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# Experimental and Finite Element Analysis of Steel Fiber Reinforced Geopolymer Concrete Beams under Flexural Loading

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**ABSTRACT**

Steel Fiber Reinforced Geopolymer Concrete (SFRGC) has emerged as a sustainable construction material due to its superior mechanical properties and reduced environmental impact compared with conventional cement-based concrete. This study presents an experimental and finite element investigation of SFRGC beams subjected to flexural loading. Beam specimens were fabricated using geopolymer concrete reinforced with hooked-end steel fibers and tested under four-point bending to evaluate their structural performance. Key parameters, including load–deflection behavior, first crack load, ultimate load, flexural strength, and failure modes, were obtained through laboratory testing. A three-dimensional finite element model was developed in ANSYS to simulate the flexural response of the beams using appropriate material properties, boundary conditions, and loading configurations. The numerical results were validated against the experimental findings to assess the accuracy and reliability of the developed model. A close agreement was observed between the experimental and numerical results in terms of load-carrying capacity, deformation characteristics, and stress distribution. The finite element model successfully predicted the structural behavior of SFRGC beams and effectively captured the failure mechanism under flexural loading. The study demonstrates that combining experimental testing with finite element analysis provides a reliable approach for evaluating the structural performance of sustainable concrete members while reducing the need for extensive laboratory experimentation. The findings confirm the potential of SFRGC beams for sustainable structural applications and provide useful guidance for the design and optimization of advanced geopolymer concrete structures.

**Keywords:** Steel Fiber Reinforced Geopolymer Concrete (SFRGC), Finite Element Analysis (FEA), ANSYS, Flexural Behavior, Sustainable Concrete, Load–Deflection Response

## 1. Introduction

The rapid growth of the construction industry has significantly increased the demand for concrete, making it the most widely used construction material worldwide.[1] However, the production of Ordinary Portland Cement (OPC), the primary binding material in conventional concrete, is responsible for substantial carbon dioxide ($CO_2$) emissions and high energy consumption. These environmental concerns have encouraged researchers and engineers to develop sustainable alternatives that reduce the ecological impact of construction while maintaining structural performance.

Geopolymer concrete has emerged as a promising sustainable construction material because it replaces cement with industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS). These alumino-silicate materials react with alkaline activators to form a strong binder, resulting in concrete with excellent compressive strength, durability, and chemical resistance. In addition to reducing greenhouse gas emissions, geopolymer concrete promotes the beneficial utilization of industrial waste, contributing to sustainable infrastructure development and the circular economy.

Despite its environmental advantages, geopolymer concrete exhibits relatively low tensile strength and brittle behavior under flexural loading, which limits its application in structural members subjected to bending stresses. To overcome these limitations, steel fibers are incorporated into the concrete matrix. Steel fibers bridge developing cracks, delay crack propagation, improve tensile and flexural strength, enhance ductility, and increase the energy absorption capacity of structural members. Consequently, Steel Fiber Reinforced Geopolymer Concrete (SFRGC) has gained considerable attention as a high-performance and sustainable material for beams, slabs, bridges, and other structural applications.[2]

Although experimental investigations provide valuable information regarding the behavior of SFRGC beams, laboratory testing is often time-consuming, costly, and limited by the number of specimens that can be tested. Finite Element Analysis (FEA) has become an effective numerical tool for predicting the structural behavior of concrete members under different loading conditions. Software such as ANSYS enables researchers to simulate stress distribution, deformation, crack development, and failure mechanisms with high accuracy. Numerical modeling also allows the evaluation of various design parameters without conducting extensive experimental programs, thereby reducing both time and cost.[3]

Therefore, the present study combines experimental testing with finite element analysis to investigate the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete beams. Experimental results are validated using an ANSYS-based numerical model to assess the accuracy of the simulation in predicting structural performance. The integration of experimental and numerical approaches provides a comprehensive understanding of the load–deflection response, stress distribution, and failure characteristics of SFRGC beams.[4]

The primary objectives of this research are to evaluate the flexural performance of Steel Fiber Reinforced Geopolymer Concrete beams through laboratory testing, develop a reliable finite element model using ANSYS, compare the numerical predictions with experimental results, validate the accuracy of the finite element model, and assess the suitability of SFRGC beams for sustainable structural applications. The findings of this study are expected to support the design and optimization of durable, high-performance, and environmentally friendly concrete structures.

