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Performance comparison of steel fiber reinforced concrete and conventional reinforced concrete cast-in-place half-scale concrete bridge decks under bending

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Abstract

The most time-consuming processes involved in bridge deck construction are laying and tying conventional reinforcement and verifying the required cover. Thus, there is a need within bridge construction technology to identify opportunities for utilizing steel fibers and replacing more conventional reinforcing bars on bridge decks and this could be a significant step in speeding up bridge construction. Although the bending strength performance of reinforced concrete decks has been the subject of many experiments and research, many considerations still need to be explored. Hence, the current experiment aims to compare and evaluate the bending strength and ductility of two half-scale concrete bridge decks reinforced by steel fiber reinforcement (SFRC) with two half-scale concrete bridge decks reinforced by conventional reinforcement (RC), 27.6 MPa (4000 psi) concrete compressive strength is used in this study, all four decks were tested under flexural loads. Load–displacement curves (*P-Δ*) are recorded as a tool to measure the ductility index (μ_E) (Spadea et al.). The result showed that the flexural stiffness of the SFRC concrete deck specimens is improved and load carrying capacity increased by 12.3% compared to RC decks. Moreover, crack width and crack are reduced by 14% since the SFRC decks offer more concrete ductility than RC decks, meaning less future maintenance and corrosion. Therefore, the use of steel fiber in concrete mixtures could be a significant step in speeding up bridge construction since it does not require laying, tying, and verifying clear cover, in addition to increasing the lifespan of bridge decks.

Keywords: Hooked end steel fibers, Strength, Bridge deck, Concrete, SFRC, Bending behavior

1 Introduction

Since concrete is recognized as a quasi-brittle material and characterized by brittle failure, once failure is initiated, concrete nearly completely loses loading capacity (Słowik 2019). Adding steel fibers as reinforcement in concrete mixture improves concrete ductility and prevents sudden failure (Vairagade et al. 2012; Patil et al. 2012; Mohod 2012; Dahake and Charkha 2016). Over the past decades, steel fiber reinforced concrete

(SFRC) has become a widely used material in concrete structures, being used in columns, beams, and slabs (Zhang et al. 2023), due to its advantages, such as increased load-bearing capacity, high durability, low maintenance cost, improve flexural properties (Pajak and Ponikiewski 2012), fast-track schedule, less corrosion, thin walls application (Abdul Ahad et al. 2015), and better behavior of crack control.

With the wide demand for high-durability concrete bridge structures, there is a great need for bridge decks with better crack control performance (Xiang et al. 2022). This higher durability keeps the bridges active for longer periods when compared to the maintenance of decks that have conventional reinforcing bars. This makes the bridges more efficient and keeps the traffic flowing. Since concrete bridge decks are the first line of defense against traffic and environmental exposure, it is necessary to design bridge decks with thoughts toward future maintenance costs during the lifecycle of the bridge structure (PCI, Bridge Design Manual 2011). In concrete bridge decks, most of the maintenance costs are related to repairs of cracks in the deck and corrosion of reinforcement. With corrosion of reinforcing bars is the most common cause of failure of bridge decks (Kirkpatrick et al. 2002), utilizing steel fibers in concrete decks reduces the cracking percentage and crack widths because steel fibers are randomly distributed in the concrete mixture and offer more crack control (ASTM C1018, 1991). Some estimate that over 46,154 bridges in the US are considered structurally deficient (American Society of Civil Engineers ASCE Report Card 2021), most of the defects are due to steel reinforcement corrosion resulting in damaging concrete spalling (Syll and Kanakubo 2022). Rebar corrosion, a common type of corrosion found in most highway bridges, occurs when chloride ions migrate to concrete material like steel bars (Mangat and Gurusamy 1988). Steel fibers have been shown to offer a more corrosion-resistant option over conventional reinforcing bars.

Past research results have shown that SFRC has offered better properties in comparison with plain concrete and most of these research studied steel fiber as a supplement reinforcement in concrete mixture (Sief aldeen Odaa et al. 2021, Peng Zhang et al. 2023, Mu et al. 2018, Weli et al. 2020). Therefore, utilizing steel fiber could be a solution for enhancing the mechanical properties of concrete. This study intends to perform an experimental investigation utilizing steel fiber as the main reinforcement in half-scale cast-in-place concrete bridge decks under a bending load and perform a results analysis. This study aims to assess the bending strength performance of the decks and evaluate the crack of the widths and spacing in comparison with decks that have conventional reinforcement, concluding that utilizing steel fiber in concrete bridge decks will reduce the time of construction and minimize future maintenance of cracks and corrosion.

2 Materials and cylinders test

2.1 Materials

2.1.1 Cement

Ordinary Portland cement type I/II was used throughout this research for casting all samples.

