Computational Analysis of Hybrid Fiber-Reinforced Concrete

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ABSTRACT
The findings of this research provide a computational evaluation of Hybrid Fiber Reinforced Concrete (HFRC) which comprises of Glass and Steel Fibers with the aim to boost mechanical characteristics such as tensile strength, toughness and crack resistance. Based on ABAQUS Finite Element Analysis, this research reports a detailed mechanical behavior of concrete cylinders and beams under displacement-controlled compression and uniformly distributed loadings respectively. Six models (M0–M5) have been prepared, with different proportions based on volume of the fibers to analyze the influence on the structural member parameters. From the simulations carried out, evidence of enhancements in the displacement resistance as well as stress distribution where fibers are incorporated is well illustrated. In particular, fiber orientation and content were proven to be predictive of load distribution and deformation behavior. M0 was found to have minimum stress resistance and the other reinforced models revealed more than doubled the maximum stress with M1 having the highest stress resistance. As such, the extent of fiber incorporation and its significance to enhancing the structure's performance are principal findings pointing to the requirement for additional computational and experimental research on the fiber orientation and content. Thus, the present research helps in filling up the knowledge gap concerning the behavior of HFRC while under load and serves as a starting point in the use of computational modelling to improve the performance and durability of concrete structures reinforced with fibers.

Keyword: Natural Hybrid Fiber Reinforced Concrete (HFRC), ABAQUS Finite Element Analysis (FEA), Structural Performance, Displacement Resistance, Stress Distribution, Fiber Orientation, Computational Analysis

1. INTRODUCTION

Concrete is one of the most important and prominently used materials in construction because of its high compression strength [1]. Some of the weaknesses or limitations of the conventional concrete are; low tensile strength, low ductility, uneven and random cracking failure under variable loads [2]. These disaggregate its application mainly to structures prone to heavy tension, dynamic loading such as earthquake, wind and temperature respectively [3]. This has created some limitations which have been addressed in the recent past by the use of fiber-reinforced concrete (FRC) [4].

The toughness and ductility of the concrete raises with the incorporation of discrete fibers in its matrix which concurrently enhancing crack resistance [5]. Hybrid Fiber Reinforced Concrete (HFRC) has the potential of being an efficient composite material in synergistically enhancing structure performance with the use of two or more fibers [6].

Hybrid fibers of steel and glass can enhance the tensile strength of concrete besides post-cracking toughness and durability [7]. Steel fibers are added as reinforcements to the concrete which improves the

tensile strength, stiffness and load bearing capability of concrete thereby reducing the chances of concrete cracking and opening due to the applied load [8]. On the other hand, glass fibers reduce micro crack and enhance the concrete toughness and increase its life span against cracks [9]. These two fibers in HFRC may provide concrete the mechanical properties to resist seismicity and high magnitude dynamic loads that in-situ structures require, thus making it ideal for mass structures such as dam wears [10].
In fact, the understanding of HFRC's behavior under numerous loading conditions is still lacking. Different parameters include fiber orientation, fiber distribution, and fiber content in the matrix have control over the performance of the fiber reinforced concrete [4]. The randomly dispersed fibers may not function in a respective manner that impacts the mechanical characteristics of HFRC [11]. Information is still sought to ensure that the optimum amount of fiber is used in enhancing the tensile strength, deformation resistance and costs. Due to the complex relationship that exists between the fibers and the concrete matrix and parameterssuch as load types and environmental effects, a better understanding of the practical sensibility of HFRC is needed [12].
Computational analysis based on finite element analysis (FEA) is now inevitable for studying the fiber reinforced concrete behavior under varied loading conditions [13]. As compared to experimental analysis, FEA predicts the behavior of materials providing insight on issues like stress distribution, displacement and failure mechanisms that are otherwise unquantifiable [14]. Common FEA tools used for the analysis of concrete structure are the powerful software package known as ABAQUS that is capable of simulating material behavior of fiber reinforcement [15]. Actually, the fiber contents, orientations, and loading conditions can be investigated in detail through the aid of the ABAQUS models of concrete structures [16].
In the present investigation, the cylindrical and prismatic specimens of hybrid fiber-reinforced concrete are tested in displacement control compression loading through ABAQUS. This paper compares the influence of fiber reinforcement on the mechanical properties of HFRC in six models (M0–M5) containing varying proportions of lathe steel and glass fibers. While M0 is the control model with no fiber reinforcement while the other models M1 to M5 are models with higher ratios of glass and steel fibers. These models are therefore exercised in the study under compression to provide real quantifiable outcomes of improvements brought about by the use of hybrid fiber reinforcement on the tensile strength, displacement resistance and the stress distribution patterns.

2. LITERATURE REVIEW

Interactions with material and structural performance have been quadratically modeled through computational analysis thereby changing the way concrete behavior is understood [17]. A method of, in a simple manner, explaining the behaviour of the concrete element under different loads and environmental conditions known as Finite Element Analysis (FEA) [18].
Fiber reinforced concrete is made by incorporating fibers into the concrete matrix in order to enhance tensile strength, ductility, and crack control [8]. Steel fibers, glass fibers, polypropylene and natural fibers are all the concrete boosters, and they include steel and glass, polypropylene, natural fibers and steel fibers [19]. The use of FRC computational analysis has assisted in the determination of these contributions and the best fibers to use as well as their quantities [20]. Steels fibers thus enhance the concrete tensile strength and load bearing capacity.
According to the ABAQUS models, it was established that through the incorporation of steel fibers in the concrete its crack resistance under load enhances [21]. Reports provided evidence that the incorporation of steel fibers in concrete leads to higher concrete stiffness and slowed crack growth thus increasing the stress bearing capacity of the material. ABAQUS analysis reveals that the steel fiber self-restriction of stress results in better performance of the structure [22].
Comparing to the effects of steel it is less efficient and raises crack resistance and durability of fiberglass as well as using glass fibers [23]. Glass fibers decrease the level of micro cracks thus increasing the lifespan of concrete structures based on computational studies [24]. In this case, FEA demonstrates that the incorporation of glass fibers in concrete leads to minimized crack width as well as enhanced durability of concrete immersed in environmental aggressors [25]. ABAQUS analyses were viable to use glass fibers to reinforce concrete and prevent crack formation and spread [26].
As a result of the aforementioned problem of single fiber reinforcement, HFRC exploits large reinforcement efficiency through multiple fibers. There has been literature interest in HFRC computational analysis since it enhances the mechanical properties of concrete [27]. Steel fibers make it more tensile strength and stiffer while glass fibers make it to be more cracking resistant and durable. Computational analysis reveals that mechanical properties of HFRC are superior to those of single fiber reinforced concrete [28]. The hybrid approach was modeled in ABAQUS and demonstrated tensile strength and crack resistance in HFRC are enhanced. In the simulations made, HFRC enhanced load-bearing capacity as well as crack propagation resistance [29].