## 2. Literature Review

### *2.1 Geopolymer Concrete*

Geopolymer concrete has emerged as a sustainable alternative to Ordinary Portland Cement (OPC) concrete because it utilizes industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binder materials. The geopolymerization process involves the reaction of alumino-silicate materials with alkaline activator solutions, producing a strong and durable binder. Numerous studies have reported that geopolymer concrete exhibits high compressive strength, excellent resistance to chemical attack, low shrinkage, and improved durability compared with conventional concrete. In addition to its mechanical advantages, geopolymer concrete significantly reduces carbon dioxide ($CO_2$) emissions by minimizing cement consumption, making it an environmentally friendly material for sustainable infrastructure development.[5]

### *2.2 Steel Fiber Reinforced Concrete*

Steel fiber reinforcement has been widely adopted to improve the mechanical properties of concrete, particularly its tensile and flexural behavior. The incorporation of hooked-end or crimped steel fibers enhances crack resistance by bridging developing cracks and preventing their rapid propagation. Previous studies have demonstrated that steel fibers increase tensile strength, flexural strength, ductility, toughness, and energy absorption capacity while reducing crack width and improving post-cracking performance. When combined with geopolymer concrete, steel fibers effectively compensate for the brittle nature of the matrix and provide superior structural performance under flexural loading.[6]

### *2.3 Flexural Behaviour of Beams*

The flexural behavior of concrete beams is an important consideration in structural engineering because beams are primarily subjected to bending loads during service. Researchers have reported that fiber-reinforced geopolymer concrete beams exhibit higher first crack loads, increased ultimate load capacity, and improved load–deflection behavior compared with conventional concrete beams. Steel fibers distribute tensile stresses more uniformly throughout the concrete matrix, resulting in delayed crack initiation, reduced crack width, and enhanced structural ductility. Experimental investigations have also shown that steel fiber reinforced beams demonstrate better energy absorption and more gradual failure mechanisms, thereby improving structural safety and serviceability.[7]

### *2.4 Finite Element Analysis (FEA)*

Finite Element Analysis (FEA) has become one of the most effective numerical techniques for analyzing the structural behavior of concrete members under various loading conditions. The method divides a structural component into a large number of small finite elements, allowing complex stress and deformation patterns to be accurately predicted. FEA enables researchers to evaluate load–deflection response, stress distribution, strain development, crack propagation, and failure mechanisms without performing extensive laboratory testing. The technique has become an essential tool for validating experimental results, optimizing structural design, and reducing research costs.

### *2.5 ANSYS Applications in Concrete Structures*

ANSYS is one of the most widely used finite element software packages for structural analysis of reinforced concrete and fiber-reinforced concrete members. It provides advanced material models capable of simulating nonlinear concrete behavior, cracking, crushing, reinforcement interaction, and large deformations. Several researchers have successfully used ANSYS to predict the flexural behavior of reinforced concrete beams, geopolymer concrete beams, and steel fiber reinforced concrete members. Numerical simulations performed using ANSYS have shown good agreement with experimental observations in terms of ultimate load, load–deflection response, stress distribution, and failure modes. Consequently, ANSYS has become a reliable tool for validating laboratory investigations and improving structural design.

### *2.6 Research Gap*

Although numerous studies have investigated geopolymer concrete, steel fiber reinforced concrete, and finite element modeling separately, limited research has integrated experimental testing with numerical simulation for Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams under flexural loading. Most previous studies have focused either on experimental evaluation or numerical analysis, while comprehensive validation of finite element models using experimental results remains limited. Furthermore, detailed comparisons of load–deflection behavior, stress distribution, crack propagation, and failure mechanisms between laboratory experiments and ANSYS simulations are scarce. Therefore, there is a need to develop and validate an accurate finite element model capable of predicting the flexural performance of SFRGC beams. The present study addresses this gap by combining experimental investigation with ANSYS-based numerical analysis to provide a comprehensive understanding of the structural behavior and sustainable application of Steel Fiber Reinforced Geopolymer Concrete beams.

