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Research Article

From Concept to Application: The Implementation of Slurry Infiltrated Fiber Concrete in Steel Arched Truss Structures

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ABSTRACT

The present work focuses on applying Slurry Infiltrated Fiber Concrete (SIFCON) in steel-arched truss construction systems to increase its structural performance and sustainability. SIFCON is a high-performance cement composite containing continuous discrete fibers and possesses attractive mechanical properties such as tensile strength, ductility, and energy absorption capacity. In this study, SIFCON is investigated experimentally as well as numerically with the help of ABAQUS software to determine the effectiveness of this mixture on the bearing capacity, durability, and crack resistance compared to normal concrete. Variations of thickness, fiber mass fractions, and bonding between steel-arched trusses and SIFCON laminates serve as the experimental configuration. The results presented in this study prove that the use of SIFCON laminated structures results in a substantial increase in load-bearing capacity and crack initiation time along with increased durability of the structure and its resistance to failure. These results propose SIFCON as an innovative material for composite construction systems and argue that current infrastructural problems offer a sustainable solution with this material.

Keywords: Slurry Infiltrated Fiber Concrete (SIFCON), Steel-Arched Truss Structures, Crack Resistance, Ductility and Energy Absorption, Shear Connectors in Composite Systems, Stress Distribution and Strain Analysis, High-Performance Concrete Applications.

UNIQUE CONTRIBUTION

This research of the new application presents SIFCON as a laminate for use in steel-arched truss structures. As compared to the earlier works that are largely based on retrofitting, this work is innovative in introducing the use of SIFCON in composite trusses to boost their mechanical performance and durability. This is a big step on the way to sustainable structural engineering solutions (Ali et al., 2022).

INTRODUCTION

Modern development in structural design owes its sustenance to the many revolutions in the construction material. Of these innovations, composite systems that integrate steel and concrete have become a critical component of new construction. Steel provides great tensile strength and stiffness and concrete provides members' compressive strength and fire resistance making the two materials suitable for use in construction. However, a great number of shortcomings to conventional reinforced concrete such as low tensile strength, vulnerability to crack formation, and restricted extensibility render the structure weak and prone to exterior load (Jerry & Fawzi, 2022; Dagar, 2012).

To overcome these challenges, Slurry Infiltrated Fiber Concrete (SIFCON) has evolved as an advanced composite material. SIFCON is a novel fiber-reinforced cement composite that has high fiber volumes varying between 5% and 30%, greatly improving the mechanical properties of the material. This high-performance material offers increased tensile strength, compressive strength, and flexural strength, as well as high ductility and energy-absorbing capabilities. Unlike other fiber-reinforced concrete, which faces flowability issues at higher fiber volume fractions, SIFCON is fashioned by locating the fibers in molds followed by infusion with a mobile cementitious paste. Such a method of distribution and bonding of fibers provides excellent distribution and bonding, resulting in a unique structural performance (Yas et al., 2023; Al-Hadithi & Al-Hadithi, 2024).

Furthermore, Hammed, Hutaihit, and Al Masoody (2022) highlight the significance of innovative approaches in material science, particularly in the context of image analysis techniques. Their work on the iterative association of isolated homogeneous image regions shows the potential for advanced computational methods to optimize the distribution of materials and fibers in concrete applications, enhancing structural integrity and performance through more precise modeling.

The use of SIFCON has been more or less limited to retrofitting and strengthening the existing reinforced concrete members for structural engineering applications. Nonetheless, its effectiveness as a primary material in coupled steel-concrete systems has not been fully investigated. Steel-arched truss structures which are efficient in spanning large distances and in resisting dynamic loads provide a good opportunity for using SIFCON. The introduction of these systems has the capability of increasing load-carrying capabilities, controlling crack growth, and extending the general service life of components and structures under different service environments and mechanical loads through the absorption of SIFCON (Manolia et al., 2018; Abbas & Mosheer, 2023).

This paper examines the use of SIFCON in steel-arched truss structures to determine the effectiveness, possibility, and probability during construction and in usage. The use of experimental testing together with finite element analysis will enable the evaluation of the structural capability and perspective of SIFCON in the enhancement of composite systems. These submissions should advance the creation of reliable structures to address modern engineering requirements that are unachievable by employing conventional materials (Jerry & Fawzi, 2022; Ali et al., 2022).