2.1.2 Coarse aggregate

Clean graded crushed gravel of maximum size 1.9 cm (3/4-inch) diameter was used.

2.1.3 Fine aggregate

Clean naturally graded sand was used and weighted to the design amount.

2.1.4 Mixing water

Portable water was used for mixing and curing throughout the experimental work.

2.1.5 Concrete

Cement, coarse aggregate, fine aggregate, and water were mixed together in a specific amount as shown in Table 1 to obtain a design compressive strength of 27.6 MPa (4000 psi) at the age of 28 days in the Civil Engineering Laboratory Building of University of Texas at Arlington, and poured into two groups, each group consists of four 10 x 20 cm (4 x 8 inch) cylinders of concrete with 0 and 41.5 Kg/m^3 (70 lb/cy) 4D hooked-end steel fiber steel fiber.

2.1.6 Steel rebar

#3 and #4 reinforcement were used for cast-in-place samples that had steel rebar as the main reinforcement to obtain the AASHTO LRFD design method of concrete bridge decks with regular reinforcement and 0 steel fiber, and 15.25 x 15.25 x 0.6 cm (6 x 6 x ¼ inch) of wire mesh was used for the cast-in-place concrete bridge deck samples that have steel fiber as the main reinforcement.

2.1.7 Steel fiber

Steel Fibers have been used in concrete for the last three decades and can be used to replace ordinary reinforcement or as a supplement to structural reinforcement. Now being produced domestically according to ASTM A820-16 Classified Steel Fiber based on the manufacturing process, some advantages of steel fibers, such as the increased load-bearing capacity of concrete, reduction of concrete slab thickness, increased durability (Soylev and Ozturan 2014), low maintenance costs, improved flexural properties, can be used on a fast-track schedule, and minimized corrosion. However, it does have some disadvantages like low workability (Alireza et al. 2014) and possibility of balling during the mixing. (Patil et al. 2016; Elavenil and Samuel Knight 2007). In this research, one form of Dramix 4D 65/60 BG steel fiber was used (see Fig. 1), and the specifications of this steel fiber are shown in Table 2 (Bekaert 2023).

A dosage of 41.5 kg/m^3 (70 pounds per cubic yard) of steel fiber was used as the main reinforcement in a concrete mixture of cast-in-place decks that have steel fiber and 15.25 × 15.25 × 0.6 cm (6 × 6 x ¼ inch) wire mesh only.

Table 1 Concrete Mix Design, Amounts for 1 cubic meter of concrete

Material	Weight Kg (lb)
Cement	403.2 (888.9)
Coarse Aggregate	739.1 (1629.4)
Fine Aggregate	1032.7 (2276.7)
Water	198.5 (437.6)
Total	2373.5 (5232.6)

Fig. 1 Hooked-end Dramix 4D 65/60 BG Steel Fiber (Bekaert 2023)

Table 2 Dramix 4D Steel Fiber Characteristics and Geometry

Material properties	
Nom. Tensile Strength	1600 MPa (232.060381 ksi)
Strain at ultimate strength	200,000 MPa (29,000 ksi)
Geometry	
Fiber Family	4D
Length (l)	60 mm (2.3622 inch)
Diameter (d)	0.9 mm (0.035433 inch)
Aspect ratio (l/d)	65

2.2 Cylinders test

All cylinders have been tested at the age of 28 days, the average results being 28.6 MPa (4150 psi) for the concrete cylinders with 0 steel fiber and 31.9 MPa (4625 psi) for concrete cylinders with 41.5 Kg/m^3 (70 lb/cy) 4D steel fiber. Figure 2 shows the failure shape of the compressive test of concrete cylinders.

3 Case study and design

3.1 Case study

The assumption of this research was taking a research topic from a continuous concrete bridge consists of simply supported concrete girders spaced 162 cm (64 inch) center to center and cast in place concrete deck of 21.6 cm (8.5 inch) thickness. The research topic assumed a bridge consisted of three pre-cast concrete girders and 484 cm (190 inch) by 142 cm (56 inch) cast-in-place concrete deck, then half scale

