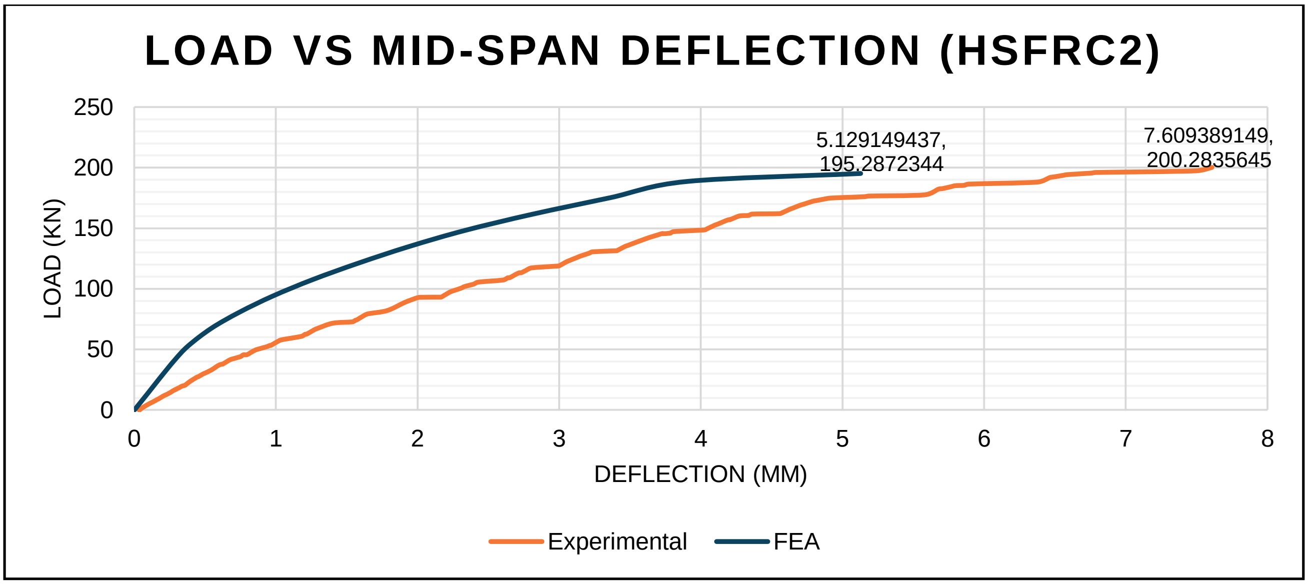
For MSFRC1, the load vs deflection both experimentally determined, and FEA show slight deviation in load values at same deflections but peak loads are almost same.



Both the experimentally determined and FEA load vs deflection curves for MSFRC2 show quite a bit deviation in loads at same deflection.



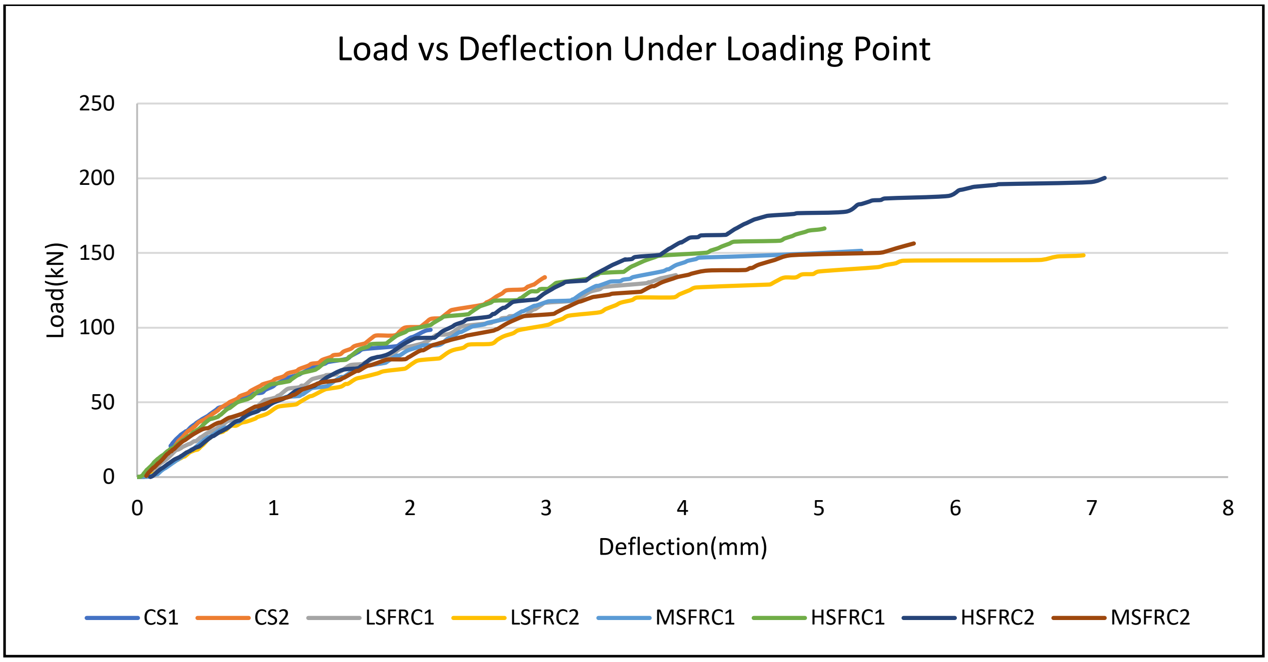
Both the experimentally determined and FEA load vs deflection curves show a consistent difference in loads at same deflection, but the peak load difference is small.



