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Flexural Behaviour of Two Ribbed SFRC Slab Reinforced with GFRP Bars

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Abstract

This study presents the results of an experimental investigation on the application of steel fibres (SF) in combination with glass fibre reinforced polymer (GFRP) bars as the steel reinforcement replacement in a ribbed slab structure. The promising ability of steel fibre reinforced concrete (SFRC) to reduce the formation of cracks and increase the tensile strength of concrete has made it an attractive composite material for numerous civil construction applications. However, previous research had shown that the performance of the steel fibres on their own to replace steel reinforcements is still in doubt. Therefore, the GFRP bar is chosen due to its structural performance with flexural reinforcement with less weight and corrosion resistance. The influence of the steel fibres and GFRP bars on the two-ribbed slab flexural performance was investigated. Three (3) numbers of slab panels were cast, consisting of one solid SFRC slab (solid-SF), one SFRC ribbed slab (rib-SF), and one SFRC ribbed slab reinforced with GFRP bars (rib-SF-GFRP). All slab samples measuring 1000 mm x 1500 mm x 75 mm thickness were tested under bending and the results showed that the SFRC ribbed slab reinforced with GFRP (rib-SF-GFRP) is efficient in the flexural performance by exhibiting the highest first crack and ultimate load.

Keywords: *Flexural behaviour, GFRP bars, SFRC, ribbed slab*

1. Introduction

Efforts have been continuously made to enhance the knowledge of concrete behaviour and, ultimately, to improve the structural and material performance of concrete. In that effort, research was initiated on steel fibre in concrete mixes to combine or replace with rebar (Abdul Rahman et al., 2017; Abdul Rahman et al., 2012; Ahmad et al., 2019). Steel fibres act as crack arrestors during the initial loading phase and increase the energy necessary for crack propagation, holding the concrete matrix intact under loading. The steel fibres that are distributed in the matrix will help to distribute microcracking, thereby enhancing the splitting tensile and flexural strengths (Li et al., 2021). In addition, the glass fibre reinforced polymer (GFRP) bar is widely used in the construction industry due to its many advantageous properties, including its light weight, strength, flexibility, corrosion resistance, and high impact resistance (Alex et al., 2022a & 2022b). FRP applications include either the replacement of steel reinforcing bars with glass fibre reinforced polymer (GFRP) or the use of FRP bars to strengthen structural beams or slabs. Meanwhile, the introduction of ribbed slabs suited the need to reduce the quantity of concrete structures. A ribbed slab functions similarly to a standard slab but is lighter and more rigid than an equivalent flat slab. Using ribbed slabs results in a reduction of the structure's self-weight and more efficient use of materials, steel, and concrete, thereby reducing the load on the foundation.

In contemporary construction, ribbed flat slabs, also known as waffle slabs, are increasingly used to reduce dead weight and maximise the efficiency of lateral load distribution. Typically, two-way ribbed slabs consist of monolithic beams spaced at regular intervals in perpendicular directions. The applications are diverse, including architectural applications for large rooms such as auditoriums, theatre halls, and showrooms where column-free space is the primary requirement (Mosley et al., 2012). The ceiling's square or rectangular voids may be utilised for concealed architectural lighting. According to clause 3.6.1.3 of BS8110-Part 1 (British Standards Institution, 2004), the rib spacing should not exceed 1.5m centre to centre, and the rib height should not exceed four times the rib width.

Samsudin et al. (2018) studied two and three-ribbed SFRC slabs. The outcome indicates that the maximum load capacity of a two-ribbed slab is greater than that of a three-ribbed slab, thus a higher strength capacity. Two ribbed slabs have less deflection than three ribbed slabs. Thus, the results open for an opportunity for additional research to determine its applicability in the modern construction industry. SFRC was studied to be both economical and highly practical, as it is simple to place, mix, and compact using standard techniques (Abdul Rahman et al., 2012). Steel fibres incorporated into conventional reinforced concrete members can increase the impact resistance and local damage of conventional RC members. It can also prevent the widening and growth of cracks and increase ductility and compression strength under earthquake and blast loads (Patnaik & Adhikari, 2012). Upon cracking, the steel fibres in case of self-compacting FRC continue to carry and distribute stresses. Steel fibres that are by intention randomly disperse throughout the fibre concrete, bridge the internal microcracks and distribute the loads, thus contributing to the cohesiveness of the material (Mohamed et al., 2019).