Researchers have employed ABAQUS to simulate HFRC with the purpose of understanding how the number of fibers and their placement influences concrete's response [30]. Studies performed with the ABAQUS software to assess the behavior of the models of HFRC when fiber ratios were varied in terms of tensile strength, displacement resistance and stress distribution. They were able to discover that some types of fibers together with their orientations could enhance the performance of concrete in seismic and dynamic loading conditions [31].

3. RESEARCH METHODOLOGY

In this section, the strategy adopted to perform FEA using ABAQUS on cylinders and beams with glass fibers and lathe steel fibers as reinforcement is explained clearly. Six cylinders namely M0, M1, M2, M3, M4 and M5 and beams with similar designations having different reinforcement arrangement are developed in this study to understand their load bearing capacity under different loading conditions. Furthermore, seismic hooks with curtailment and a non-reinforced beam are investigated to ascertain the review and strength of the material and structure. At first stage, the cylinders and beams were simulated with different proportions of glass and lathe steel fibers. The specific compositions for each model were as follows:

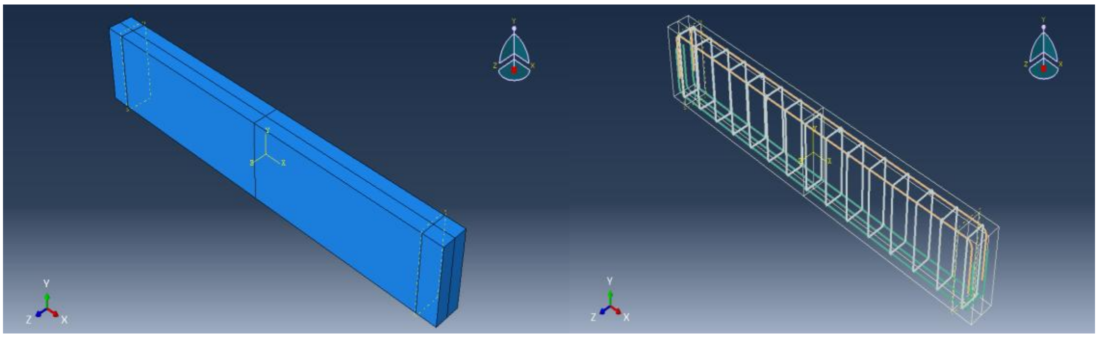

Figure 1. Control Beam with No reinforcement and Fibers and Beam with Reinforcement Only

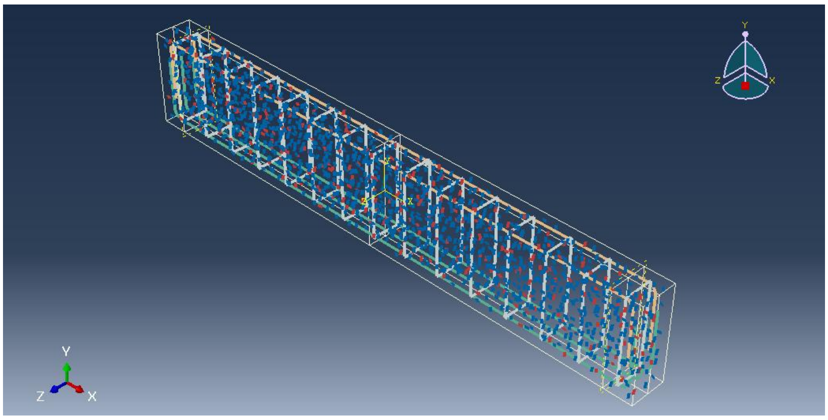

Figure 2. Beam with Reinforcement and Fibers only

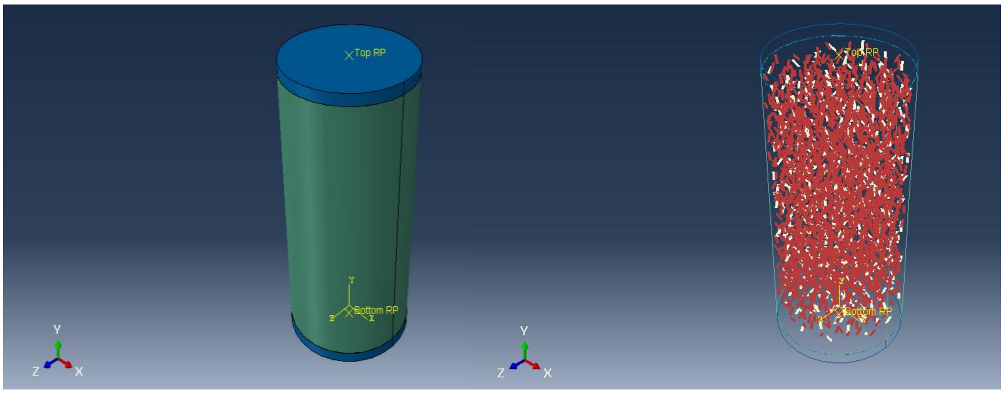

Figure 3. Cylinder with No Fiber reinforcement and Cylinder with Fiber reinforcement

For the cylinders, M_0 did not contain any fiber reinforcement to which the other models were compared to assess the impact of the fibers on the strength of the composite. The same logic was applied for the beams and this is why the analysis was consistent. The development of the models started with the definition of the geometry of cylinders and beams using importing by scripting in ABAQUS/CAE. Every cylinder and beam was drawn in detail and extruded exactly to the specified shape with help of python scripting. The material properties for each model were then defined with reference to the ratios of glass fibers and steel fibers.

