Topology Optimization and Structural Performance Analysis of Steel Fiber-Reinforced Concrete Beams

Husnain Rehmat [1*], Intizar Ali [1], Mujtaba Ahmed Lashari [1], Esha Waris [1], Mutahir Abbas [1], Malik Sarmad Riaz [1]

[1] Civil Engineering Department-National University of Technology (NUTECH), Islamabad, Pakistan
* Corresponding: husnainrehmatf21@nutech.edu.pk

Abstract

The increasing environmental impact of conventional concrete production necessitates finding new ways to mitigate this problem, which must improve both the structural performance and the ecological sustainability of construction. This study focuses on topology optimization and the homogenized modeling of steel fiber-reinforced concrete (SFRC) beams to enhance structural performance. Using the Concrete Damage Plasticity Model (CDPM) in Abaqus for three-dimensional beam analysis to investigate the performance of SFRC beams under uniform pressure with varying steel fiber content 0.22%, 0.44%, and 0.89% by volume. Steel fibers with a 1 mm radius and 12 mm length are modeled as embedded, and their interaction with the concrete matrix is simulated. Topology optimization is performed using Abaqus' TOSCA module, emphasizing reducing strain energy while keeping to a 30% volume constraint. The results indicate notable enhancements in material efficiency, crack resistance, and cost-effectiveness, offering important insights into the sustainable and economical structural design of SFRC. The results suggested that material usage can be reduced, while simultaneously enhancing load-bearing capacity and fracture resistance, facilitating the creation of lighter and stronger components with diminished reliance on conventional concrete steel reinforcement.

Keywords: Topology Optimization, Steel fiber reinforced Concrete (SFRC), Homogenized model, Concrete Damage Plasticity Model, Abaqus.

1. Introduction

Cement is a dominant material in the construction industry due to its durability and high binding capability. However, the biggest issue with using cement is that it has greatly contributed to the production of greenhouse gases, generating up to 8% of the world's total CO_2 emissions [1]. Addressing this environmental impact requires novel techniques to mitigate the negative effects of cement use while preserving its beneficial properties. The Paris Agreement seeks to keep global temperature rise to well below 2°C over pre-industrial levels, with attempts to keep it under 1.5°C [2] ; therefore, the building sector must develop solutions to offset the negative impact of this material. While cement remains irreplaceable due to its unique properties, its usage can be optimized through design improvements, low-carbon clinker, and nanotechnology-based replacements. Recycling materials such as fly ash, industrial byproducts, and blast furnace slag further enhances sustainability. In comparison to traditional cement, these substitutes are more environmentally friendly and offer superior strength and durability. For example, silica fumes can be used to make high-strength concrete with certain industrial and agricultural wastes and other pozzolanic

 https://doi.org/10.64615/fjes.1.Special Issue.2025.28

ingredients [3], [4] Given the crucial need to reduce cement usage, structural design techniques such as topology optimization provide a viable method for lowering material consumption while improving mechanical properties.

With advancements in architecture and structural engineering, traditional construction methods have become less efficient due to their high costs and compromised structural performance. So, it is necessary to integrate structural engineering with architectural design principles further. One Promising approach that has been increasingly recognized for its effectiveness is topology optimization, which is a mathematical approach that provides a shape to the material accordingly while maximizing the performance of the system, promoting sustainability and cost efficiency, and providing better results than the conventional trial-and-error approach [5]. Numerous structures have been designed utilizing topology optimization techniques, including the Airbus A320 wing bracket, the GE jet engine bracket, the Singapore Sports Hub roof, Siemens gas turbine components, and the Qatar National Convention Centre, and a 3D bike printer utilized topology optimization to reduce weight and enhance structural efficiency as illustrated in Fig. 1. This technique has also demonstrated versatility across various industries, including architectural design, where it can provide both structural and aesthetic benefits.

(a) (b)

Fig. 1 illustrates two examples of topology optimization (a) Qatar National Convention Center, an example of innovative design where topology optimization was applied to achieve both structural efficiency and aesthetic appeal. and (b) Topology Optimization of Bike design highlights the versatility of this technique in different fields [16], [17]

Jewett and Carstensen [6] presented a topology-optimized plain beam using a density-based approach. Their method incorporates elastic models to address topology optimization challenges and material safety aspects. The first model utilizes minimal material while ensuring the design remains robust and efficient. The other model applies the Drucker-Prager criterion to constrain stress levels. However, this study shows that the stress limit is only applicable theoretically, and it requires a lot of research for implementation in the real world, as the structure and features are complex and require pre-processing. Lee et al. [7] demonstrated that optimizing material layouts enhances the structural performance of high-rise buildings and bridges. Hvejsel and Lund [8] demonstrate the advancement in topology optimization by using the interpolation SIMP (solid isotropic material with penalization) and RAMP (Rational Approximation of Material Properties) to allow the multi-material design, including anisotropic. Linear constraints are employed to ensure that only a single material is utilized in each segment of the design area. They facilitate advancements in engineering and materials science by emphasizing the potential to extend the current two-phase problem to multi-material designs. The study is the key foundation as it addresses the challenges while adapting the multi-material topology optimization by addressing penalization, handling of constraints, and adoption of the algorithm. Hafezolghorani et al. [9] carried out studies to enhance reinforced concrete structures by nonlinear analysis utilizing the SCDP model. The SCDP model is a simplified variant of the CDP model utilized for the analysis of unconfined concrete. This study simplifies the analysis of the nonlinear behavior of concrete in reinforced concrete structures and allows easier and more efficient use of finite elements in structural engineering. Stoiber and Kromoser [10] on concrete construction carried out an extensive quantitative as well as qualitative review of practical and numerical applications and noted the industry lacks advanced modeling and sustainability. Furthermore, researchers have explored the integration of FRC with topology optimization to improve its structural efficiency, offering solutions to these challenges. Topology optimization using FRC is a promising technique that enhances sustainability by optimizing material use, improving durability, and expanding design possibilities. It is a technique that is consistent, cost-effective, lightweight, and energy-efficient for architectural designs. Fiber-reinforced concrete is defined as a composite material that contains cement, mortar, or concrete and discontinuous uniform fiber, which helps to increase tensile strength, reduce shrinkage, and enhance durability [11].