## 3. Materials and Experimental Program

### *3.1 Materials*

The Steel Fiber Reinforced Geopolymer Concrete (SFRGC) used in this study was prepared using fly ash and Ground Granulated Blast Furnace Slag (GGBS) as the primary binder materials. Fly ash served as the main source of alumino-silicates, while GGBS enhanced the early-age strength and overall mechanical performance of the geopolymer matrix. Sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$) solutions were used as alkaline activators to initiate the geopolymerization process.[8]

Natural river sand conforming to standard grading requirements was used as the fine aggregate, whereas crushed granite with a maximum nominal size of 20 mm was used as the coarse aggregate. Hooked-end steel fibers were incorporated into the concrete mixture to improve tensile strength, crack resistance, ductility, and energy absorption capacity. Clean potable water was used for preparing the alkaline solution and maintaining the required workability of the concrete mix.

### *3.2 Mix Design*

The geopolymer concrete mix was designed to achieve the required compressive and flexural strength for structural applications. The binder consisted of fly ash and GGBS activated by a combination of sodium hydroxide and sodium silicate solutions. Steel fibers were added at an optimum dosage to ensure uniform dispersion without affecting the workability of the fresh concrete.[9]

The mix proportions were selected based on previous research and standard guidelines for geopolymer concrete. Trial mixes were prepared to obtain satisfactory workability, strength, and durability. The fresh concrete was thoroughly mixed until a homogeneous consistency was achieved before casting the beam specimens.

### *3.3 Beam Specimens*

Beam specimens were prepared to evaluate the flexural performance of Steel Fiber Reinforced Geopolymer Concrete. The beams had standard dimensions of **150 mm × 150 mm × 700 mm** and were reinforced with conventional steel reinforcement according to structural design requirements.

Two groups of specimens were prepared:

- **Control Geopolymer Concrete (GPC) beams** without steel fibers.
- **Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams** containing hooked-end steel fibers.

Each specimen was properly labeled to facilitate identification during experimental testing and result analysis.

### *3.4 Casting and Curing*

All dry materials, including fly ash, GGBS, fine aggregate, and coarse aggregate, were first mixed thoroughly to obtain a uniform blend. The alkaline activator solution was then added gradually while mixing continuously. Steel fibers were introduced slowly into the fresh concrete to ensure their uniform distribution throughout the matrix and to prevent fiber balling.

The concrete was poured into beam moulds in three layers, with each layer compacted using a vibrating table to eliminate entrapped air and ensure proper compaction. After casting, the moulds were covered with plastic sheets to minimize moisture loss. The specimens were demoulded after 24 hours and cured under controlled laboratory conditions for **28 days** before flexural testing.

### *3.5 Flexural Test Setup*

The flexural behavior of the beam specimens was evaluated using a **Universal Testing Machine (UTM)** under **four-point loading** conditions. The beams were simply supported at both ends, and two equal loads were applied symmetrically to create a constant bending moment in the central portion of the beam.

A calibrated load cell was used to measure the applied load, while a **Linear Variable Differential Transformer (LVDT)** was installed at the mid-span to record vertical deflection throughout the test. The load was applied gradually at a constant rate until failure occurred. During testing, observations were made regarding the first crack load, ultimate load, load–deflection response, crack propagation, crack pattern, and failure mode. The collected experimental data were subsequently used for comparison with the finite element analysis results obtained from ANSYS.[10]

## 4. Finite Element Modeling

### *4.1 ANSYS Software*

The finite element analysis of the Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams was carried out using **ANSYS Workbench** to simulate their flexural behavior under static loading. ANSYS was selected because of its advanced nonlinear analysis capabilities and its ability to accurately predict the structural response of concrete members. The numerical model was developed to evaluate load–deflection behavior, stress distribution, deformation characteristics, and failure patterns. The simulation results were compared with the experimental findings to validate the accuracy of the finite element model.[11]

### *4.2 Geometry of Beam*

A three-dimensional beam model was created in ANSYS using the same dimensions as the experimental specimens. The beam dimensions were **150 mm × 150 mm × 700 mm**, ensuring consistency between the numerical and laboratory investigations. The geometry also included the reinforcement layout and loading arrangement identical to the experimental setup.[12]

### *4.3 Material Properties*

The material properties assigned to the numerical model were based on the experimentally determined mechanical properties of Steel Fiber Reinforced Geopolymer Concrete. Parameters such as compressive strength, tensile strength, modulus of elasticity, Poisson’s ratio, and density were defined in the software. Steel reinforcement and steel fibers were modeled using the mechanical properties of structural steel, while appropriate nonlinear material behavior was assigned to simulate concrete cracking and crushing under flexural loading.