During the assembly of the models, the parts of the models were neatly arranged so that the interactions between the parts were correct. This was done with the Python scripting for shared coordinate system and hence the efforts were very useful for assemblage of modeling the parts. In the case of the models assembling seismic hooks with curtailment, the hooks were anchored and involved bonding to the main structure. The interaction properties were introduced to capture the physical connections as close as possible such as the embedded region constraint and others.

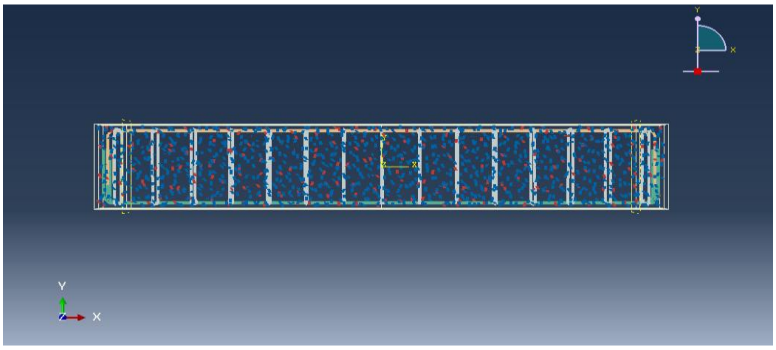

Figure 4. Fibers in Beam

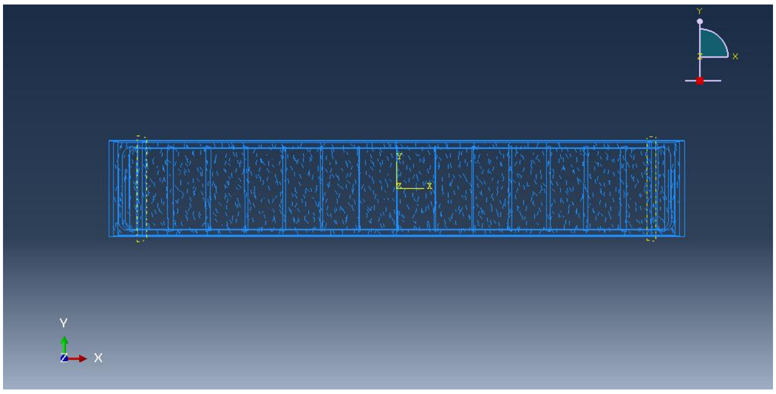

Figure 5. Fibers embedded in Beam

These boundary conditions and the loading scenarios were then applied. For Pin and Fix supports the same was defined where required and forces or pressure was applied of authentic like situation i...e for the beam. What this meant for the beams was taking into consideration reinforced and non-reinforced types of beams. The un-reinforced beam was used in order to assess the overall influence of reinforcement. It is on the same note that displacement control analyses are utilized in the cylinders while force control analyses are applied in beams.

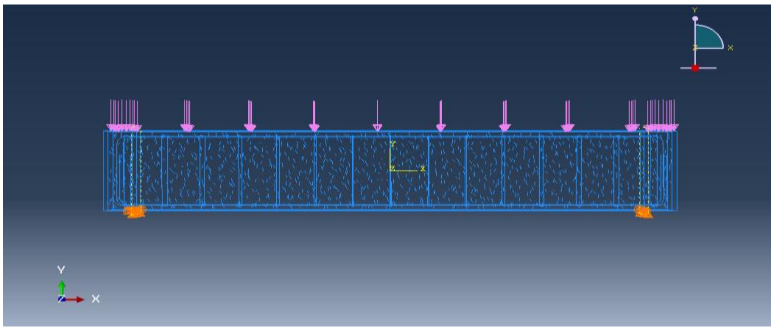

Figure 6. UDL on beam

Post-processing includes literally the result analysis in the software ABAQUS/CAE through the in-built visualization tools. The stress distribution, displacement and other related results were also determined from the models. The impact for each reinforcement scheme was assessed relatively with each other and with fibers composition to find out the efficiency of every configuration. As a part of quality assurance, verification and validation techniques were applied in order to check the accuracy of the data acquired from simulation.
The elaborate procedure mentioned above gave a systematic approach for the assessment of cylinders and beams with diverse fiber types and reinforcement strategies. Comparing the relative proportions of glass fibers and lathe steel fibers using seismic hooks with curtailment provided a clear picture of the material and structural performance.

4. ANALYSES AND RESULTS

The Analyses and Results offers an elaborate evaluation of the FEA results derived from ABAQUS of the cylinders and beams containing various ratios of glass and lathe steel fibers. This section presents a detailed comparison of each model structural behavior under a particular loading conditions based on stress distribution, displacement, and other mechanical characteristics. They also consider the effect with curtailment and the behaviour of un reinforced specimens.