In recent years, researchers have investigated the potential of combining FRC with topology optimization. Matheus et al. [12] conducted extensive research by utilizing the homogeneous model and investigating the linear elastic and elastoplastic properties of steel-reinforced fiber concrete. According to research, it is challenging to completely replace traditional steel-reinforced concrete with fiber-reinforced concrete. This is because of the difficulties associated with consistently dispersing fibers, which leads to variable performance and the development of weak areas. In elevated constructions, the increased tensile forces render it challenging for fiber concrete to withstand these stresses and preserve structural integrity. They conduct real-world experiments to ensure the stability, efficiency, and practicality of the design. Li et al. [13] developed a bi-material element that enables structural topology and continuous fiber techniques and addresses diverse issues through an integrated approach including topology, fiber path, and fiber morphology, offering a cohesive framework for these components. Li et al. [5] worked on a bi-directional evolutionary structural optimization in which more than one material is used, enabling flexibility and efficiency in the design. This work proves that advanced topology optimization is used in real-world projects. The Xiong'an Wings project demonstrates the implementation of multi-material topology optimization through the Bi-Directional Evolutionary Structural Optimization (BESO) approach, resulting in substantial cost savings. Tu et al. [14] observed 3D concrete printing that allows the creation of complex structure designs with minimal use of material waste. This technology can construct the structure more efficiently, quickly, and sustainably as it doesn’t require time for curing unlike the conventional method, and it reduces the material waste, which makes it more economical.

This study employs a nonlinear constitutive model to numerically model the steel fiber-reinforced concrete (SFRC) components using Abaqus CAE. The Concrete Damage Plasticity (CDP) model is widely used in concrete simulations; however, most research uses simplified or two-dimensional models, which fail to depict concrete's genuine 3D behavior under stress. Especially for stress states, cracking, and failure processes, underexplored is SFRC beam 3D modeling with the CDP model. This work fills in 3D by analyzing SFRC beams under homogeneous loads. Combining this technique with 3D printing might generate sustainable, reasonably priced, and lightweight buildings that allow creative and environmentally beneficial development.

2. Methodology

The present research uses a homogeneous method to assess and optimize beams by modeling concrete and fibers as unitary materials with integrated attributes. The finite element analysis program Abaqus is used to model, evaluate, and optimize the structural component due to its complete capabilities and computational efficiency. Steel fibers are employed as a reinforcing component in the material design to achieve the strength requirements.

2.1 Properties of Steel Fibers (SF)

The use of steel fibers in concrete leads to an increase in the material resistance of concrete and a reduction in cracking as compared to plain cement concrete. Also, it improves the global stability and bearing capacity of structures [15] . The response of SFRC varies with the fiber's percentage of volume fraction in the concrete mix. The classification fraction percentage can be classified into 3 categories: low volume fraction mix has steel fibers <1%, which helps to reduce shrinkage cracks; moderate volume fraction ranges between 1% to 2%, which increases the toughness and dynamic resilience of materials; and high-volume fraction has steel fibers >2%, which causes strain-hardening and leads to high-performance materials [10]. In this study, low-volume fractions with 3 various ratios were used to compare the results and enhance accuracy. The fibers with a 1 mm radius and 12 mm length have an elastic modulus of 20000 MPa, shear strength of 480 MPa, and Poisson's ratio of 0.3. Each beam has a varying volume of fibers, which includes 37699.11 mm³, 75398.22 mm³, and 150796.45 mm³. The different volumes are achieved by changing the number of fibers to explore the relationship between the structural responses.

2.2 Material Properties of Concrete

Researchers have employed diverse concrete models to depict concrete; in this instance, the Concrete Damage Plasticity (CDP) model is utilized to simulate concrete qualities, effectively yielding intricate outcomes through the integration of damage behavior and plasticity. The model effectively captures structural deterioration, including tensile cracking and compressive crushing, providing a detailed representation of failure mechanisms under various loading conditions." This model also provides a link between the real and numerical properties of concrete [18] . The CDP model relies on the following stress-strain relationship:

$$\sigma = (1 - d_c)\sigma_c + (1 - d_t)\sigma_t \quad (1)$$

The stress σ in concrete is determined by the damage variables for compression dc and tension dt, which scale the compressive stress σc and tensile stress σt, respectively. These damage variables account for the material degradation under different loading conditions. The model depicts the behaviors of concrete as uniaxial tension and uniaxial compression in **Error! Reference source not found.** below.