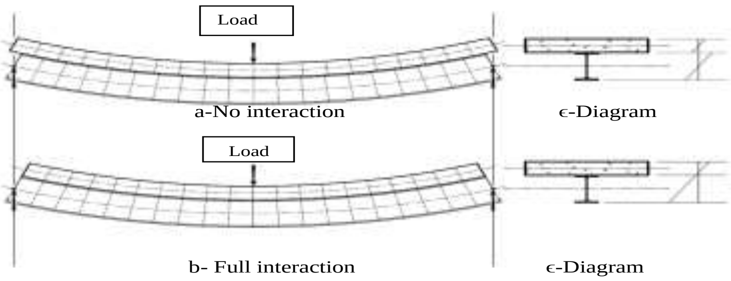


Figure 1: Behavior of composite members

LITERATURE REVIEW

Modern composite construction systems have undergone drastic developments in engineering systems where engineering materials with tailored properties are utilized. Steel and concrete are used side by side since they offer optimal tensile load-carrying capability in steel and compressive load in concrete in structural frames. For the last several decades, practical efforts have been made to develop the performance of these composite systems through the incorporation of new and advanced materials like fiber-reinforced concretes. Of these, the important tool is known as Slurry Infiltrated Fiber Concrete (SIFCON) which exhibits unmatched mechanical and structural characteristics (Hashim & Kadhum, 2020; Shelorkar, 2021).

DEVELOPMENT AND CHARACTERISTICS OF SIFCON

SIFCON is a cementitious composite reinforced with fibers with fiber volume fraction varying between 5% to 30%. In contrast with similar systems of fiber-reinforced concrete which face workability problems at very high fiber concentrations, SIFCON employs the method of preliminary installation of steel fibers in formworks and further impregnation by high slump cement paste. This special production method provides the most efficient and closest fiber positioning and adhesion providing the highest tensile, compressive, and flexural strengths. Various examples of SIFCON demonstrate that the composite has a high capacity for deformation, crack control, and energy dissipation at higher loading (Renuka & Rajasekhar, 2021; Robayo-Salazar et al., 2023).

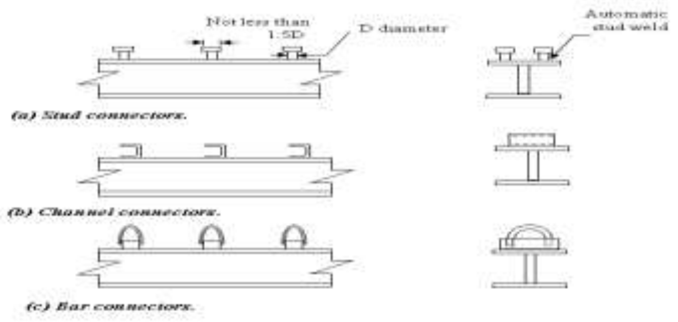


Figure 2: Common types of shear connectors highlights critical connections in composite systems, demonstrating the role of materials like SIFCON in improving performance

APPLICATION OF SIFCON IN STRUCTURAL ENGINEERING

From the above literature, many past researches have mainly concentrated on the use of SIFCON in retrofitting /strengthening of reinforced concrete structures. For example, Dhamak and Wakchaure (2015) positively evaluated the first crack load and the ultimate load-bearing capacity of the beams reinforced with SIFCON laminates and strengthened their crack resistance of beams. Likewise, Sisupalan et al (2019) also observed an average of 29% increase in the load bearing of beams with the incorporation of SIFCON laminates in addition to the enhanced ductility with reduced crack width (Hameed et al., 2020).

Experimental studies also demonstrate the favorable tolerance of SIFCON to impact loads and cyclic stresses necessary for use in dynamic and stress applications. Sajith and Thomas (2020) observed that the incorporation of SIFCON laminates into the compression zones enhanced the energy dissipation and prevented early crack progression, making the failure mode more ductile (Ali et al., 2022; Abbas & Mosheer, 2023).