Steel fibres are divided into five (5) groups according to BS EN 14889-1 (British Standards Institution, 2006), including cold-drawn wire, cut sheet, melt extracted, shaved cold drawn wire, and milled from blocks. To ensure the effectiveness of the steel fibre incorporation and to maximise the contribution to the structural application, it is crucial to consider the fibre geometry, aspect ratio, volume fraction, and distribution (Soulioti et al., 2011). This is especially true when considering the effects on the workability of the concrete mix. The higher surface area is the result of the steel fibre shape, which is longer than the size of the aggregates. Additionally, the steel fibres' stiffness alters the granular skeletal structure by forcing particles that are larger than the fibre length apart, increasing the porosity of the mixture. The flow of the mix was significantly impacted by the steel fibres' different surface properties from those of the cement and aggregates (Grünewald & Walraven, 2009). The strength and elastic modulus of the concrete, as well as the interface between the fibres and the matrix, also influence the effectiveness (ACI_Committee_544-96, 2002).

The type of steel fibre varies according to the material's fibre strength, fibre shape (such as fibres with or without hooks), fibre geometry (length and diameter), and surface fibre characteristics (rough, smooth, or deformed). Although there are numerous types of steel fibre, hooked-end steel fibre is the most effective and widely used. To achieve a stronger bond between fibres and matrix, however, it is crucial that the steel fibre is adequately anchored in the matrix. Therefore, steel fibres with a hooked end are utilised to resolve the issues. According to (Abdallah & Rees, 2019), the pullout value of physical testing for hooked-end steel fibres indicates that the fibres' maximum capacity is reached as they pull through. This indicates that at high deformations, the fibres reach their full capacity. This results in greater energy absorption and necessitates ductility to prevent brittle failure. Abdul Rahman et al. (2012) analysed the effectiveness of steel fibres by employing steel fibres with hooked ends as the primary reinforcement to enhance adhesion and anchorage within the cement matrix. The ability to stitch or bridge cracks in structural members is dependent on the length of the steel fibres' hooked ends. Therefore, the optimal length of the hooked-end steel fibre should be selected in order to maximise the structural components' strength. This investigation revealed that the ultimate load of the slab and wall panels is increased 50% when using steel fibres with hooked ends.

At hardened state research agrees that hooked end fibres could contribute to better concrete (Abdul Rahman et al., 2012; Pajak & Ponikiewski, 2013; Soulioti et al., 2011). The application of hooked-end steel fibres has the ability to contribute to a higher maximum load of samples. Furthermore, it also contributes to the improvement of flexural tensile strength as compared to straight fibres (Pajak & Ponikiewski, 2013). The inclusion hooked end fibres showed better behaviour by having a gradual load decrease upon achieving the ultimate load. On the other hand, the inclusion of straight steel fibres resulted in a sudden load drop after the ultimate load (Pajak & Ponikiewski, 2013). Soulioti et al. (2011) compared the effectiveness of hooked end fibres to the waved type and reported that it resulted in higher toughness and residual strength values by exhibiting deflection hardening behaviour. The maximum achieved load was observed to be higher with the inclusion of hooked end fibres as compared to the straight ones and it also increases linearly with the increase of the volume fraction (Madandoust et al., 2015; Pajak & Ponikiewski, 2013).

Kim and Kim (2019) investigated hybrid FRP-steel reinforcement in structural members such as a beam. The study found that the load of the specimens with FRP bar and reinforcing bars employed as tensile reinforcements was gradually increased to the maximum strength as the FRP bar resisted the extra loads even after the rebar began to yield. Specimen with FRP reinforcement that had a low elasticity modulus, at its yield strength, had a displacement that was more than 3.5 times greater than the specimen with steel reinforcement. Additionally, the FRP-reinforced specimen produced more cracks. A study by Adam et al. (2021) indicated that the GFRP bars bonded in a reinforced concrete slab can improve the loading-carrying capacity, deflections, and ductility when using small diameters, which increased the bond between concrete and bars.

Chang and Seo (2012) tested simply-supported FRP-reinforced concrete slabs to evaluate the deflection of members in bending. The tested GFRP-reinforced slabs behaved in bilinear elastic until failure. It can be seen that the stiffness of the slabs reinforced with GFRP bars was significantly reduced after the initiation of cracks in comparison to the steel-reinforced slabs. Studies also suggested that higher reinforcement ratios are needed to ensure enough flexural stiffness for deflection control (Chang & Seo, 2012; Wiater & Siwowski, 2020).

Based on previous studies, most researchers explored the potential of steel fibres and GFRP bars individually. However, a very limited study was done in a combination of both materials to observe its potential performance. Thus, this paper will be discussing on the results of the experimental investigation on ribbed slab sample that is reinforced with both steel fibres and GFRP bars. The objective of this research is to examine the flexural behaviour of ribbed SFRC slabs with and without GFRP bars, as well as the effect of steel fibres and GFRP bars as reinforcements within the SFRC slabs.