### *4.4 Element Types*

Suitable finite elements available in ANSYS were selected to accurately represent the behavior of concrete and steel reinforcement. Three-dimensional solid elements were used to model the geopolymer concrete beam, while reinforcement bars were represented using embedded link elements. These element types enabled the simulation of nonlinear material behavior, stress transfer between concrete and reinforcement, and the development of cracks under increasing load.[13]

### *4.5 Meshing*

The beam model was discretized into a finite number of small elements using the ANSYS meshing tool. A finer mesh was provided in regions expected to experience high stress concentrations, particularly near the loading points and mid-span section. Mesh refinement improved the accuracy of stress prediction and deformation analysis while maintaining computational efficiency. A mesh convergence study was considered to ensure that the numerical results were independent of the selected mesh size.

### *4.6 Boundary Conditions*

Boundary conditions were defined to replicate the experimental four-point bending test. The beam was modeled as simply supported, with one end restrained against both vertical and horizontal displacement while the opposite end was allowed to move horizontally to avoid unnecessary restraint forces. These support conditions accurately represented the laboratory testing arrangement and ensured realistic structural behavior during analysis.

### *4.7 Loading Conditions*

The external load was applied through two loading points positioned symmetrically about the beam center, reproducing the four-point loading configuration used during experimental testing. The load was applied incrementally to capture the complete nonlinear response of the beam, including crack initiation, stiffness reduction, and ultimate failure. Incremental loading also improved the convergence of the numerical solution.

### *4.8 Solution Procedure*

A nonlinear static structural analysis was performed to evaluate the flexural response of the SFRGC beams. The analysis considered material nonlinearity associated with concrete cracking and steel yielding. During the solution process, the software calculated the load–deflection response, equivalent (von Mises) stress distribution, principal stresses, total deformation, and strain distribution. The numerical predictions were then compared with the experimental results to validate the finite element model. A close agreement between the experimental and numerical outcomes confirmed the capability of ANSYS to accurately simulate the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete beams and demonstrated its usefulness as a reliable tool for structural analysis and design.[14]

## 5. Results and Discussion

### *5.1 Experimental Results*

The experimental investigation demonstrated that Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams exhibited superior flexural performance compared with conventional geopolymer concrete beams. During testing, all specimens behaved elastically until the formation of the first visible crack. After crack initiation, the SFRGC beams maintained their load-carrying capacity for a longer period due to the crack-bridging effect of steel fibers. The experimental observations confirmed improvements in first crack load, ultimate load, ductility, and post-cracking behavior. The inclusion of steel fibers also resulted in a more gradual failure process, indicating enhanced structural toughness.[15]

### *5.2 Numerical Results (ANSYS)*

The finite element analysis performed using ANSYS successfully simulated the flexural behavior of the SFRGC beams. The numerical model accurately predicted the deformation profile, stress distribution, and structural response under four-point loading. The maximum stresses developed near the loading points and the tension zone at the bottom surface of the beam, which closely matched the experimental observations. The numerical analysis also identified the critical regions where cracking was expected to occur, demonstrating the capability of ANSYS to represent the nonlinear behavior of geopolymer concrete beams.[16]

### *5.3 Load–Deflection Curve*

The load–deflection curves obtained from both the experimental and numerical investigations showed similar trends throughout the loading process. Initially, both curves exhibited linear elastic behavior. As the applied load increased, stiffness gradually reduced due to crack formation. The SFRGC beams displayed lower deflection values at similar load levels compared with conventional geopolymer concrete beams, indicating higher flexural stiffness. The close agreement between the experimental and ANSYS load–deflection curves confirmed the reliability of the developed finite element model.[17]

### *5.4 Stress Distribution*

The stress contours generated in ANSYS indicated that compressive stresses were concentrated in the upper portion of the beam, while tensile stresses developed in the bottom region under flexural loading. The highest stress concentration occurred at the mid-span section, where the bending moment was maximum. Steel fibers effectively reduced localized tensile stress concentrations by distributing stresses more uniformly within the concrete matrix. This stress redistribution contributed to improved crack resistance and increased load-carrying capacity.[18]

### *5.5 Crack Pattern*

The experimental crack pattern closely resembled the crack zones predicted by the finite element model. Initial flexural cracks developed near the beam's mid-span and gradually propagated upward with increasing load. Conventional geopolymer concrete beams exhibited fewer but wider cracks, whereas SFRGC beams developed a larger number of fine and closely spaced cracks due to the crack-bridging action of steel fibers. The ANSYS simulation accurately identified the regions of maximum tensile stress where crack initiation was observed experimentally.