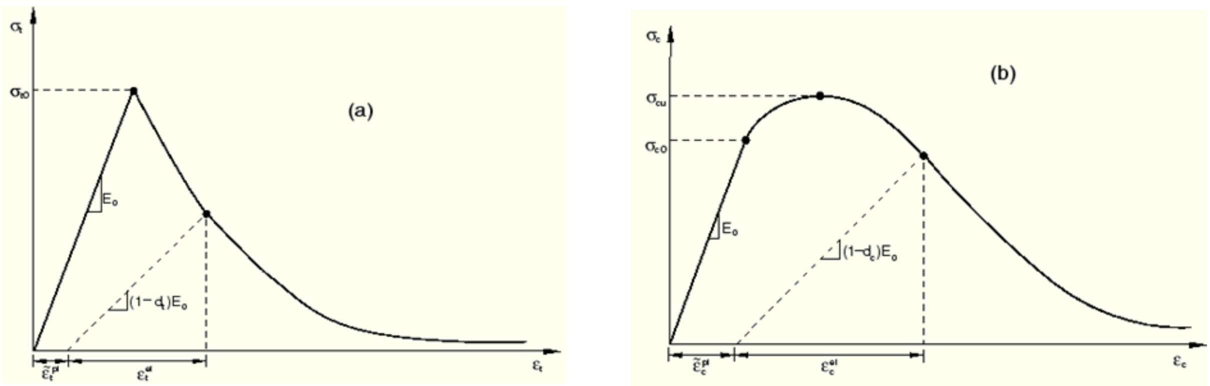

Fig 2. Stress-strain behavior of concrete under (a) uniaxial compression and (b) Uniaxial tension. [21]

The following table summarizes the key mechanical and physical properties of the concrete used in numerical analysis, including values for the dilation angle, eccentricity, and other material properties that define the concrete's behavior under stress.

Table 1. Parameters for the Concrete Damage Plasticity (CDP) model used in numerical analysis.

Dilation angle	Eccentricity	Fb0/fc0	K	Viscosity Parameter
38	1	1.12	0.666	0.001

The dimensions of the concrete beam of 150x150x750 mm as shown in Fig.2 Geometry ensures a precise representation of a functional beam for structural analysis. Additionally, the properties are summarized below in a tabular form:

Table 2. Concrete properties are the same for each trial.

Volume of concrete (V_m)	Elastic Modulus of Concrete (E_m)	Poisson's ratio (v_c)	Tensile Strength ($f_{t, matrix}$)
16875000	26600	0.2	3

2.2.1 Properties of Steel-Fiber Reinforced Concrete (SFRC)

Approaching the beam design with a homogeneous material perspective for simulation properties of both concrete and steel fibers are combined to ensure accuracy, the following formulae are used to calculate the combined properties:

$$V_c = \frac{V_f}{V_f + V_m} \quad (2)$$

$$E_c = f * E_f + (1 - f)E_m \text{ A} \quad (3)$$

$$v_c = f * v_f + (1 - f)v_m \quad (4)$$

$$f_t = f_{t,matrix} + k * f * f_{t,fiber} \quad (5)$$

The key parameter in the equations are fiber volume fraction determines the proportion of fibers within the composite material. V_c; combined elastic modulus quantifies overall stiffness considering fiber modulus and matrix modulus E_c; combined Poisson's ratio v_c is influenced by Poisson's ratios of fiber v_f and matrix v_m, affecting deformation characteristics; combined tensile strength f_t is derived from matrix tensile strength $f_{t,matrix}$ and fiber tensile strength $f_{t,fiber}$, defining tensile resistance; and k Represents the interaction factor, essential in determining the mechanical properties of steel fiber-reinforced concrete (SFRC) as modeled in the given equations.

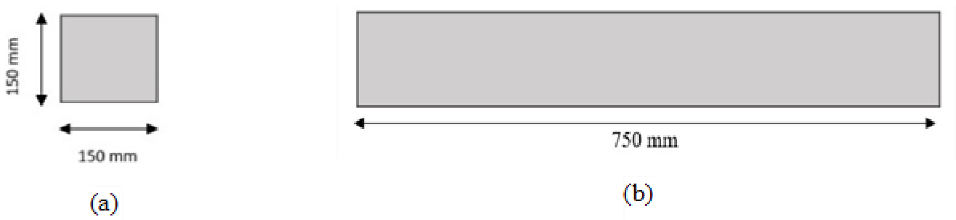

Fig.2 (a) The cross-sectional geometry of the SFRC beam, (b) Dimensions 150 mm x 150 mm x 750 mm.

Table 3. Mechanical properties of steel fiber-reinforced concrete

Steel fiber (%)	0.22	0.44	0.89

Elastic modulus (MPa)	26986.6	27371.4	28135.8
Poisson's ratio	0.20	0.20	0.20
Tensile strength (MPa)	3.80	4.60	6.19

2.2.2 Nonlinear Finite Element Modeling

A Finite Element Analysis (FEA) tool Abaqus is employed for the numerical modeling of beams and property simulation owing to its superior and precise analysis capabilities. The steel fibers are first modeled and incorporated into the concrete via the explicit fiber modeling technique. The outcomes of this model are subsequently verified against a homogenized method in which concrete and fibers function as a singular material entity. The beam is depicted through three-dimensional solid components. Although Abaqus is widely used for finite element analysis, it is important to acknowledge potential numerical errors that may arise, especially when modeling complex composite materials like steel fiber-reinforced concrete (SFRC). These errors may result from factors such as mesh discretization, element type selection, or convergence issues during nonlinear analysis. However, numerical errors can still influence the precision of stress and strain outcomes, particularly in areas of high-stress concentration or where material properties exhibit sharp gradients. Validation through experimental data and sensitivity analysis would further help mitigate these errors and improve model reliability.