Table 1. Cylinder Specimens Detail

Cylinder Name	**Lathe Waste Added %**	**Glass Fiber Added %**	**Maximum U2 (mm)**	**Minimum U2 (mm)**	**Maximum Misses (Mpa)**	**Minimum Misses (Mpa)**
M_0	0	0	0.046	-1.786	34.05	0.044
M_1	0.5	0.15	0.039	-1.979	40.01	0.019
M_2	1	0.3	0.012	-1.572	37.41	0.016
M_3	1.5	0.45	0.035	-1.680	32.67	0.032
M_4	2	0.6	0.023	-1.770	38.10	0.023
M_5	2.5	0.75	0.032	-1.833	34.30	0.032

Table 2. Beam Specimens Detail

Beam Name	**Lathe Waste Added %**	**Glass Fiber Added %**	**Maxi. U2 (mm)**	**Mini. U2 (mm)**	**Maxi. Misses (Mpa)**	**Mini. Misses (Mpa)**
M0 (With Flexural and Shear Reinforcement)	0	0	0.766	-6.949	450	0.0453
M_1	0.5	0.15	0.752	-6.887	550	0.0152
M_2	1	0.3	0.776	-7.077	550	0.0162
M_3	1.5	0.45	0.786	-7.331	550	0.0162
M_4	2	0.6	0.750	-7.023	550	0.0021
M_5	2.5	0.75	0.761	-6.984	550	0.0008

M_0 Cylinder: The analysis of M_0 indicated that a considerable stress is applied at the points of load application and in the height of the cylinder as well.
M_1 to M_5 Cylinders: introducing more amounts of glass and Lathe Steel fibers increased stress distribution from worse to reasonably better. Out of the four specimens, $M_5$is the one with the highest fiber ratio had the least stress concentration and, therefore, the highest load bearing capacity. These fibers played an important role in providing support for distribution of the stresses across the cylinder.

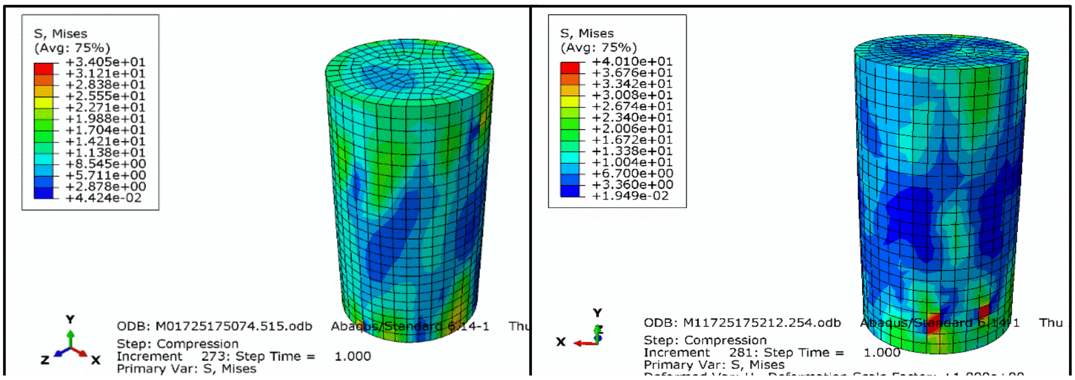

Figure 7. Stresses in cylinder M0 and M1

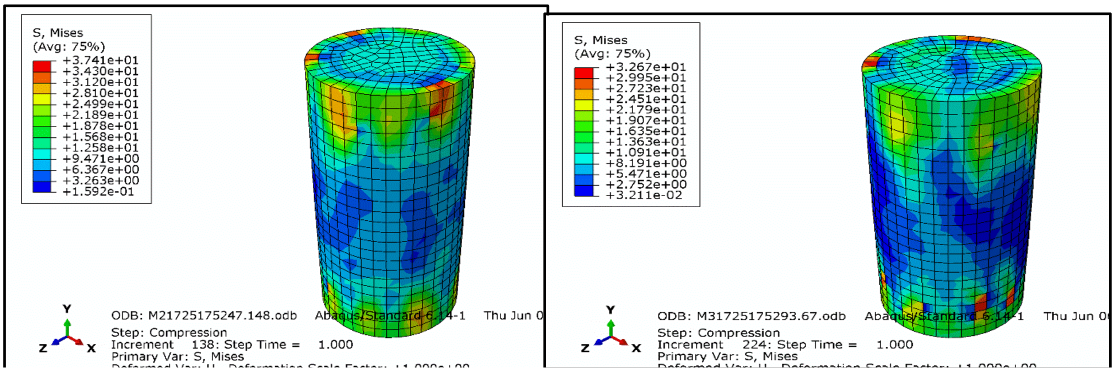

Figure 8. Stresses in cylinder M2 and M3

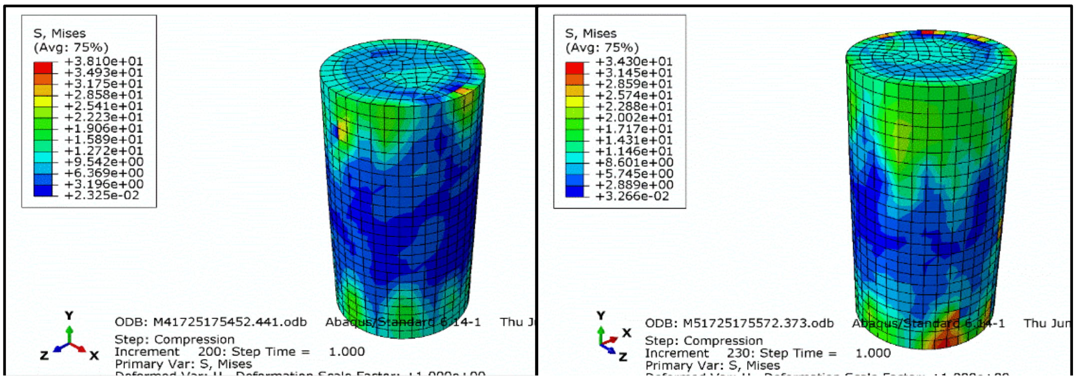

Figure 9. Stresses in cylinder M4 and M5

The displacement results pointed to the fact of less load-carrying capacity because of lack of fibers as confirmed by the limited structural deformation. In other words, it was found out that, when fiber content is increased there is a significant decrease in displacement. Thus, it was seen that the least deformation was in M5 and this was an indication of the reinforcement offered by fibers.