### *5.6 Deformation Profile*

The deformation profile obtained from ANSYS showed maximum vertical deflection at the beam center, which agreed well with the experimental measurements. The SFRGC beams exhibited lower maximum deformation than conventional geopolymer concrete beams because the steel fibers increased the stiffness and flexural resistance of the concrete matrix. The numerical deformation contours clearly illustrated the beam bending behavior and confirmed the effectiveness of steel fibers in improving structural rigidity.[19]

### *5.7 Experimental vs Numerical Comparison*

A comparison between the experimental and numerical results demonstrated good agreement in terms of first crack load, ultimate load, mid-span deflection, stress distribution, and failure behavior. Minor differences between the two approaches were attributed to assumptions made during material modeling, idealized boundary conditions, and unavoidable experimental variations. Nevertheless, the percentage variation remained within acceptable engineering limits, indicating that the finite element model effectively represented the actual structural behavior of the SFRGC beams.[20]

### *5.8 Validation of FEA Model*

The close correlation between the laboratory results and the ANSYS simulations validates the accuracy and reliability of the developed finite element model. The numerical model successfully predicted the flexural response, deformation characteristics, stress distribution, and failure mechanism of Steel Fiber Reinforced Geopolymer Concrete beams. Therefore, the validated FEA model can be confidently used for future parametric studies, structural optimization, and the design of sustainable geopolymer concrete members, reducing the need for extensive experimental testing while maintaining reliable prediction accuracy.

. Conclusions Key findings Accuracy of the ANSYS model Structural performance of SFRGC beams Sustainability benefits

## 6. Conclusions

The present study investigated the flexural behavior of Steel Fiber Reinforced Geopolymer Concrete (SFRGC) beams through both experimental testing and finite element analysis using ANSYS. The results demonstrated that the combination of laboratory experiments and numerical modeling provides a reliable approach for evaluating the structural performance of sustainable concrete members.

The key findings indicate that the incorporation of steel fibers significantly improved the flexural performance of geopolymer concrete beams by increasing the first crack load, ultimate load, flexural strength, ductility, and energy absorption capacity. Steel fibers effectively controlled crack initiation and propagation, resulting in smaller crack widths, enhanced post-cracking behavior, and a more gradual failure mechanism compared with conventional geopolymer concrete beams.

The finite element model developed in ANSYS accurately predicted the load–deflection response, stress distribution, deformation profile, and failure behavior of the beam specimens. A close agreement was observed between the experimental and numerical results, confirming the reliability and accuracy of the developed ANSYS model. Minor variations between the two sets of results were attributed to material assumptions and idealized boundary conditions used in the numerical simulation. Overall, the validated finite element model proved to be an effective tool for predicting the flexural behavior of SFRGC beams.

From a structural perspective, Steel Fiber Reinforced Geopolymer Concrete beams exhibited superior load-carrying capacity, improved stiffness, enhanced crack resistance, and greater ductility than conventional geopolymer concrete beams. These improvements indicate that SFRGC is a suitable material for structural members subjected to bending loads and can provide enhanced safety, durability, and service life in practical engineering applications.

In addition to its structural advantages, SFRGC offers significant sustainability benefits by utilizing industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binder materials, thereby reducing the dependence on Ordinary Portland Cement. This contributes to lower carbon dioxide emissions, conservation of natural resources, and effective utilization of industrial waste. Therefore, Steel Fiber Reinforced Geopolymer Concrete can be considered an environmentally friendly and sustainable construction material for future infrastructure development. The validated experimental and numerical findings of this study provide a strong foundation for the design, analysis, and practical implementation of SFRGC beams in sustainable structural engineering.

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