For the random dispersion of fiber in a concrete matrix A custom Python script was written using the Abaqus Scripting Interface [19]. This technique provides an even spatial distribution of fiber initiation locations within the beam volume. Fiber orientations were randomized utilizing spherical coordinates, with the azimuthal angle (ψ) varying from 0 to 2π and Theta from 0 to π, resulting in a completely random three-dimensional orientation. A minimum separation of 2.5 mm (2.5 times the fiber radius) was mandated between fibers to prevent implausible overlap. The Python script utilized for fiber production ensures full repeatability and a random seed was established using np. random. seed (0) at the commencement of the script. After the creation of distinct fibers, all fiber instances were consolidated into a singular component ('Fibers Only') inside the Abaqus assembly utilizing the Instance from Boolean Merge function. This creates a unified 'Fibers Only' part within the assembly, representing the complete fiber reinforcement ready to be combined with the concrete matrix. Steel fibers are represented as truss elements; their mechanical parameters, including elastic modulus and tensile strength, ensure precise modeling of their role in the composite material's strength and stability. Fig.3 (a) illustrates the random configuration of fibers within the concrete beam, and these fibers are embedded through interaction within the concrete.

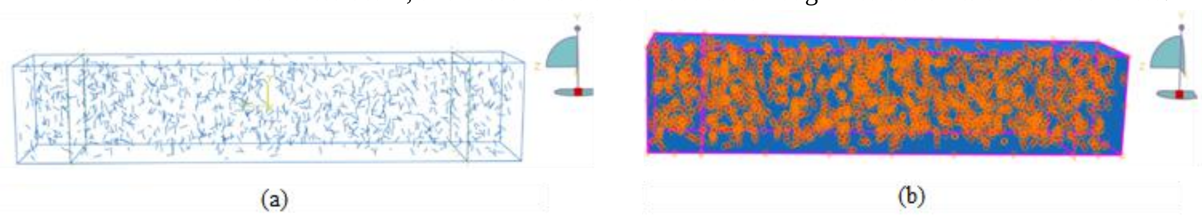

Fig.3 Random orientation of fibers (a) and fibers embedded in the beam (b), illustrating the distribution and alignment of fibers within the beam structure.

This detailed fiber geometry, generated by the Python script, serves as the input for the Abaqus finite element model. During the simulations, the meshing of a 3D 8-node linear brick element (C3D8R) is utilized to model the concrete beam, while the steel fibers are modeled using 2-node linear 3D truss components (T3D2). in which the fibers are depicted as distinct phases inside the matrix. Finer meshes are preferred to obtain precise results, as Fig.4 Represents the beam with an 8 mm mesh size with a uniform loading of $5x10^5$ N/m^2.

Fig.4 (a) Applied pressure over the beam and (b) meshing of the beam, showing the loading conditions and discretization for finite element analysis.

To assess the response of the SFRC beam Fig.4 Represents the uniform pressure applied over the SFRC beam to assess its response. The material properties of the beam are obtained from the composite characteristics of the concrete and the implanted steel fibers. Following the completion of the explicit fiber modeling, the findings are confirmed by comparison with those obtained from the homogenized model, concrete and fibers act as a unified substance. This validation guarantees the reliability of the approach for further research.

2.2.3 Material Topology Optimization

This topology optimization process for the beam may be beneficial, as optimized regions are replaced with 3D-printed low-strength concrete to meet architectural requirements. This research utilized the TOSCA module alongside Abaqus which focuses on minimizing the strain energy of the structure while adhering to a volume constraint, hence optimizing the material arrangement under defined boundary conditions and applied loads. Employing penalized interpolation of element relative density, the Solid Isotropic Material with Penalization (SIMP) model, with a finite element-based optimization approach, effectively differentiates solid as (1) and void as (0) regions by estimating material stiffness. The stiffness of each component is determined by its density and a penalty factor, set at 3, which inhibits intermediate densities from achieving a discrete topology. The penalty factor guarantees that material stiffness corresponds with actual structural circumstances by deterring intermediate densities. The SIMP model, with its ability to blend multiscale approximation and numerical homogenization, felt like the perfect approach for this study. It enabled us to identify the ideal material layout, striking a balance between structural efficiency and design constraints.

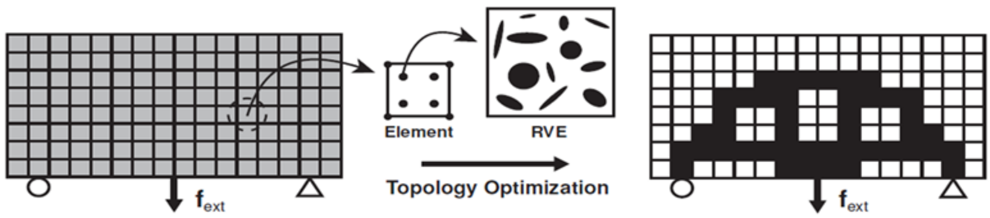

Fig.5 Schematic of Multiscale topology optimization [10]

Under the uniform pressure loads, maintained a 30% volume constraint of the original design area, ensuring the process stayed practical and precise. This guarantees material efficiency while preserving structural integrity. TOSCA's homogenized methodology streamlines the process by supposing isotropic material qualities, enhancing computational efficiency, and recognizing constraints in accurately representing anisotropic effects, including fiber alignment or directional stresses. Subsequent research may Encompass evaluations under various loading situations to enhance the validation of the methodology. Fig.5 Depicts the multiscale topology optimization of the beam.