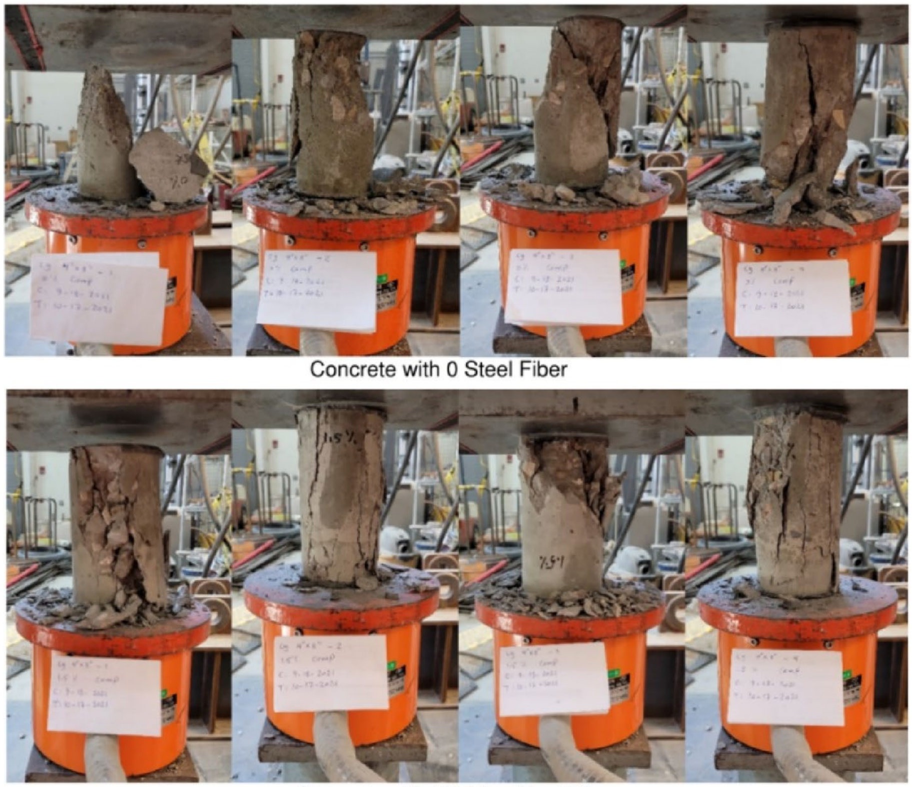

Fig. 2 Compression Test, 0 and 41.5 kg/m^3 (70 lb/cy) Steel Fiber

has been assumed (50% scale) for handling and testing purposes, therefore, the final dimensions of the deck were 81 cm (32 inch) center to center girders spacing, 10.8 cm (4.25 inch) concrete deck thickness, 242 cm (95 inch) by 71 cm (28 inch) concrete deck, as shown in Fig. 3.

3.2 Specimen design

3.2.1 Conventional bars reinforced concrete deck (RC).

Two specimens of cast-in-place concrete decks have been designed and reinforced by conventional reinforcement, designed per AASHTO LRFD method. #3 and #4 reinforcement bars were used as main reinforcement considering dead load, future wearing load, and HL-93 truck as live load, (see Table 3 and Fig. 4).

3.2.2 Steel fiber reinforcement concrete deck (SFRC)

Two cast-in-place concrete decks were designed and reinforced with steel fiber as the main reinforcement and wire mesh. 41.5 kg/m^3 (70 pounds per cubic yard) of Dramix 4D 65/60 BG steel fiber was used in the concrete mixture as the main reinforcement with two layers of 15.25 × 15.25 × 0.6 cm (6-inch by 6-inch by 1/4-inch) wire mesh as a distribution reinforcement (see Fig. 5).