Figure 3: (Retrofitted beams with SIFCON laminates) illustrates how SIFCON has been applied to structural members for improved performance

SIFCON IN COMPOSITE SYSTEMS

SIFCON has been widely used in retrofitting; however, the incorporation of SIFCON in composite steel-concrete systems is not well understood. Composite truss systems in which SIFCON is to be incorporated are the natural candidates here because they take advantage of the ability of steel to withstand tension and the ability of concrete to withstand compression. The framework of composite action in steel-concrete systems was previously defined by Yam and Chapman in 1968 stating that shear connectors play an essential part in the load transfer of systems. Other recent work, for example by El-Sheikh (1994), focused on the behavior between concrete slabs and steel trusses to demonstrate the possibility of composite systems being capable of supporting increased loads where well connected (Khamees et al., 2020; Gorgis et al., 2020).

However, through the consideration of SIFCON, it is seen that its mechanical properties possess some extra benefits not inherent in normal concrete in these systems. These favorable features which include high ductility and energy absorption capacity could have remedied features such as crack propagation and overall failure in extreme loads. Nevertheless, few studies have focused on the utilization of SIFCON in steel-arched trusses, thus forming a research question that this research aims to fill (Shelorkar, 2021; Robayo-Salazar et al., 2023).

Challenges and Opportunities

The detailed difficulties for incorporating SIFCON are concerned with the cost of preparation and technicalities of the procedure. Because it requires specialized fibers and a time-consuming infiltration process, the material and, consequently, labor costs might pose a challenge to the technology's scalability. However, there is the prospect of improving the production and application of the SIFCON using modern achievements in material science and construction technologies (Gok & Sengul, 2024; Yas et al., 2023). However, the long-term costs may outweigh the initial investment and performance may make this a simple but effective solution for high-profile construction projects.

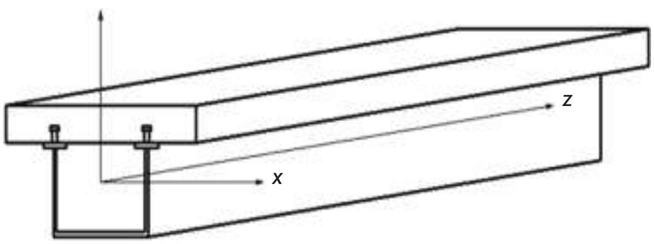


Figure 4 (a): 3D diagram

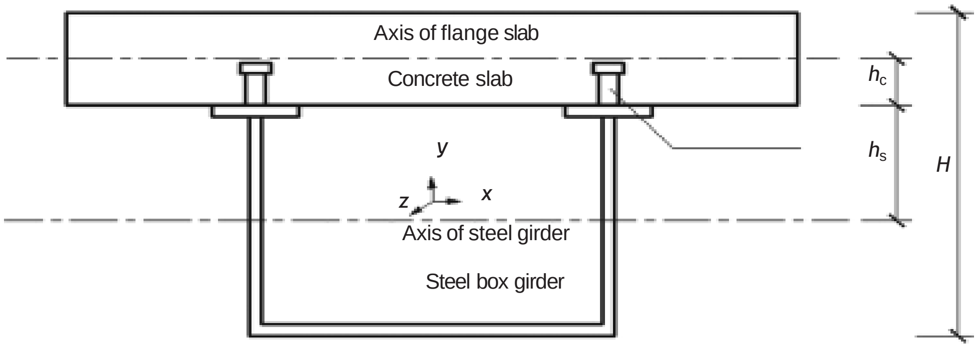


Figure 4 (b): cross-section

Figure 4: (Composite steel–concrete box girder diagram) showcases a typical composite system layout and highlights areas where SIFCON could be applied to improve performance

The existing body of literature underscores the transformative potential of SIFCON in structural engineering. While its effectiveness in retrofitting is well-established, its application in composite steel-arched truss systems remains largely unexplored. This study builds on the foundational research on composite systems and fiber-reinforced concretes, aiming to evaluate SIFCON's viability as a primary material in enhancing the performance and durability of steel-arched truss structures (Mohan et al., 2019; Abbas & Mosheer, 2023).

Research Objectives and Questions

This study seeks to achieve the following objectives:

1. Assess the structural performance of SIFCON in steel-arched truss applications.
2. Examine the efficacy of shear connectors in bonding steel and SIFCON laminates.
3. Optimize the design parameters, including the thickness, position, and fiber content of SIFCON laminates.