2. Materials and Methods

According to BS1881 (British Standard Institution, 1997 Edition), there are five stages involved in the design of a concrete mix: target water-cement ratio, free water content, determined cement content against specified maximum or minimum value, total aggregate required, and selection of fine and coarse aggregates. Table 1 presents the amount of water, cement, fine and coarse aggregate, and steel fibre required to prepare 1m^3 of concrete slabs. According to the calculation, the target compression strength of concrete must be reached 30 N/mm^2 at 28 days.

Table 1: Concrete mix design for SFRC

Cement (kg/m^3)	Water(kg/m^3)	Sand (kg/m3)	Coarse aggregate (kg/m^3)	20% of Steel fiber (kg/m^3)
373.125	223.875	779.284	991.816	40.310

The experimental program consists of casting of three (3) numbers of Steel Fiber Reinforced Concrete (SFRC) slabs: a solid SFRC slab (solid-SFRC), a ribbed SFRC slabs (rib-SFRC), and a ribbed SFRC slab with GFRP bar (rib-SFRC-GFRP). The cross-sectional dimensions of the slabs are depicted in Figure 1(a) – (c), meanwhile Figure 2 shows the plan view of the slab. Figure 1(a) – (c) depicts the cross-sectional view of all SFRC slabs with the dimension of 1500 mm length, 1000 mm width, and 75 mm depth. All samples were reinforced with hooked-end steel fibres with a diameter of 0.75 mm and 60 mm in length as shown in Figure 2. The aspect ratio of the steel fibres is 80 with a minimum tensile strength of 1100 MPa.

Figure 2: Hooked-end steel fibres

The rib-SF-GFRP samples were reinforced with GFRP bars in each rib along its length. The GFRP bar with a diameter of 10 mm and lengths of 1300 mm and 250 mm was arranged to resemble the arrangement of B3 mesh rebar. Figure 3(c) shows the configuration of GFRP bars. Two sets of GFRP bars were used to construct the two-ribbed slab with GFRP bars in each rib. The tensile strength is 249 MPa, the modulus of elasticity is 200 GPa and the Poisson ratio of the GFRP bar is 0.32.

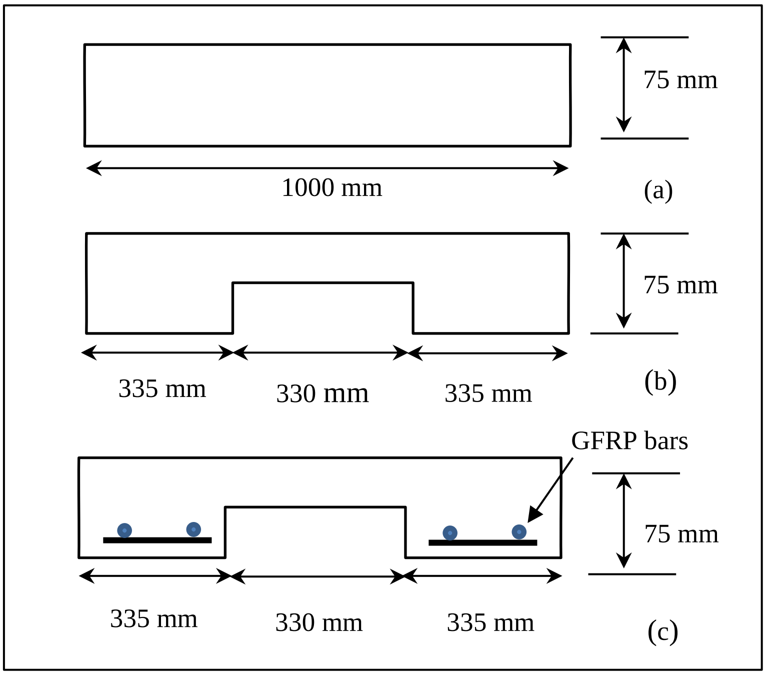

Figure 3: The cross section of (a) solid-SF (b) rib-SF and (c) rib-SF-GFRP

The flexural strength test was conducted on all specimens after 28 days of curing. Before testing is conducted, all specimens were painted in white color for clear visibility of cracks. All the specimens were tested using the flexural testing procedure. The 1000 kN Universal Testing Machine in the Heavy Structure Laboratory, UiTM Shah Alam was used to conduct the flexural strength test. The arrangement of loading distributed using a steel distributor along mid - span of slabs is shown in Figure 3 and 4.