Both the experimentally determined and FEA load vs deflection curves show quite a bit deviation in loads at same deflections.

All the graphs show that the initial stiffness of Experimental and FEA is different that might be characterized by the quality and calibration error in LVDTs as mentioned in the previous section.

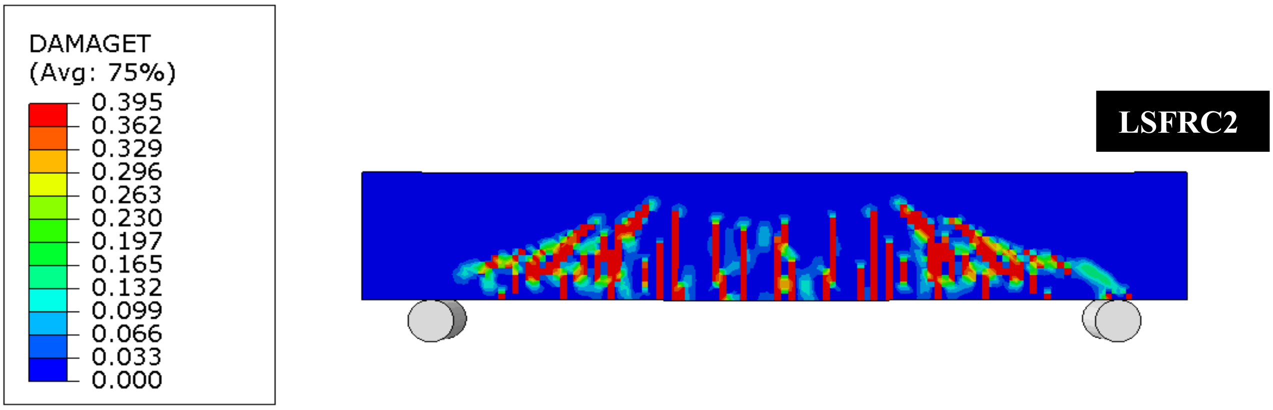
7.3.4 Load vs Deflection in Beams (under loading point):