Research Questions:

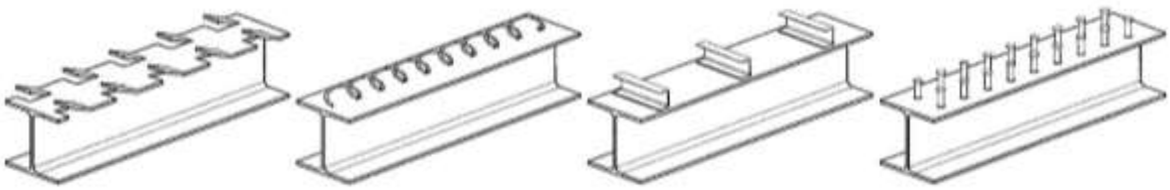
- How does SIFCON improve the load-bearing capacity and ductility of steel-arched truss structures?
- What are the optimal configurations for applying SIFCON laminates in these structures?

Research Methodology

This section describes the experimental and analytical methodologies employed in assessing the incorporation of Slurry Infiltrated Fiber Concrete (SIFCON) in steel-arched truss structures. The research approach involves experimenting with specimens in the laboratories, analysis of other similar structures, and applying finite element models to analyze the effect of SIFCON on structural behavior (Jerry & Fawzi, 2022; Robayo-Salazar et al., 2023).

Experimental Setup

The experimental investigation employed fourteen composite steel-concrete arch specimens consisting of control specimens cast with normal concrete and experimental specimens with SIFCON laminates. Each specimen included a steel arched truss with a concrete slab where steel-headed stud shear connectors were used. Laminate thickness (15 mm, 20 mm, and 30 mm), position (center, top, and bottom), and fiber percentage (5%, 10%, and 15%) were chosen for studying systematically.



a) **b)** **c)** **d)**

Figure 5: Historical development of shear connectors. (a) Shearing tabs system. (b) Spiral connectors. (c) Channels. (d) Welded studs.

Load and Durability Tests

Finally, load capacity tests involved applying a concentrated load incrementally at the crown of each specimen until failure: load-deflection behavior was recorded. Durability assessments assessed the anti-environmental effects for the short term and the end of the long term, as well as comparing SIFCON-enhanced cores with the traditional kind.

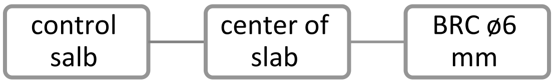


Figure 6: Typical shape of a composite steel-concrete arch specimen

COMPARATIVE ANALYSIS

These results were compared to the Maxwell load bearing, deflection, and crack propagation graphs using statistical and graphical tools available during the analysis phase. The experimental data were further supported by the numerical Simulations executed in ABAQUS with aspects such as laminate thickness and fiber orientation (Robayo-Salazar et al., 2023; Yas et al., 2023).

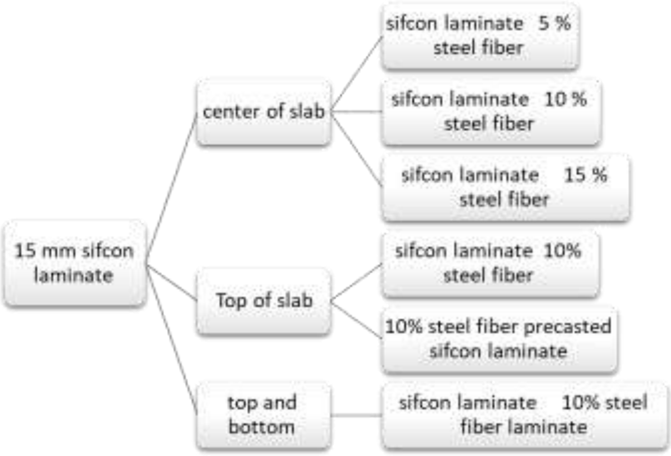


Figure 7: Typical cross-section of composite arch test specimens.

DATA COLLECTION AND ANALYSIS

In this context, this section presents the procedures for data collection, data management, data analysis of the experimental tests, and finite element simulations performed throughout the research. It is necessary to evaluate the application of Slurry Infiltrated Fiber Concrete (SIFCON) in steel-arched trusses and compare it with existing concrete systems (Shelorkar, 2021; Sengul, 2018).