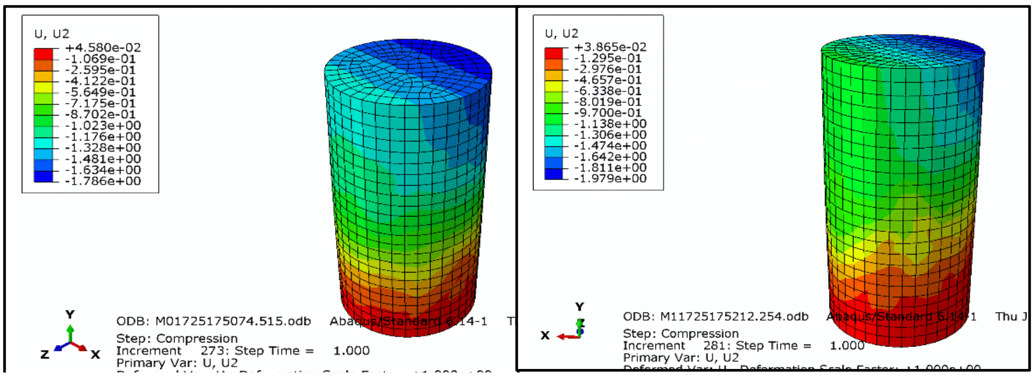

Figure 10. Displacement in Vertical Direction in M0 and M1

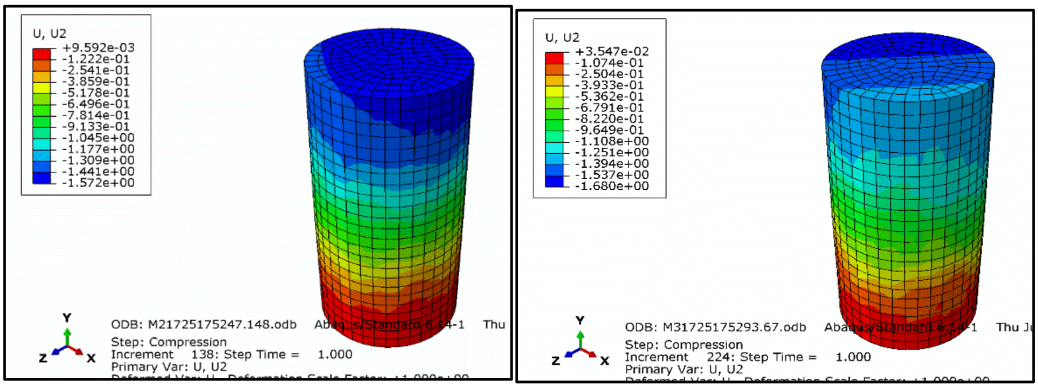

Figure 11. Displacement in Vertical Direction in M2 and M3

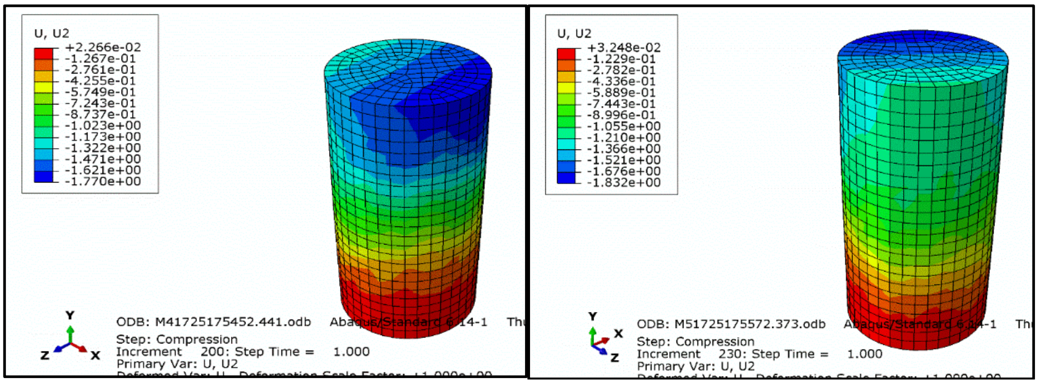

Figure 12. Displacement in Vertical Direction in M4 and M5

Overall, M_0 Beam presented the weak mechanical response under load with no presence of structural fiber, there by showing the non-structural nature of the material. It is evident from the study revealed that with the increment in density of fiber content, the displacement decreases in a progressive manner. From the results, M_5 had the least deformation which pointed out to stiffness and load bearing capacity enhancement.