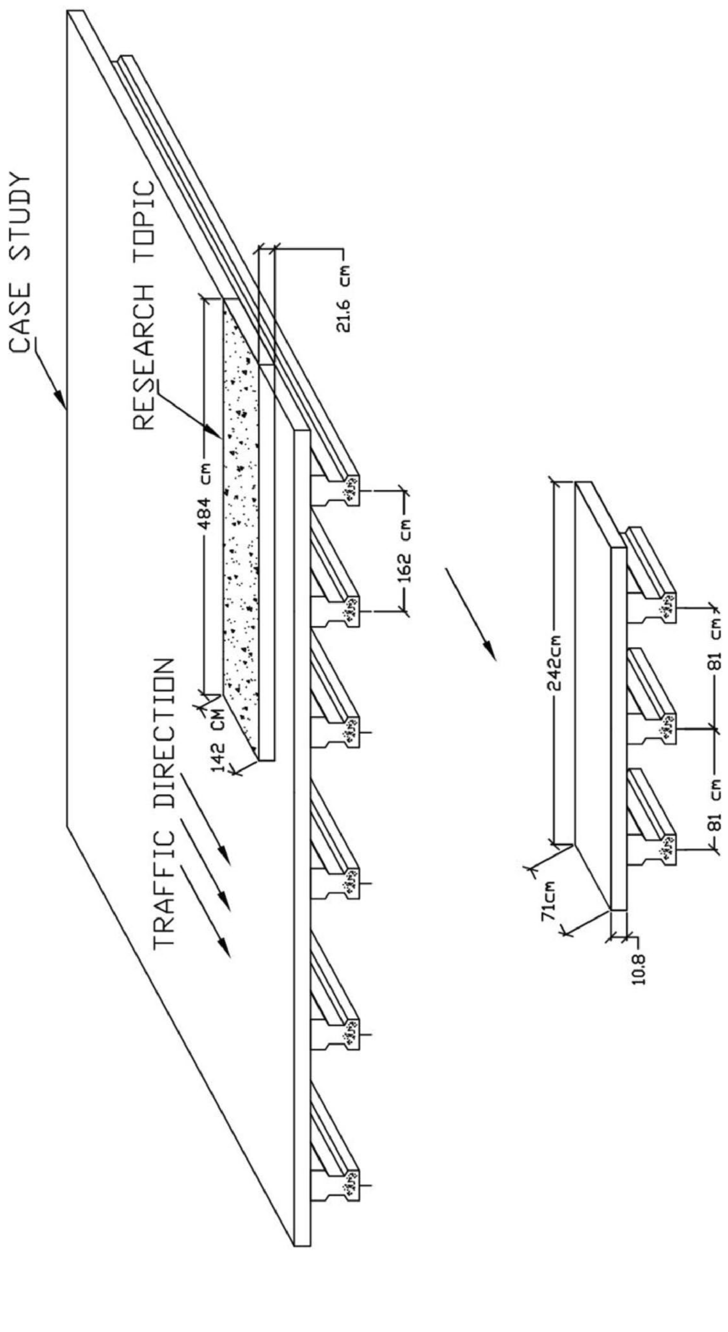

Fig. 3 Case Study

Table 3 AASHTO LRFD reinforcement for RC Decks

Moment location	Reinforcement
Positive moment reinforcement (+M)	#4 @18 cm (7 inch)
Negative moment reinforcement (-M)	#4 @ 13 cm (5 inch)
Distribution reinforcement	#3 @ 18 cm (7 inch)
Shrinkage and Temperature reinforcement	#3 @ 30 cm (12 inch)

4 Test procedure

All specimens were tested at the age of 28 days in the Civil Engineering Laboratory Building at University of Texas at Arlington. Specimens were placed under the 180 Ton compressive machine to apply the load. The load was applied on the center of the concrete deck and then distributed to the middle of each span through a load distributed steel beam as a concentrated load. 5 cm (2-inch) thickness of steel plates have dimensions of 25.4 cm (10-inch) length (perpendicular to the direction of travel) by 12.7 cm (5-inch) width were between the distribution load beam and deck top surface, the dimensions of the plate represented 50% scale of AASHTO LRFD tire contact area (American Association of State Highway and Transportation Officials (AASHTO) 2014, 3.61.25). The load cell was applied between the load distributed steel beam and the 180 Ton machine. Linear Variable Differential Transformer (LVDT) have been set up in mid of each span to measure the change in deflection with the changing of loads. Strain gauges have also been installed in the middle of each span at the bottom surface of the deck to measure the strain with the applied stress. All strain gauges, LVDTs, and load cell are connected to the Data Acquisition System (DAS) to collect the readings during the load test as shown in Figs. 6 and 7.

5 Results and discussion

All the outcomes have been recorded during the test including Load–displacement data (P-Δ), maximum loads, stresses, strains, initial cracks, and crack width, the average results of four spans of two concrete decks that contained steel fiber reinforcement (SFRC-1), and (SFRC-2) showed a difference in behavior compared with the average results of four spans of two decks that were reinforced with conventional reinforcement (RC-1), and (RC-2) as follow:

5.1 Load – displacement characteristics

The values of load–displacement (P—Δ) were measured in this study for all specimens by using load cell and LVDT devices, the displacement was recorded at the mid-span of each spacing between girders of all decks, the comparison measured (% increasing rate) were estimated by Eq. 1.