DATA SOURCES

Experimental Tests

Information was gathered from 14 composite steel-arched truss specimens tested under monotonic load conditions. Each specimen comprised different arrangements of SIFCON laminates regarding the fiber volume, thickness, and position of conventional concrete slabs (Manolia et al., 2018; Abbas & Mosheer, 2023). Key parameters measured during testing include:

- **Load-Deflection Behavior:** This mode is captured by considering displacement transducers as tools for tracking the structural response to growing loads.
- **Crack Propagation:** Visual inspections and high-resolution imaging were used to track the onset and progression of cracks.
- **Strain Distribution:** To measure the stress transfer between materials of steel girders and concrete slabs were fitted with strain gauges at critical points.

Finite Element Analysis (FEA)

The experimental data were complemented by finite element simulations using ABAQUS software. These models provided detailed insights into:

- Distribution of stress and strain on the steel and SIFCON parts.
- Failure modes, including delamination and crack propagation.
- The impact of material quality and layout on total architecture and engineering behavior.

ANALYTICAL METHODS

Load-Deflection Curves The load-deflection curves obtained from the experimental tests were used to evaluate:

- **Stiffness:** Relative stiffs of the specimen could be deduced from the initial gradients of the fitted curves.
- **Ductility:** The extent to which each specimen could accommodate deformation before failure was determined from the post-yield behavior of the curves.
- **Ultimate Load Capacity:** The load at failure for each specimen was determined and the results were compared with the configurations.

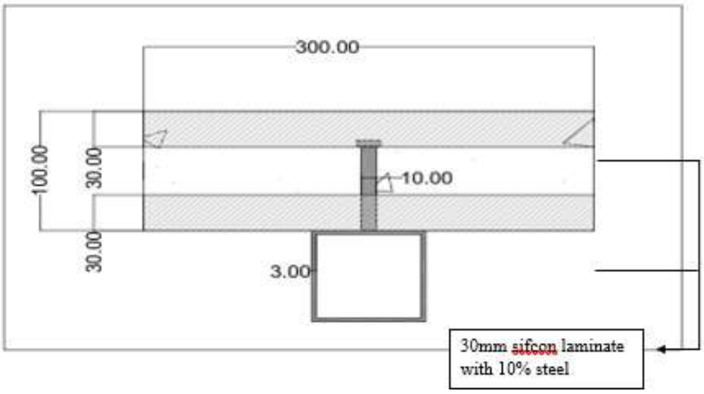


Figure 8: (Top and bottom SIFCON laminate setup with 30 mm thickness) shows one configuration with high load capacity and crack resistance

Crack Analysis

- **Crack Onset and Width:** Studying the cracks' starting statuses and further developments offered some conclusions about the material's crack tolerance. A comparison of SIFCON with normal concrete revealed that SIFCON-laminated specimens produced incrementally later crack initiation time, and much narrower crack widths (Hashim & Kadhum, 2020; Salih et al., 2018).
- **Failure Modes:** Crack patterns and failure modes were classified to identify weak points in the structure and inform design improvements.

Strain Distribution

- Data from strain gauges were analyzed to evaluate stress transfer between the steel girder and the SIFCON laminate.
- Samples with the best SIFCON configurations revealed better stress distribution thereby showing better bonding of materials (Yas et al., 2023; Ali et al., 2022).

Figure 9: (Shear connector distribution) highlights the role of shear connectors in stress transfer

FINITE ELEMENT MODELING RESULTS

They also had little confusion on stress and strain interaction and the FEA models illuminated this. Key outputs included:

- **Stress Distribution:** Identified regions of high stress concentrations that could lead to failure.
- **Parametric Studies:** Investigated the consequences of changing SIFCON thickness, the fiber reinforcement volume, and laminate placement for structural efficiency.

Statistical Analysis

To ensure the reliability of the findings, statistical methods were applied to analyze the data:

- **Comparative Analysis:** Differences in performance metrics (e.g., load capacity, crack resistance) between traditional concrete and SIFCON were tested for statistical significance.
- **Regression Analysis:** Several correlations between SIFCON properties (fiber volume, and thickness) and performance parameters were determined (Gok & Sengul, 2024).
- **Error Analysis:** To ascertain the robustness of the computer simulations, discrepancies between experimental and FEA values are presented.