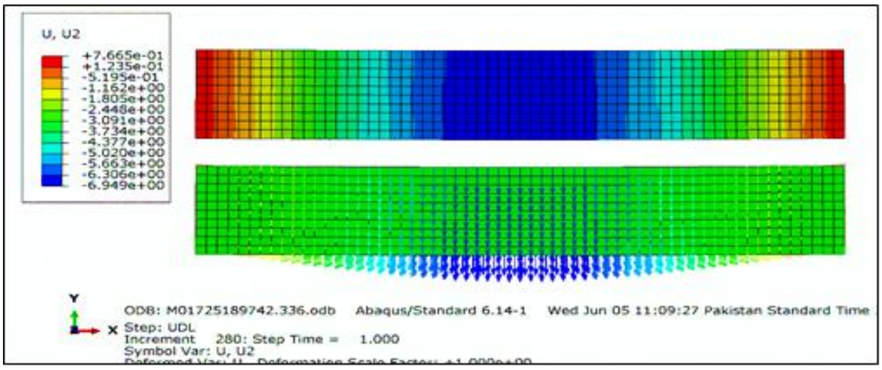

Figure 13. Displacement in Vertical Direction in M0

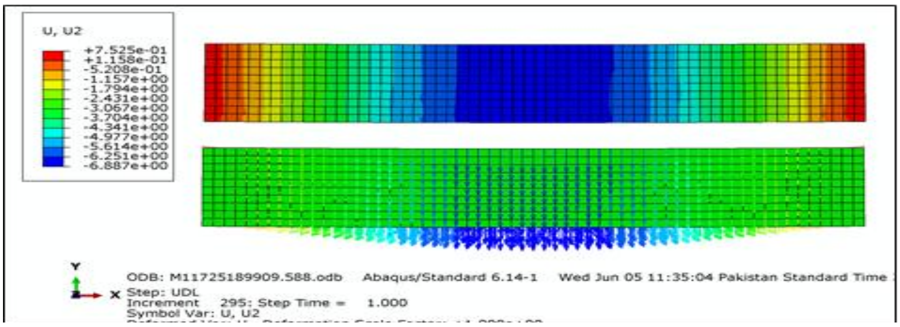

Figure 14. Displacement in Vertical Direction in M1

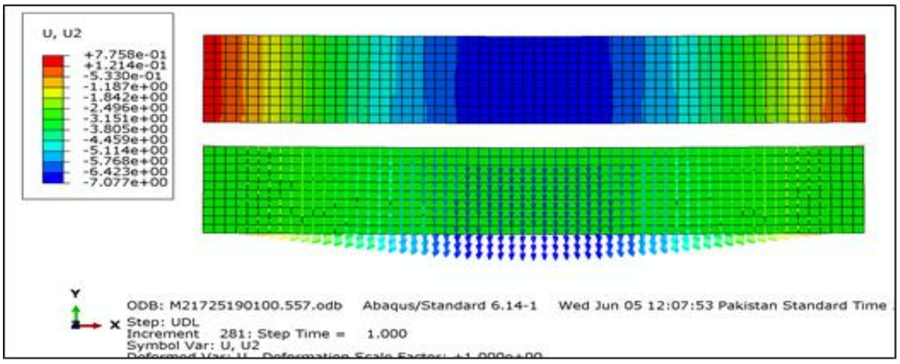

Figure 15. Displacement in Vertical Direction in M2

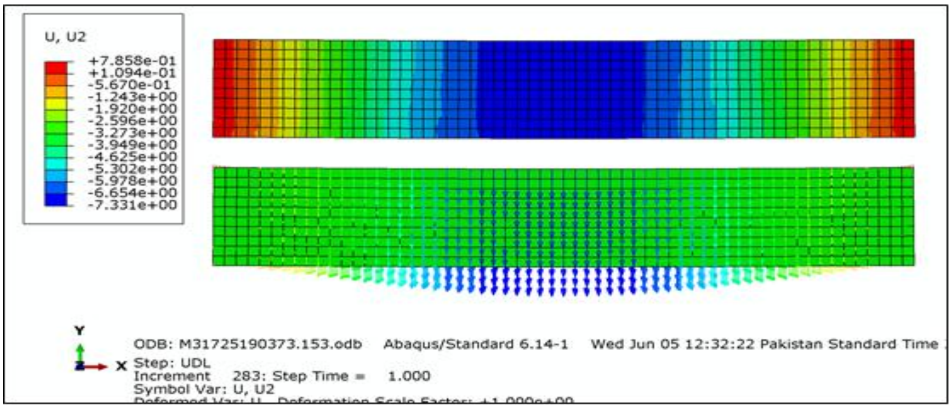

Figure 16. Displacement in Vertical Direction in M3

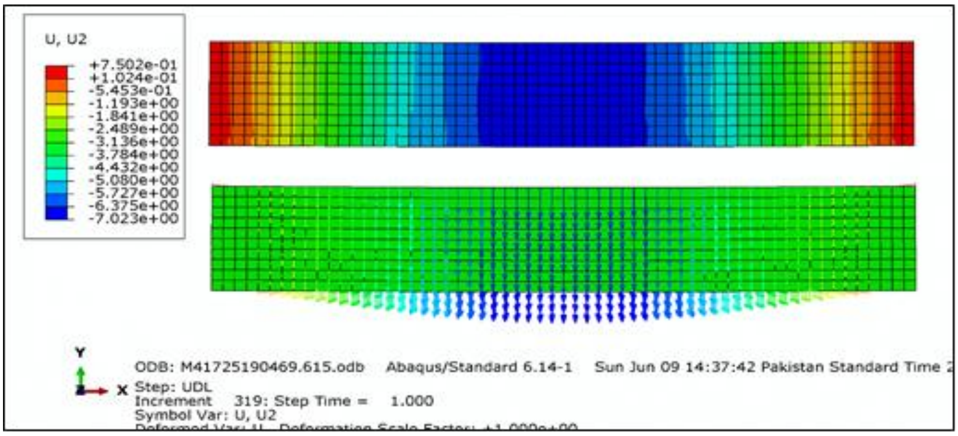

Figure 17. Displacement in Vertical Direction in M4

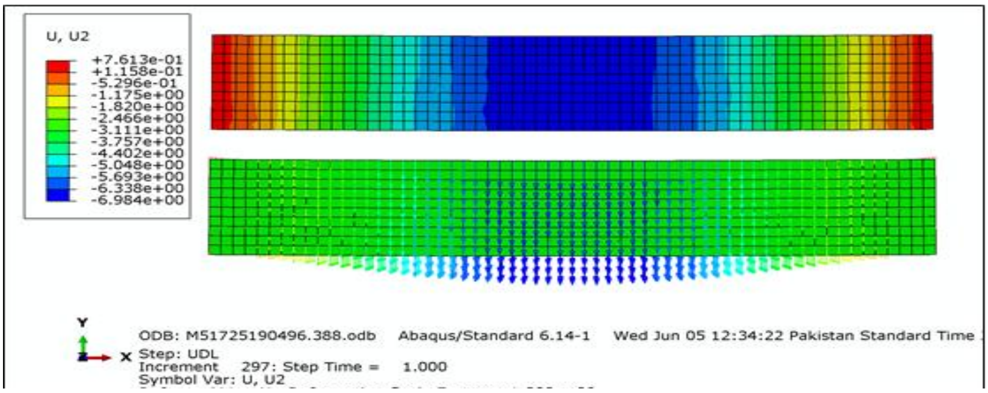

Figure 18. Displacement in Vertical Direction in M5

Non-Reinforced Beam showed the highest deformation, underscoring the need for reinforcement in beams.