$$\%\ increasing = \frac{X\mathrm{SFRC} - X\mathrm{RC}}{X\mathrm{RC}} \tag{1}$$

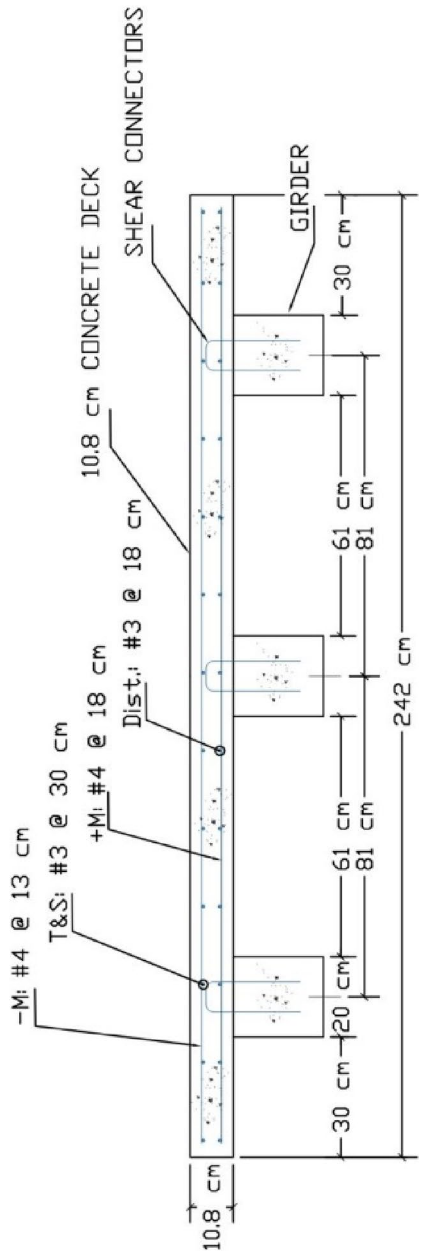

Fig. 4 AASHTO LRFD Concrete Deck Design

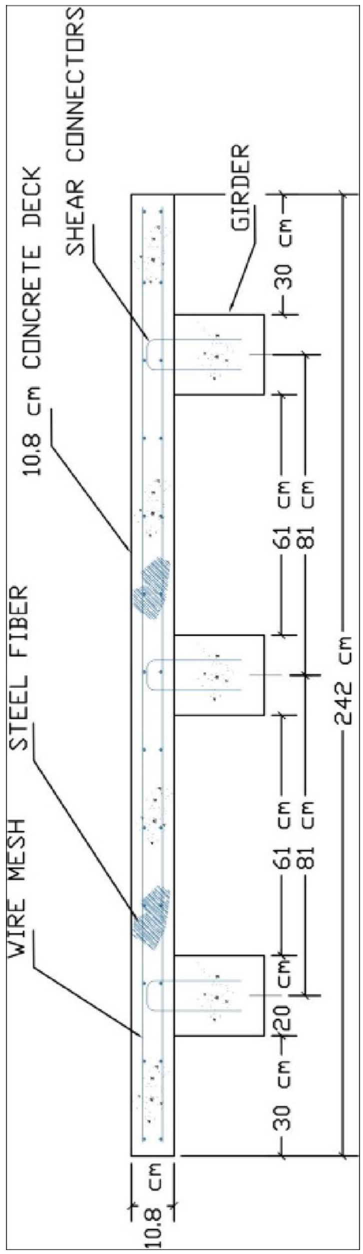

Fig. 5 Steel Fiber Concrete Deck Design

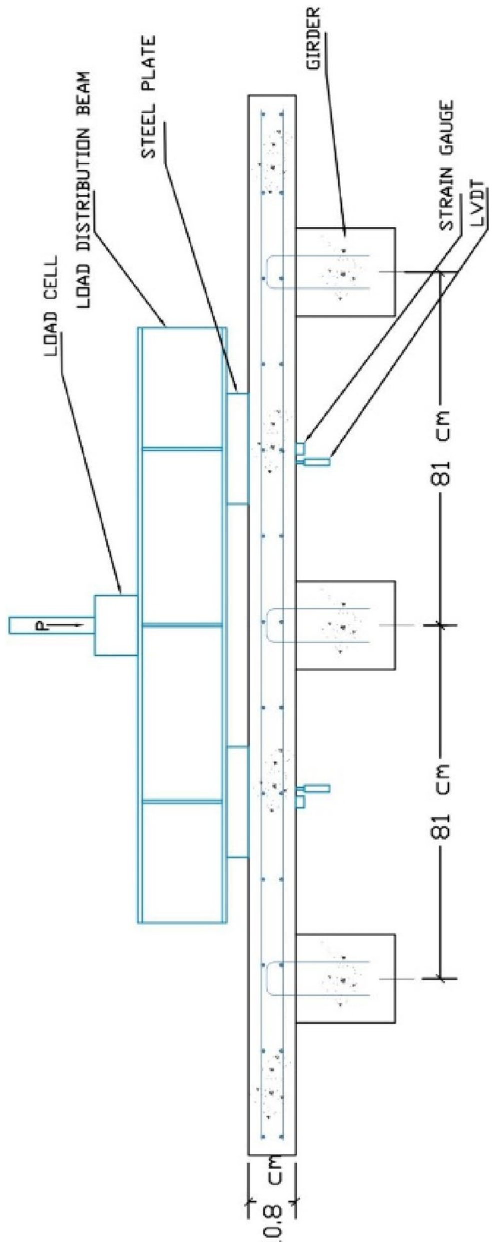

Fig. 6 Schematic Testing Setup

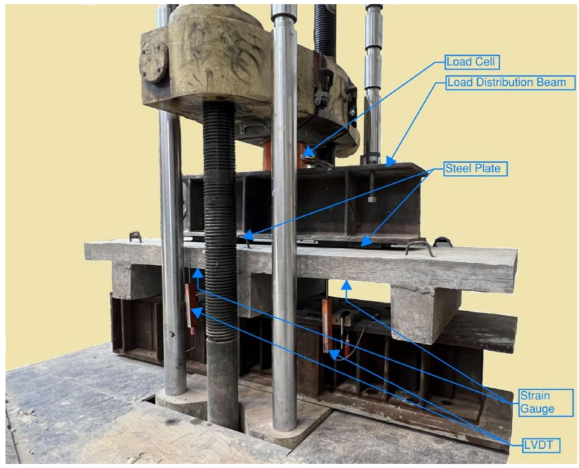

Fig. 7 180 Ton Machine, Test configuration

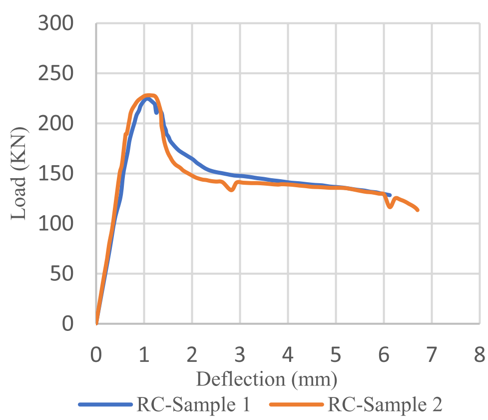

Fig. 8 SFRC Decks Load–Deflection Curve

where X_{SFRC}, X_{RC} are values of load capacity, stiffness, and energy of SFRC and RC decks respectively.

The average ultimate load of RC decks was 227 KN (51 Kips) while the average ultimate load of SFRC decks was 255 KN (57 Kips), meaning that the ultimate load capacity of SFRC was improved by 12.3%. The average maximum deflection of RC was 6.45 mm (0.25 inch), while the maximum deflection of SFRC was 7.40 mm (0.29 inch) before failure, meaning the SFRC decks exhibit more ductile behavior than RC decks (Figs. 8 and 9). Additionally, the area under the load–deflection curve represents the absorbed energy, (Spadea et al. 1997) suggested an equation (Eq. 2) to compute the energy ratio (ductility index μ_E) for RC and SFRC decks as shown in Fig. 10.

$$\mu E = \frac{\text{Etot}}{\text{E75\%Pmax}} \quad (2)$$

where μ_E is the ductility index, E_{tot} is the total energy, $E_{75\%Pmax}$ is the energy of 75% of the maximum load.