Discretization achieved by minimizing strain energy (c), as:

$$\min c(x) = U^T K U = \sum_{i=1}^{n} (x_i)^p {u_i}^T k_i u_i \quad (6)$$

$$V(x) \leq vf\, V_0 \quad (7)$$

$$0 < x_{min} \leq x_i \leq 1 \quad (8)$$

Here in the *U* and *K*, there are global displacement and global stiffness matrices respectively, and u_i and k_i are the element displacement and stiffness respectively. *x* is the relative density of elements (design variable), *n* is the number of discretized elements, *p* represents the penalty factor, V_0, and *V(x)* show design domain volume and material volume respectively, and v_f suggests the volume fraction.

The flow chart below gives an overview of the methodology followed here

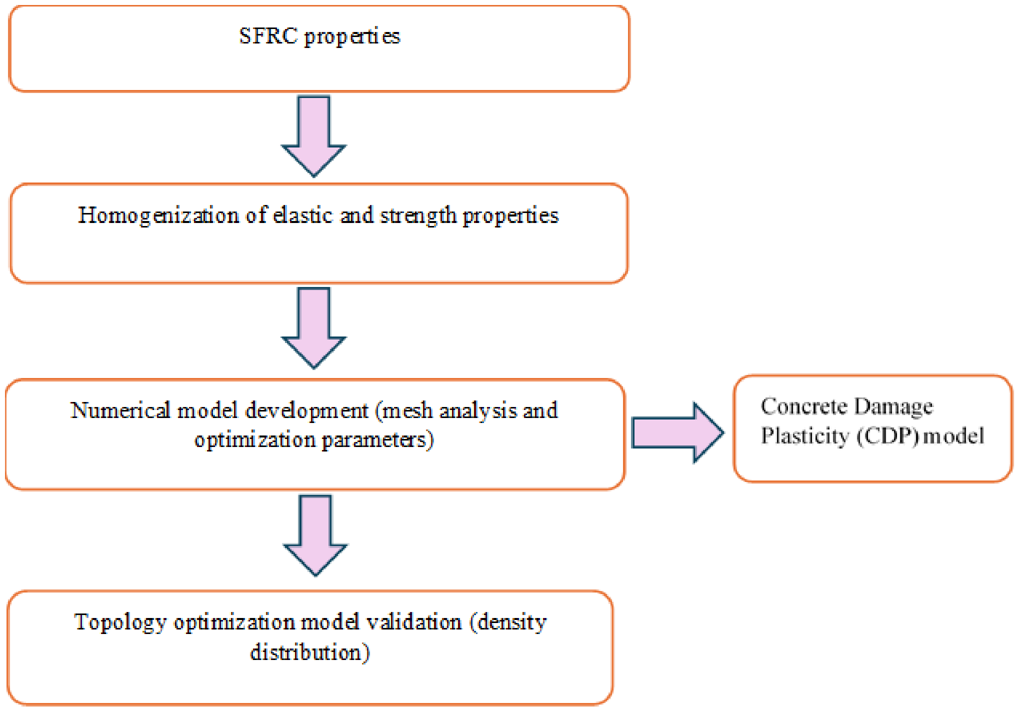

Fig 9 Flow chart of the SFRC beam modeling and topology optimization process using the Concrete Damage Plasticity (CDP) model.

2.2.4 Validation of the Homogenized Approach

After determining the optimal material distribution using topology optimization, it is essential to verify whether these optimized designs perform effectively under applied loads. Directly modeling SFRC as a composite material is computationally expensive due to the complex fiber-matrix interactions. Instead, a homogenized approach is used to simplify numerical analysis while ensuring accuracy. This study's results confirm the efficacy of the homogenized approach for modeling steel fiber-reinforced concrete beams subjected to applied pressure. A finite element analysis was performed on a beam exposed to a uniform pressure of 0.5 MPa to evaluate the accuracy of the simplified homogenized method in comparison to composite modeling. The displacement findings derived from both methods were examined across incremental time steps. The displacement values derived from the homogenized approach nearly correspond to those produced by the composite modeling method, as illustrated in Fig.6 The results reveal an insignificant variation in displacement over all time intervals, suggesting that the homogenized method can accurately forecast the structural response of the beam under the designated loading conditions.

This validation confirms that in steel fiber-reinforced concrete, the simplified homogenized approach provides a consistent and computationally effective replacement for the composite modeling technique. This finding is interesting as it preserves structural analysis's precision while lowering computing costs. By viewing concrete and steel fibers as a single material with integrated characteristics, the homogenized approach simplifies the modeling process and becomes a practical choice for large and complex simulations.