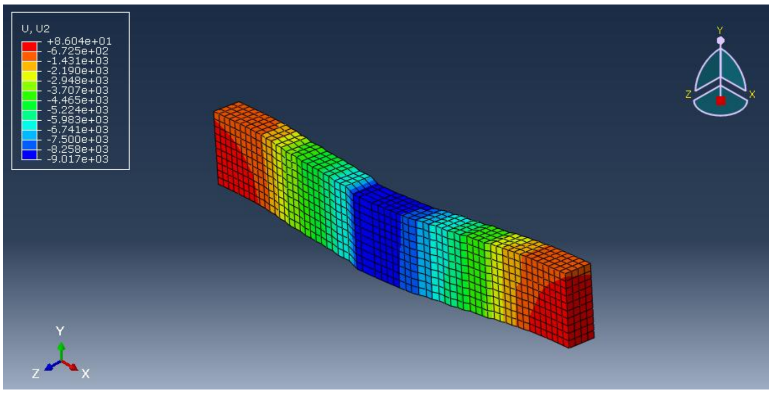

Figure 19. Displacement in Vertical Direction in Control Beam

This research uses ABAQUS tool for the finite element analysis of HFRC with varying proportions of lathe steel and glass fibers with various findings on its behavior under compressive load. In the absence of fiber reinforcement as evident with the control sample (M0), there was excessive deformation with high minimum and maximum displacement hailing the inefficiency of plain concrete in load resisting deformations. On the other hand, the introduction of fibers in general was seen to yield reduced minimum displacements across the reinforced cylinders, (M1–M5 signifying enhanced Strengthening against deformation. Indeed, increasing fiber content up to M3 to M5 levels even reduced minimum displacements to indicate better deformation resistance but samples like M5 depicted larger maximum displacements due to fiber composite complexities of directions. Calculations of stress distribution also revealed that control sample represented poor stress resistance with elevated Misses stress values, whereas fiber reinforced cylinders represented enhanced maximum Misses stresses, and among those the M5 sample represented maximum stress resistance. This shows that fibers augment the properties of concrete to bear stress and also the capability of the material to distribute stress at localized region, especially in M3 which of the least values of minimum Misses stress. Fiber orientation and content were found to exert influence as every change in the fiber alignment influenced the load carrying capacity and deformation properties, it was shown that fiber arrangement demands precision. Higher fiber ratios yielded a higher and stiffer structural performance, although M5 demonstrated the best stress bearing but complicated deformation profile; therefore the optimal fiber ratio and orientation matter. Conclusively, the paper outlines the performance improvement of concrete through the incorporation of HFRC and focuses on the necessity of optimizing the reinforcement of the fiber for optimum real life application.
This discussion will center on the findings of, whereby the displacement behaviour, stress distribution as well as the effect of; fiber content and orientation will be discussed on the cylinders.

Table 3. Global response of Cylinders

Cylinder Name	**Lathe Waste Added %**	**Glass Fiber Added %**	**Maximum Misses (Mpa)**	**Displacement (Compression)-mm**	**Force at 1.5mm displacement(N)**	**Peak Force (N)**
M_0	0	0	34.05	1.5	159645.66	202202.95
M_1	0.5	0.15	40.01	1.5	132021.20	1047942.94
M_2	1	0.3	37.41	1.5	202202.95	1124465.75
M_3	1.5	0.45	32.67	1.5	162082.92	1083105.25
M_4	2	0.6	38.10	1.5	155652.48	1083127.88
M_5	2.5	0.75	34.30	1.5	158572.06	1060761.25

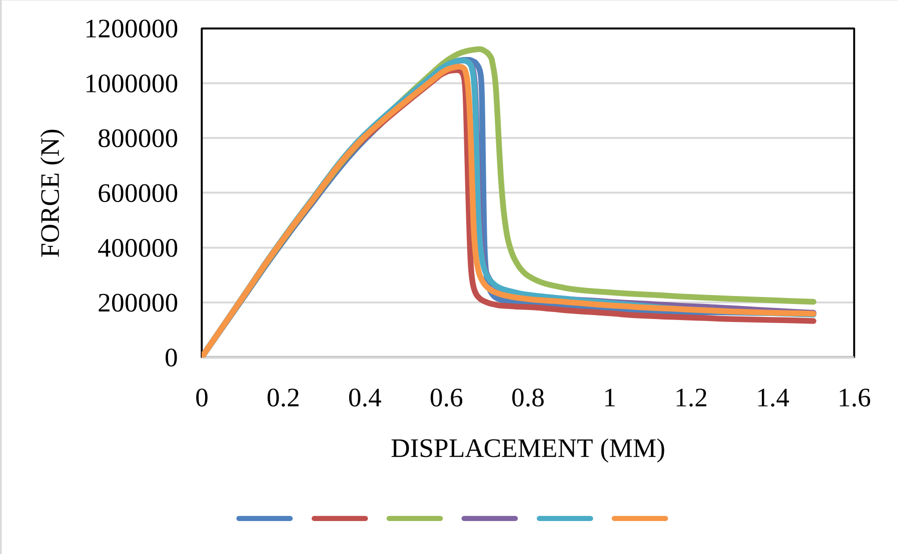

Figure 20. Force Displacement Curve for Cylinders

Table 4. Global response of Beam

Beam Name	Lathe Waste Added %	Glass Fiber Added %	Maximum Misses (Mpa)	Displacement (mm)	Maximum Load (N)
M0 (With Flexural and Shear Reinforcement)	0	0	450	6.949	619075.13
M1	0.5	0.15	550	6.887	61907 50
M2	1	0.3	550	7.077	619072.13
M3	1.5	0.45	550	7.331	619074.81
M4	2	0.6	550	7.023	619075.44
M5	2.5	0.75	550	6.984	619072.38
Control Beam	0	0	211.689	8491.737	278766 0