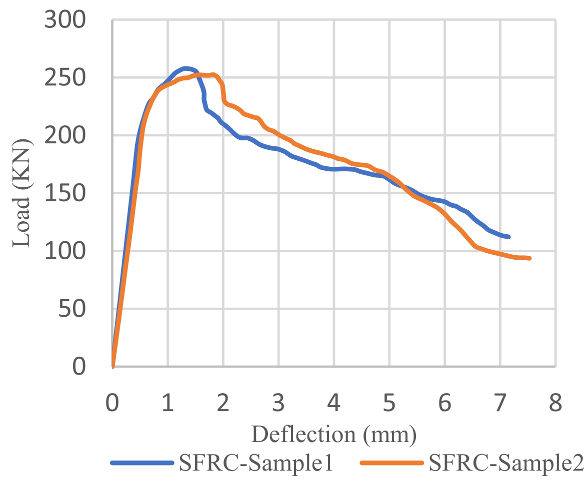

Fig. 9 Ductility index estimation curve

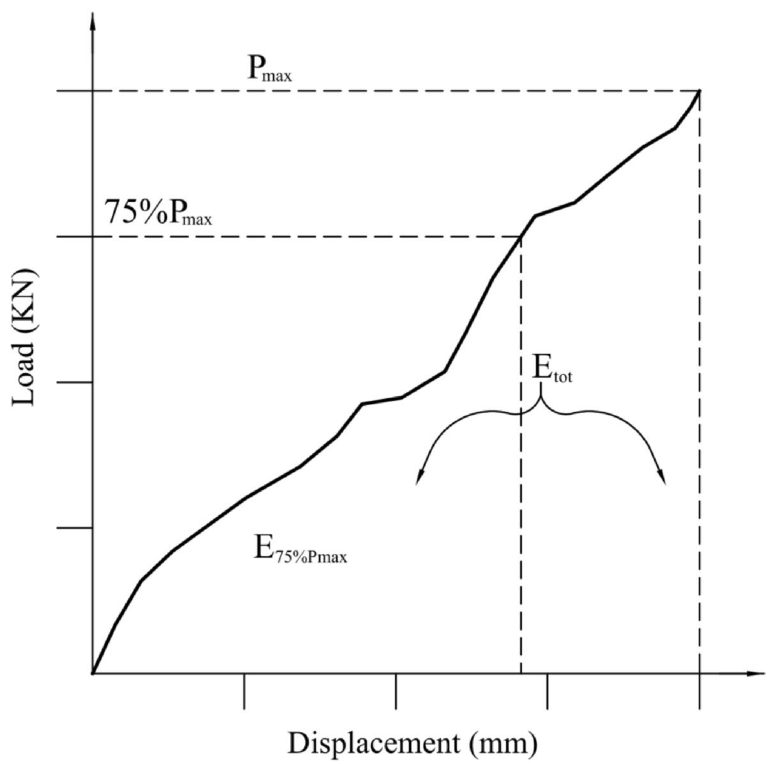

Fig. 10 RC Deck Load–Deflection Curve

The ductility index was calculated from the load–displacement curves by applying Spadea's equation. The μ_E values of SFRC decks were measured and compared with RC decks. Table 4 shows that utilizing steel fiber in concrete decks has improved energy absorption and ductility by 191.2%.

5.2 Stress–strain

Stress–Strain values were measured by installing load cell and concrete strain gauges, strain gauges were installed at the bottom of the mid-span of each spacing between girders of all decks. In SFRC decks where the highest strength was reported, a

Table 4 Absorbed Energy and Ductility Index

Deck ID	Δ_{max} mm	P_{max} KN	$\%P_{increase}$ KN	E_{tot} KN.mm	$E_{75\%Pmax}$ KN.mm	$\%E_{tot}$ Increasing	μ_E	$\%\ \mu_{E\ Increasing}$
RC1	6.2	226.0	12.3	141.6	47.3	99.8	2.99	191.2
RC2	6.7	228.0		169.8	52.2		1.34	
SFRC1	7.2	258.0		254.9	47.7		5.34	
SFRC2	7.6	252.0		367.4	50.3		7.30	

significant strength was achieved since steel fibers contributed remarkably to concrete cracking strength as well as the overall compressive and tensile strength. The ultimate stress recorded indicated that the influence of hooked-end steel fiber was greater than those caused by the conventional reinforcement. Figures 11 and 12 show the stress–strain curves of RC and SFRC decks respectively, with the average ultimate stress of RC

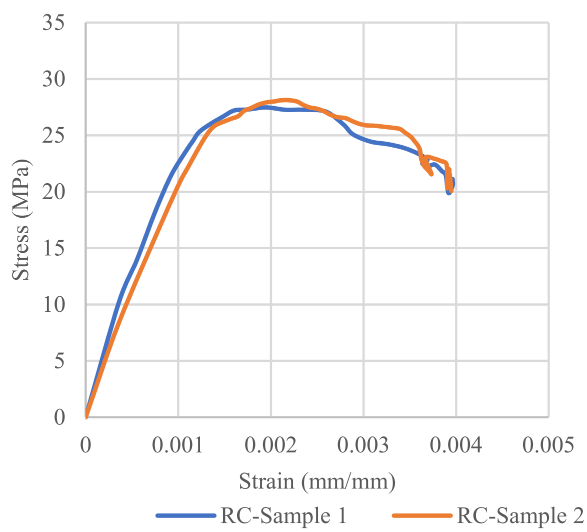

Fig. 11 RC Decks Stress–Strain Curve

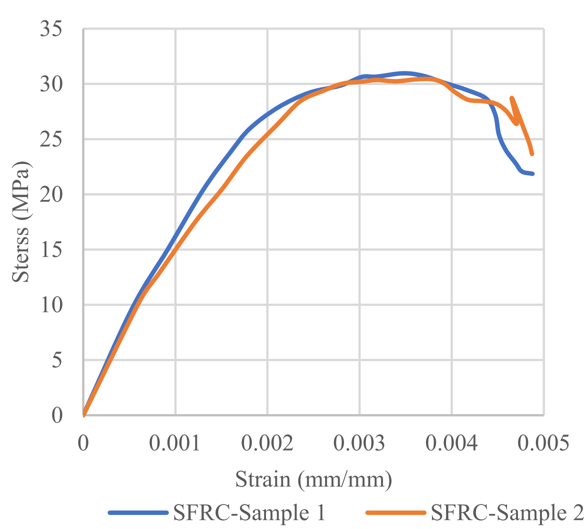

Fig. 12 SFRC Decks Stress–Strain Curve

Table 5 Stress–Strain values

Deck ID	Stress $_{max}$ MPa	%Stress $_{increase}$ MPa	Strain $_{max}$ mm/mm	Area $_{under\ the\ curve}$ Area Unit	%Area $_{increase}$
RC1	27.5	11.8	0.0039	17.6	27
RC2	28.5		0.0039	17.7	
SFRC1	31.5		0.0048	22.6	
SFRC2	31.1		0.0048	22.3	