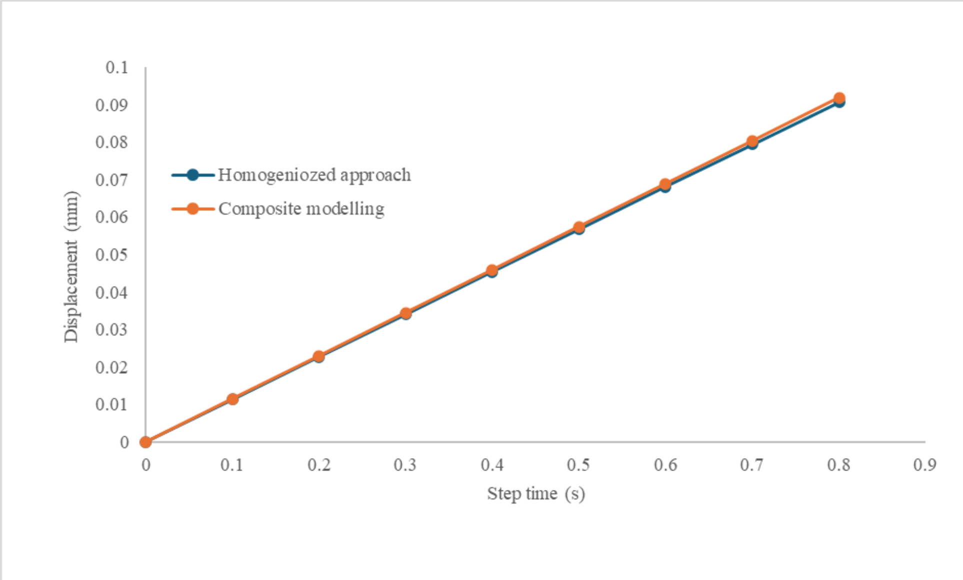

Fig.6 Validation of Results

3. Results and Discussion

The analysis of the steel fiber-reinforced concrete (SFRC) beam under loading conditions was conducted using the Concrete Damage Plasticity (CDP) model in Abaqus. The beam was subjected to a uniform pressure load of 0.5 MPa, and the resulting stress distributions were evaluated to assess the structural behavior. The Von Mises stress distribution highlights the regions of high-stress concentration, primarily near the supports and edges of the beam, where the maximum stress reached approximately 17.19 MPa. These areas are critical for structural integrity, as they bear most of the applied load and are at a higher risk of yielding or failure. Conversely, the low-stress regions, indicated by the blue zones, exhibit minimal contribution to the overall stiffness and are less significant in the structural performance of the beam. The maximum principal stress analysis further provides insights into the tensile and compressive forces acting on the beam. The tensile stresses, represented by positive values, reached a peak of 3.56 MPa in areas under tension, which are more susceptible to cracking. The compressive stresses, represented by negative values, were observed to reach -19.72 MPa, predominantly in the lower portion of the beam where compressive forces dominate. This stress distribution aligns with the expected behavior of concrete, which performs better under compression than tension. The results confirm that the critical tensile zones coincide with the high-stress regions observed in the Von Mises stress distribution, emphasizing the need for proper reinforcement in these areas.

Overall, the analysis validates the beam's ability to withstand the applied loading conditions while highlighting the importance of maintaining the material in high-stress regions to ensure structural stability. The stress patterns also demonstrate the efficacy of the CDP model in accurately capturing the nonlinear behavior of concrete under combined tensile and compressive stresses. Here **Error! Reference source not found.** Shows Optimized model results at the different fiber content.