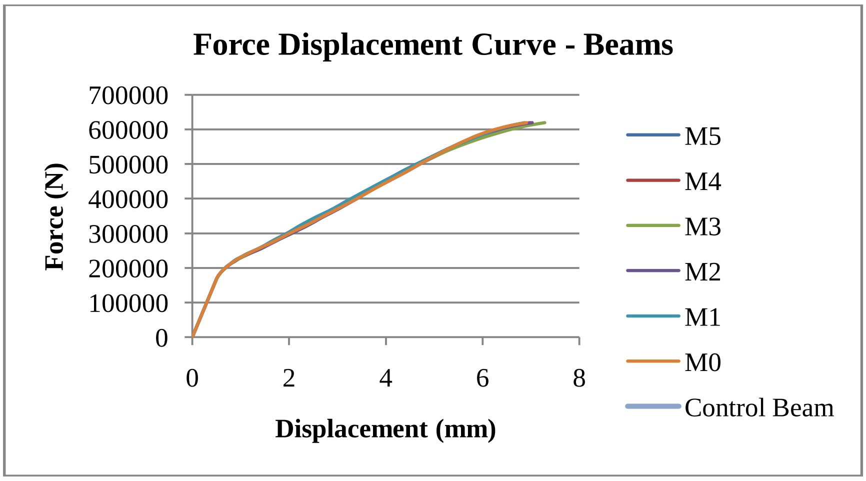

Figure 21. Force Displacement Curves for Beams

This analysis proves that ABAQUS simulations can verify that fiber reinforcement improves concrete cylinder and beam mechanical properties under compressive loads. The control sample (M0) had no fiber reinforcement and the highest displacement and lowest stress resistance, showing that plain concrete cannot handle deformation and stress loads. However, M1 to M5 samples show that fibers improved composite mechanical properties. Compared to M0, M1 had higher maximum Misses stress and lower minimum Misses stress but lower load carrying capacity than other fiber reinforced samples. Thus, the

M2, with intermediate fiber content, had the highest mechanical properties with a force value of 1. load-carrying capacity and stress resistance improve; TH maximum displacement and peak force are 5 mm. M3 and M4 samples had higher fiber content and showed greater improvement, but not always proportionally. M5 had the highest Misses stress but complex displacement behavior, proving the importance of fiber orientation and distribution. In beam tests, fiber-reinforced beams (M1 to M5) had lower displacement and higher stress than the control beam. Beam M3, with a middle fiber ratio, had higher ductility and maximum displacement at maximum load. This supports the idea that fibers improve concrete performance as content increases, but it also emphasizes that matrix fiber direction matters. Random-angled fibers can cause stress response and displacement issues. To maximize fiber reinforced concrete structural performance, fiber orientation and content should be controlled during mixing and casting.

Displacement and stress distribution reveal much about the concrete beam in different reinforcement scenarios. Control beam deformation in ok column without reinforcement ranges from -9016.89 mm to 86. The 0374 mm of plain concrete indicates low load carrying and deformation capacity. However, M0 beam, which only had flexural and shear reinforcement steel and no fibers, improved with reduced displacement range (-6.946mm to 0.766mm), which mutations with deformations imply improvement based on conventional reinforcement approaches for increased deformation resistance. The graph showed that adding fibers to the beams (M1 to M5) decreased minimum displacements, with M1 slightly better than M0 and M3 having the highest minimum displacement. The maximum displacements of fiber reinforced beams ranged from 0.752 mm to 0. 786 mm, indicating stable deformation resistance. Max Misses stress distribution confirms these results, with control beam having the lowest value 211. 689 MPa and least efficient stress distribution than M0 and fiber-reinforced beams. The peak Misses stress for the M0 beam was 450 MPa, higher than the control and fiber reinforced beams' 550 MPa, improving beam stress handling efficiency. The M5's minimum Misses stress was 0.000770819 MPa. Fiber orientation and content greatly affect the system, with displacement behavior varying among matrix fibers, highlighting the need to control fiber arrangement during mixing and casting. As fiber content increased, performance improved, but the structures deformed, especially those with more fiber volume, indicating that a successful optimal fiber ratio and orientation ratio is essential to improving structural features. Composite reinforcement with fibers improves concrete beam mechanical properties, especially when the fiber volume is high, but displacement performance is complicated.

CONCLUSION

The performance of concrete cylinders and beams containing different proportions of glass and lathe steel fibers in a displacement-control compression loading test was evaluated using ABAQUS finite element analysis (FEA) for this study. The findings show that fiber reinforcement increases the displacement resistance as well as stress capacity significantly. More particularly, the results have demonstrated that lower minimum displacements and higher stresses have been obtained in fiber-reinforced specimens as compared to non-fibered ones and these changes depend on the orientation and quantity of fibers included. Control of the fiber ratio and orientation is only possible using this excellent value, and this is necessary for the most significant structural improvements. Recommendation are as follows Minimum fiber ratios, control on fiber orientation, experimental check on the above, and generation of an overall design directive. The results obtained in this research highlights the possibility of improving structural behaviour by using FRC with a practical use in the field of high load and seismic applications and stressed the need to future research to identify long term performance and durability of FRC.

RECOMMENDATION

According to the results of the study, the further practice should employ the middle ratios of lathe steel and glass fibers as the components for the concrete beams to achieve the maximum load-bearing capacity and the best stress resistance. To improve load-carrying capacity and to reduce deformation, certain methods should be used to try to influence the orientation of fibers during mixing and placing. Ad hoc tests are mandatory for the calibration of FEA and further improvement of the design recommendations. It would be desirable to have specific recommendations concerning the fiber incorporation so that the engineers can better manage fiber content and orientation. Fiber reinforced concrete is more efficient in region of high loads and or regions frequently affected by earthquakes. However, one can only wonder if more can be done in terms of controlling the fiber orientation; performance and durability studies must also be undertaken long term under different environmental conditions.

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