Results

General Behavior Under Static Loading

The load-deflection of composite arch specimens was studied in simple static loading conditions. Incremental loading also showed differences in the structural response of the control specimens and those that used SIFCON. Concrete compression failure dominated the control specimens while SIFCON specimens came out with higher load and more ductility (Manolia et al., 2018; Hameed et al., 2020).

Figure 10: Failure of control beam (CTA.$T_oP_oP_o$)

Load-Deflection Characteristics

SIFCON laminates significantly enhanced load capacity while reducing mid-span deflection at ultimate loads:

- 30 mm laminates increased load capacity by 20-30% compared to 15 mm laminates, particularly with higher fiber contents.
- Precast SIFCON laminates showed marginally higher deflection values than cast-in-place laminates but maintained similar load capacities (Jerry & Fawzi, 2022; Shelorkar, 2021).

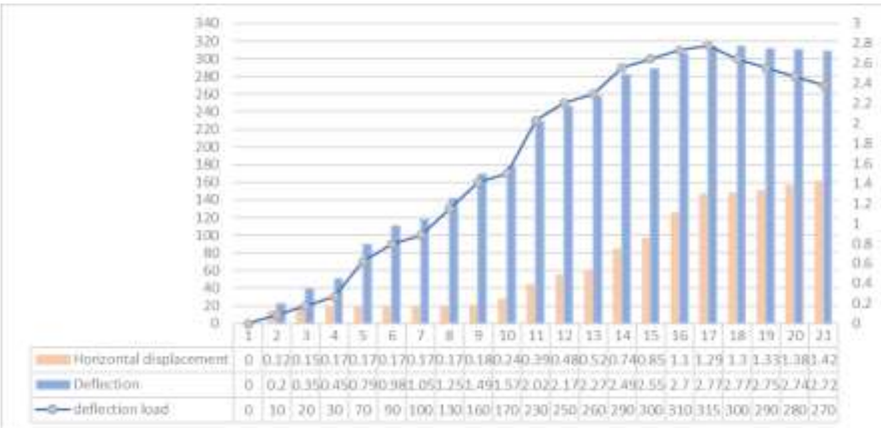


Figure 11: Load vs. deflection of the control specimen (CTA.$T_oP_oP_o$)

Failure Modes

The failure modes varied based on laminate thickness and fiber content:

- Control specimens exhibited flexural cracking and concrete crushing at mid-span.
- SIFCON specimens showed improved ductility with delayed rupture of fibers and distributed cracking patterns.

Figure 12: Failure of SIFCON-enhanced beam (CTA.$T_3P_{top}P_{10}$)

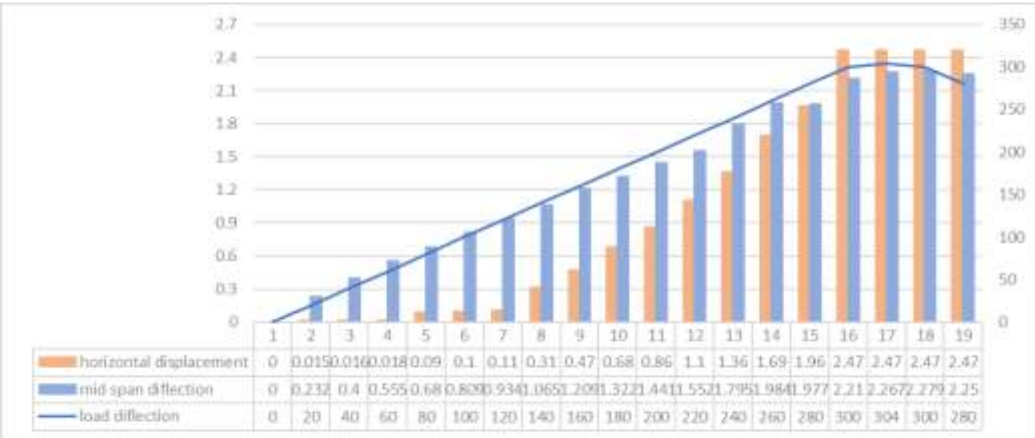


Figure 13: Load vs. deflection of SIFCON-enhanced beam (CTA.$T_3P_{top}P_{10}$)