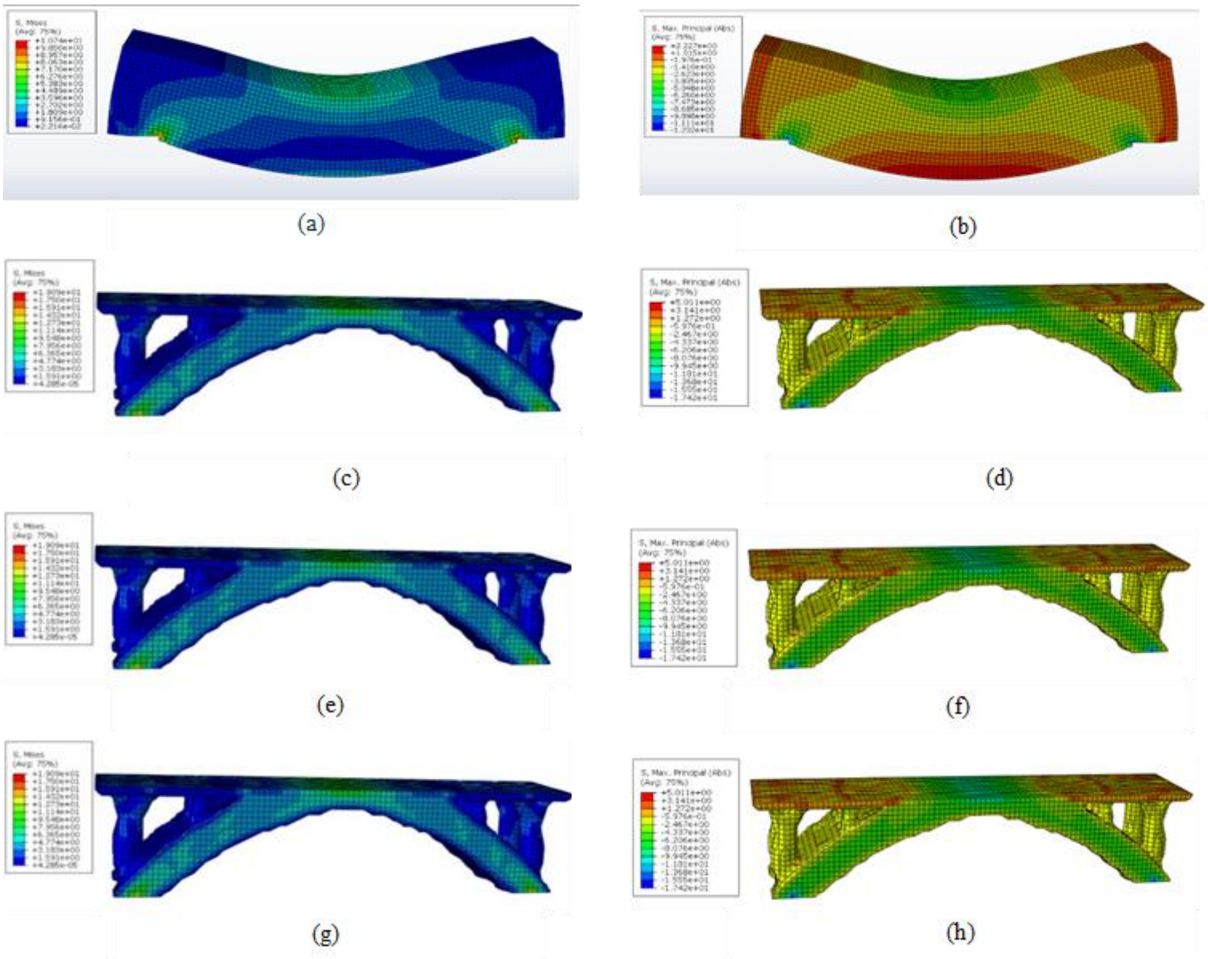

Fig. 8 Stress distribution in beams with varying fiber content. (a) von Mises stresses before topology optimization, (b) principal stresses before topology optimization, (c) 0.02% fiber content von Mises stresses, (d) 0.02% fiber content principal stresses, (e) 0.04% fiber content von Mises stresses, (f) 0.04% fiber content principal stresses, (g) 0.06% fiber content von Mises stresses, and (h) 0.06% fiber content principal stresses. Increasing fiber content reduces crack propagation and decreases the deflection in the beam.

This improvement had an immediate effect on sustainability by lowering the amount of cement used and CO_2 emissions, which would save the material. Because of these improvements, SFRC beams are better for the environment and cheaper than other building products. This is because it lowers the cost of building and keeps the longevity. The incorporation of fibers transforms concrete's brittle nature, enhancing its ductility. The suggested method can be used in some real-world situations. In a modern world where the trend for high-rise buildings is increasing day by day, the use of lightweight constructions, industrial flooring that must be extremely crack-resistant, and new architectural parts made from 3D printing all benefit greatly from optimized SFRC beams. Meeting the needs of contemporary building techniques while integrating Design optimization enables the optimal use of materials that would be sustainable for the environment.

3.1 Limitations of the Homogenized Approach

While a computationally efficient method for modeling steel fiber-reinforced concrete (SFRC) is provided, several limitations must be recognized. The homogenized model presumes isotropic material characteristics, considering the concrete matrix and steel fibers as a singular cohesive material. This assumption streamlines the modeling process but neglects the possible variability in material properties at multiple scales, such as microstructural variations in concrete or fiber bonding characteristics, which may result in disparities between the model and actual material behavior. Furthermore, the model inadequately represents the intricate interactions between the steel fibers and the concrete matrix, especially with the bonding behavior. This interaction is crucial for the entire performance of SFRC, particularly under tensile loading or shear stress, and is essential for accurately forecasting crack propagation and fracture resistance. The homogenized technique assumes that fiber orientation is random or isotropic; nevertheless, in practical applications, fibers often align in specific directions due to the casting process or other factors. This alignment can significantly affect the material's performance, particularly in load-bearing applications where aligned fibers improve strength in particular directions. An anisotropic homogenization method, which accounts for directional variations in fiber behavior, would yield more accurate predictions in these cases. Furthermore, the model may neglect microstructural defects, such as vacancies, micro-cracks, or irregular fiber distributions, which can significantly influence the mechanical properties of SFRC, especially under high-stress conditions. Another limitation of the homogenized method is its inability to include the multi-scale properties of SFRC, where the material's behavior at the microscopic (fiber) level influences its macroscopic (beam) performance. A thorough multi-scale modeling approach could bridge this gap by combining local fiber dynamics with global structural behavior to produce more accurate and realistic predictions. The homogenized model presumes a reasonably homogeneous fiber distribution; but, in reality, fiber dispersion may be non-uniform, resulting in localized discrepancies in mechanical characteristics across the beam. This non-uniformity may lead to discrepancies in the performance across various regions of the beam, necessitating resolution in subsequent models via a more comprehensive depiction of fiber distribution and its influence on structural behavior. future research should concentrate on validating the homogenized technique across various loading circumstances and creating anisotropic homogenized models to accommodate the directional discrepancies in fiber behavior. Furthermore, experimental testing may be performed to identify failure processes such as fiber pull-out or stress concentrations, which are intrinsically averaged in the homogenized model, hence enhancing the model's predicted accuracy and dependability. Integrating these elements into forthcoming research would yield a more thorough comprehension of SFRC's practical performance and strengthen the validity of the homogenized modeling methodology.

4. Conclusion

This study demonstrates the considerable potential of topology optimization in the development of sustainable construction using steel fiber-reinforced concrete (SFRC) beams. Through intentional material allocation aligned with structural requirements, we noted significant reductions in material usage along with preservation and, in some instances, enhancements in the beam's load-bearing capacity and crack resistance of the optimized beam. Using a verified homogenized model that incorporates the Concrete Damage Plasticity Model allows one to find a reliable and efficient method for examining SFRC behavior. The results emphasize the need to consider the unique characteristics of SFRC, particularly fiber content, in Design optimization. Each SFRC mix results in a distinct ideal design, emphasizing the need for a personalized approach. This paper recognizes the limits of fundamental material models and the need for additional experimental validation, particularly under complicated loading scenarios, while also giving significant insights into the application of topology optimization to SFRC of 3D beams. The findings presented here improve the comprehension of SFRC design and construction, facilitating the creation of lighter, stronger, and more environmentally sustainable structures. The ongoing advancement of sophisticated modeling techniques, alongside experimental research and innovative fabrication technologies such as 3D printing, aims to fully realize the potential of SFRC and transform the construction industry.