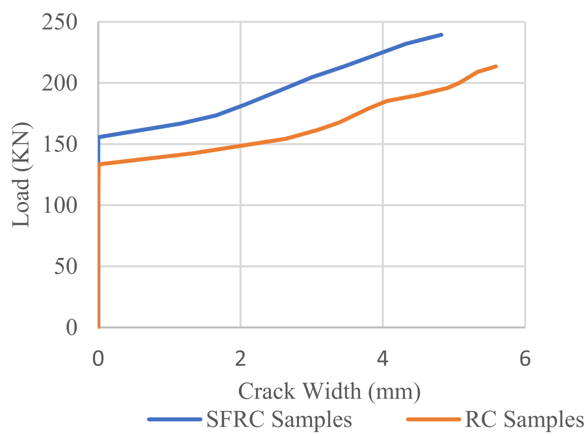

Fig. 13 Load vs. Crack width

decks being 28.0 MPa (4061 psi) while the average ultimate stress of SFRC decks was 31.3 MPa (4540 psi), in another meaning, the ultimate stress of specimen SFRC decks marked an increase reach (11.8%) as compared to RC decks (see Table 5). Moreover, the area under the SFRC curve is larger than the area of the RC curve by 27%, this means the energy has been absorbed and carried by the decks since the SFRC decks behaved as a more ductile material, it was able to deflect and absorb more energy before failure.

5.3 Crack width

It was also noticed that SFRC decks exhibited more ductile behavior than the RC decks, thus, the main first cracks in SFRC decks arose after the RC decks. During loading, crack progress was recorded for all loading steps' a specific crack was identified and its width was measured in all specimens. The main cracks were located at the bottom of the mid spans of each deck (positive moment) and at the top of the deck near the edge of the girders (negative moment), (load vs. crack width curve shown in Fig. 13), Furthermore, as loading continued, the crack started appearing at the load of 155.6 KN (35 kips) for SFRC decks while it started appearing at the load of 133.4 KN (30 kips) for RC decks, moreover, the crack width in SFRC decks reached a maximum of 4.8 mm (0.19 inch) with the maximum crack width being 5.59 mm (0.22 inch) on the RC decks. Based on the experimental work results of this study, utilized steel fibers in the concrete mixture had a substantial effect on resisting crack initiation and growth; steel fibers improved

Fig. 14 RC Decks Failure Mode, and Cracks

Fig. 15 SFRC Decks Failure Mode, and Cracks

concrete tensile strength, thus minimized the crack's maximum width by 14%. Figures 14 and 15 shows the failure of RC and SFRC concrete decks respectively.

6 Conclusions

The evaluation of utilizing Dramix 4D steel fiber as a mine reinforcement in bridge decks and the comparison with the conventional reinforcement have been studied in this research. The conclusion of utilizing steel fibers significantly improved the overall structural behavior of the SFRC decks as follows:

- The average ultimate load capacity of SFRC was improved by 12.3%.
- The SFRC decks exhibit more ductile behavior than RC decks since the maximum deflection was greater than the deflection of the RC decks.
- The absorbed energy by SFRC decks is more than the reference decks (RC decks). The SFRC decks exhibited more ductile performance, which carried higher energy relative to the RC decks. The ductility index (μ_E) significantly increased by 191.2%.

- Steel fibers were more efficient at improving tensile strength and bending behavior. The crack widths were less than the RC decks by about 14%. Steel fiber delayed the initial main cracks in all SFRC decks. Thus, this improves the resistance of concrete decks against traffic and environmental influences.
- The average ultimate Stress capacity of SFRC was improved by 11.8%. The area under the stress–strain curve of SFRC decks was greater than the RC decks by 27%, meaning the absorbed energy was higher.
- Utilizing steel fiber improves the opportunity for economical implementation by speeding up construction since it requires fewer work hours and requires less future maintenance since it is significantly less corrosion compared to conventional reinforcement (Tran et al. 2011).

Abbreviations

DAS	Data Acquisition System
E_{tot}	Total energy
$E_{75\%Pmax}$	Energy of 75% of the maximum load
LVDT	Linear Variable Differential Transformer
μ_E	Ductility index
RC	Conventional reinforced concrete deck
SFRC	Steel fiber reinforced concrete deck
X_{SFRC}	Values of load capacity, stiffness, and energy of SFRC decks
X_{RC}	Values of load capacity, stiffness, and energy of RC decks

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Authors' contributions

RA provided the experiment procedure, number of samples, dimensions of samples, concrete mix design and reinforcement design, SK made the formworks of the samples, reinforcement works, concrete casting, concrete curing, samples test, data collection, data analysis and interpretation, and was a major contributor in writing the manuscript, both authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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