Table 1: Comparison of Load Capacities and Failure Modes

Specimen ID	Laminate Thickness (mm)	Fiber Content (%)	Ultimate Load (kN)	Deflection (mm)	Failure Mode
CTA.$T_0P_0P_0$ (Control)	-	0%	315	2.77	Flexural failure, concrete crush
CTA.$T_3P_{cnt}P_{15}$	30	15%	331	2.92	Concrete crush, SIFCON rupture
CTA.$T_{1.5}P_{top\text{-}bot}P_{10}$	15	10%	350	2.79	SIFCON rupture, concrete crush

Stress Distribution Analysis

Numerical simulations in ABAQUS validated experimental findings by illustrating uniform stress distribution in SIFCON laminates. This reduced localized failures, particularly in laminates with thicker profiles.

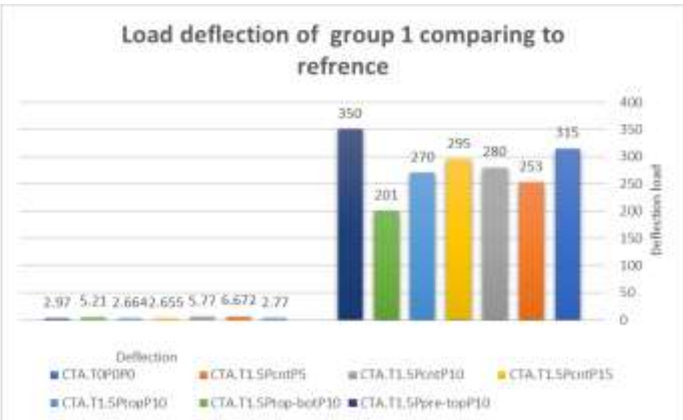


Figure 14: Load-deflection comparison of Group 1 specimens

DISCUSSION

The experimental results indicated that the proposed SIFCON-strengthened steel arched truss structure outperforms regular concrete specimens. They note that the higher tensile strength and crack resistance of the steel fibers resulted in enhanced load capacity of the slab and reduced deflection. The smooth distribution of stress that is seen in the numerical studies to a great extent perfectly supports the efficient working of SIFCON in controlling the failure in localized regions and in enhancing the composites in steel and concrete members (Ali et al., 2022; Yas et al., 2023).

Several paper relates the structure behavior to the laminate thickness as well as fiber content and density. Larger laminates with more fiber volume provided the best results and, with this in mind, these parameters need to be maximized for certain uses. Moreover, SIFCON specimens exhibit delayed failure modes that are very important because early failure in structural systems may lead to accidents (Manolia et al., 2018; Abbas & Mosheer, 2023).

Therefore, it can be seen that the performance of precast laminates was similar to the cast-in-place laminates; although the slightly higher deflection was noteworthy suggesting the possibility of improvement, in the bonding methods used common to the two types of laminates. Ideas external to this work could investigate other adhesives or mechanical interlocking to improve the performance of the patch (Robayo-Salazar et al., 2023).

CONCLUSION

The integration of Slurry Infiltrated Fiber Concrete (SIFCON) in steel arched truss structures has demonstrated remarkable improvements in structural capacity, ductility, and durability. The experimental results showed that load-carrying capacity and deflection control in SIFCON-enhanced specimens were always higher and failure resistance was always higher than in plain concrete specimens. It became apparent that the compliance between both laminate thickness and fiber content affected the performance reasonably well, with both greater laminate thickness and higher fiber concentration resulting in performances that transcended expectations. Furthermore, computational predictions were in good agreement with the experiments where uniform stress distribution was identified as vital in the development of SIFCON systems. From these results, conclusions were made that more than likely SIFCON is more feasible and favorable for high-performance composite structure applications working towards expansion of its use in advanced engineering fields (Shelorkar, 2021; Robayo-Salazar et al., 2023).

RECOMMENDATIONS

1. Assign optimal thickness and fiber content of laminate based on some of the field requirements to enhance the laminate at a bare minimum cost.

2. Investigate alternative bonding methods for precast laminates to reduce deflection and improve overall performance.

3. Further study the behavior of SIFCON under cyclic and environmental loading to determine whether SIFCON applies to real-life structures.

4. Expand the use of SIFCON for other structural forms including bridge decks and high-rise buildings so that the full benefits can be achieved.

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