Acknowledgements. We are thankful to the National University of Technology Islamabad, Pakistan, for providing the resources and facilities that helps in this research.

Disclosure of Interests. The authors declare no competing interests

References

1 Ahmed, I., Reichenbach, S., & Kromoser, B. (2024). Flexural behavior of reinforced concrete beams with voids: Topology optimization basis. Structures, 67, 107037. https://doi.org/10.1016/j.istruc.2024.107037

2 Stoiber, N., & Kromoser, B. (2021). Topology optimization in concrete construction: A systematic review on numerical and experimental investigations. Structural and Multidisciplinary Optimization, 64(4), 1725–1749. https://doi.org/10.1007/s00158-021-03019-6

3 Ganesan, K., Rajagopal, K., & Thangavel, K. (2007). Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. Construction and Building Materials, 22(8), 1675–1683. https://doi.org/10.1016/j.conbuildmat.2007.06.011

4 Khatib, J. M. (2016). Cement replacement material. In Sustainability of construction materials (pp. 717–721). Elsevier.

5 Li, Y., Ding, J., Zhang, Z., Zhou, X., Makvandi, M., Yuan, P. F., & Xie, Y. M. (2023). Practical application of multi-material topology optimization to the performance-based architectural design of an iconic building. Composite Structures, 325, 117603. https://doi.org/10.1016/j.compstruct.2023.117603

6 Jewett, J. L., & Carstensen, J. V. (2019). Topology-optimized design, construction, and experimental evaluation of concrete beams. Automation in Construction, 102, 59–67. https://doi.org/10.1016/j.autcon.2019.02.001

7 Lee, D.-K., Yang, C.-J., & Starossek, U. (2012). Topology design of optimizing material arrangements of beam-to-column connection frames with maximal stiffness. Scientia Iranica, 19(4), 1025–1032. https://doi.org/10.1016/j.scient.2012.06.004

8 Hvejsel, C. F., & Lund, E. (2011). Material interpolation schemes for unified topology and multi-material optimization. Structural and Multidisciplinary Optimization, 43(6), 811–825. https://doi.org/10.1007/s00158-011-0625-z

9 Hafezolghorani, M., Hejazi, F., Vaghei, R., Bin Jaafar, M. S., & Karimzade, K. (2017). Simplified damage plasticity model for concrete. Structural Engineering International, 27(1), 68–78. https://doi.org/10.2749/101686616x1081

10 Stoiber, N., & Kromoser, B. (2021). Topology optimization in concrete construction: A systematic review on numerical and experimental investigations. Structural and Multidisciplinary Optimization, 64(4), 1725–1749. https://doi.org/10.1007/s00158-021-03019-6

11 The Constructor. (2021). Fiber reinforced concrete – Types, properties, and advantages of fiber reinforced concrete. Retrieved from https://theconstructor.org/concrete/fiber-reinforced-concrete/150/

12 Barbosa, M., Cedrim, M., Lages, E. N., Da, A., & Ramos Barboza, S. (2024). Numerical analysis of steel fiber-reinforced concrete beams using topology optimization techniques. International Journal of Advanced Engineering Technology, 17(4), 289–302. https://doi.org/10.5281/zenodo.13833389

13 Li, H., Gao, L., Li, X., & Tong, H. (2021). Full-scale topology optimization for fiber-reinforced structures with continuous fiber paths. Computer Methods in Applied Mechanics and Engineering, 377, 113668. https://doi.org/10.1016/j.cma.2021.113668

14 Tu, H., Wei, Z., Bahrami, A., Ben Kahla, N., Ahmad, A., & Özkılıç, Y. O. (2023). Recent advancements and future trends in 3D concrete printing using waste materials. Developments in the Built Environment, 16, 100187. https://doi.org/10.1016/j.dibe.2023.100187

15 Wang, X., Fan, F., Lai, J., & Xie, Y. (2021). Steel fiber-reinforced concrete: A review of its material properties and usage in tunnel lining. Structures, 34, 1080–1098. https://doi.org/10.1016/j.istruc.2021.07.086

16 Amalaki4. (2024). Why Qatar National Convention Centre's architectural design reflects the perfect blend of tradition and modernity. QNCC. Retrieved from https://www.qncc.qa/post/why-qatar-national-convention-centre-s-design-reflects-the-perfect-blend-of-tradition-and-modernity

17 Formlabs. (n.d.). Topology optimization 101: How to use algorithmic models to create a lightweight design. Retrieved from https://formlabs.com/asia/blog/topology-optimization/

18 Fakeh, M., & Jawdhari, A. (2024). Recommended concrete damage plasticity parameters and constitutive models for UHPC in Abaqus [Preprint]. https://doi.org/10.2139/ssrn.4934176

19 Husnainrehmat395. (2024). SFRC/readme.md at main – Husnainrehmat395/SFRC. GitHub. Retrieved from https://github.com/Husnainrehmat395/SFRC/blob/main/README.md?plain=1

20 Gülbahçe, E., Sezgen, H. Ç., & Çakan, A. (2019). Topology design and modal analysis of a bracket via FEA. Applied Engineering Letters Journal of Engineering and Applied Sciences, 4(3), 102–105. https://doi.org/10.18485/aeletters.2019.4.3.5

21 Dassault Systèmes. (2006). Abaqus analysis user's manual (Version 6.6). Retrieved from https://classes.engineering.wustl.edu/2009/spring/mase5513/abaqus/docs/v6.6/books/usb/default.htm?startat=pt05ch18s05abm36.html