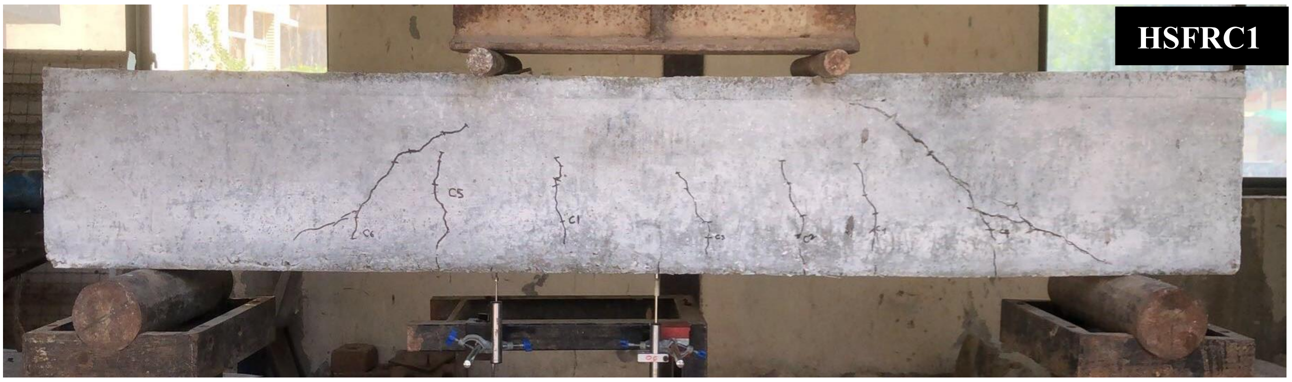


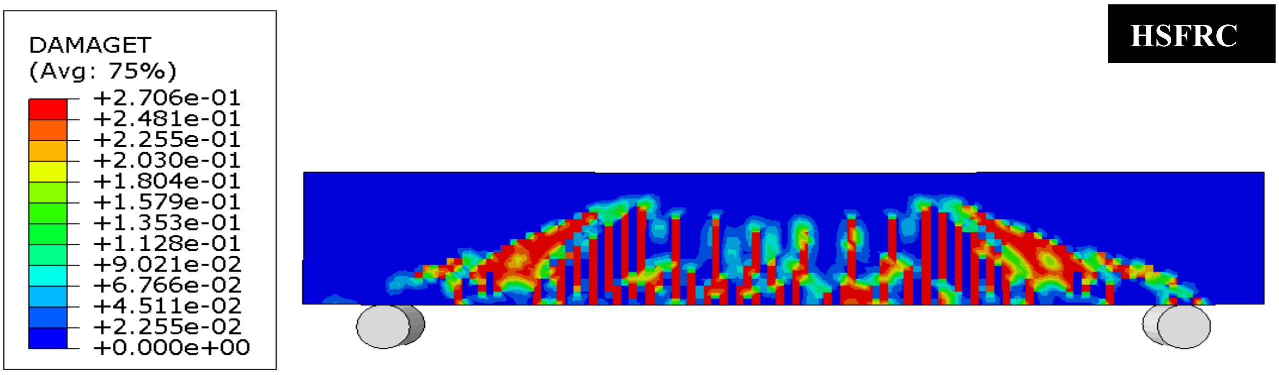
Beam Type	**Peak Load(kN)**	**Max Deflection under Load Point(mm)**
CS1	**98.55**	**2.15**
CS2	**133.607**	**2.98**
LSFRC1	**135.19**	**3.95**
LSFRC2	**148.3**	**6.94**
MSFRC1	**151.4**	**5.31**
MSFRC2	**156.2**	**5.69**
HSFRC1	**166.36**	**5.04**
HSFRC2	**200.28**	**7.094**

The CS2 beam with no fibers had the peak load of 133.6kN and max deflection of 2.98mm and the SFRC beam with highest fiber content had peak load of 200.28 kN and max deflection of 7.094mm. The common trend shows that increasing fiber strength increases peak load or load at failure also the deflection the beam undergoes also increases considerably. Beam with the highest fiber and strength with a 1% fiber volume fraction shows both the maximum load and maximum deflection before undergoing failure.

7.3.5 4.4.5 Experimental vs FEA crack patterns:







The crack patterns are almost identical to their propagation observed in the actual experimentation, thus validating the model further. The failure shear crack showing major stress area indicating failure at that point identical to how the failure occurred in the tested beams. The red zone in the simulation shows the areas of extreme stress and are at the same locations as those of the beams experimentally tested.

7.4 CONCLUSIONS AND RECOMMENDATIONS

7.4.1 Summary:

The project aimed to test the effectiveness of strength of steel fibers with fiber volume fractions of 0.75% and 1% on the strength and the shear capacity of the Steel Fiber Reinforced Concrete (SFRC) beams. 4-point loading tests were performed to determine the peak load and shear capacity of the beams the load-deflection curves, and crack widths were also in the consideration and scope of our study. Concrete cylinders were tested in deflection controlled uniaxial compression to determine the ultimate strength and post-peak behavior of concrete, and split tensile test to determine the tensile strength of the concrete for the FEA modelling in ABAQUS for as accurate modelling as possible, to compare and validate the results drawn both experimentally and through the usage of software.

7.4.2 Conclusions:

1. Almost 50% increase in shear strength of beams has been observed due to the fibers and the tensile strength of fibers has had a direct effect on the strength
2. At the same load, high-strength fibers reinforced concrete beams had lower crack widths due to the fiber bridging effects.
3. The concrete damage plasticity (CDP) model gives accurate results even when used for SFRC beams.
4. Based on the results of the current study, it is recommended to use high-strength steel fibers to achieve desired properties thereby reducing the volume fraction of fibers which will ultimately result in workable and economical aspects.

7.4.3 Recommendations:

In this study, the beams which were tested under 4-point loading had a 6’ length and cross-section of 6” by 12” so the failure was controlled by flexure and shear. To fully test the effect of the strength of steel fibers on the shear capacity of the beam, there is a need to reduce the length of the beam further so that the failure is purely governed by the shear force acting on the beam.

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8.1 ASTM Standards Used:

1. ASTM D695 standard for Compression tests
2. ASTM D790 standard for Flexure strength tests
3. ASTM C393 standard for Beam Flexure test
4. ASTM E111 standard for Young's Modulus of Elasticity
5. ASTM C1550 standard for Flexural Toughness of Steel Fiber
6. ACI 318-19 standard for Reinforcement placement