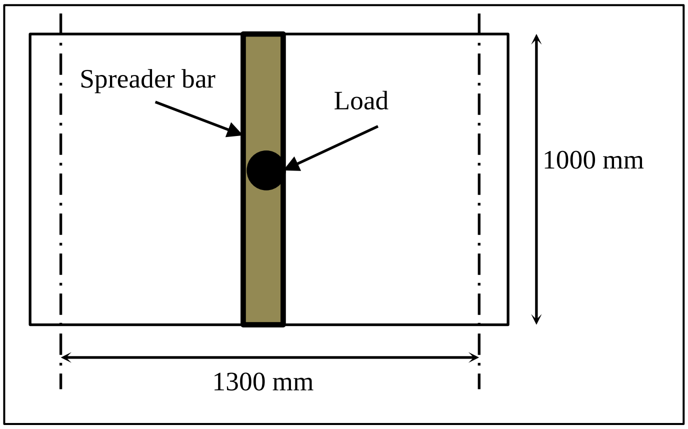

Figure 2: The plan view of SFRC Solid and Two Ribbed Slab

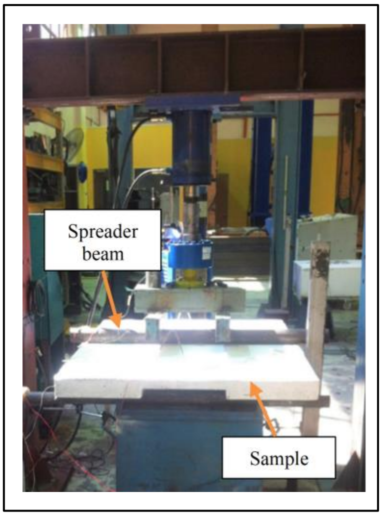

Figure 3: Sample tested under three-point load set-up

This study determined the maximum load and deflection of the two-ribbed SFRC slab with GFRP bars. Therefore, the formulas from ACI 435R-95 (American Concrete Institute, 1995) were used to calculate the deflection of two-way slabs to determine the deflection. This method is based on the crossing beams analogy, where the deflection of the middle panel is calculated as the sum of the deflections of the column and middle strips. Equation 1 presents the appropriate formula.

$$\delta = \frac{KW\ ln\hat{}4}{384EcIe}$$

Where, K = Factor to account for span boundary conditions and can be taken as 1.4 for interior panels and 2.0 for exterior panels without edge beams, W = Uniformly distributed load, kN/m, ℓn = Clear span (mm), E_c = Modulus of elasticity of concrete, N/mm^2, I_e = Effective moment of inertia, mm^4

Prior to being presented in this form, the formula has undergone the process of derivation. This formula can be used to determine the deflection of numerous structural elements. Due to the fact that the maximum deflection depends on the element's shape and material, it can also be applied to other elements with varying forms and compositions. The magnitude of deflection is proportional to the applied loads on the structure. Consequently, the deflection of the structural member will increase as the applied load increases. In order to complete the formula, it is necessary to first determine the modulus of elasticity and the moment of area.

3. Results and Discussion

All samples were tested under static loading conditions, and the result of the experimental work shows a slight difference. However, the use of steel fibres with hooked ends is highly effective in improving the mechanical properties of all slab samples. In addition, the experimental results for each slab sample are compared to their theoretical calculations.

Compressive test, tensile test, and three-point load test results were obtained. The solid-SFRC control slab was tested to determine the effect of the rib on the slab. To gain a greater understanding of steel fibre, the performance of steel fibre was investigated, with a focus on the effect of steel fibre on slab deflection. In addition, the rib-SFRC-GFRP bars were evaluated to determine the effect of the GFRP bars on the final product, as compared to the rib-SFRC sample. Three slab samples were examined and tested in order to gain an understanding of hooked-end steel fibres, GFRP bars, and ribbed slabs by comparing their results. In the future construction industry, all the results may be used as a guide for the design of ribbed slabs or structural components with the presence of steel fibre and GFRP bars as a combined reinforcement material.

3.1. Compressive and tensile strength

The compressive strength test of the concrete cube was conducted to determine the cube's strength after 7, 14, and 28 days of curing. The size of the concrete cubes, which are 150 mm x 150 mm x150mm, was determined by the design mix. For each test, three cubes of concrete were prepared. The table displays the average result of the cube test, which indicates that the compressive strength increases as the number of curing days increases. Typically, the increase in compressive strength after 7, 14, and 28 days represents %, 90 percent, and 99 % of the 28-day strength, respectively (Table 2).

Table 2: Compressive strength at 7, 14, and 28 days

Days	Weight (kg)	Density (kg/m^3)	Maximum loading, P (kN)	Compressive strength, f_c (N/mm^2)
7	8.15	2.40	768.57	34.16
14	8.17	2.40	947.87	42.13
28	8.15	2.40	1003	44.58

The tensile test was performed to measure the ultimate stress, strain and the deformation of glass fiber reinforced polymer (GFRP) bar. The fracture of the GFRP bar is also determined. The young modulus of GFRP bar given by the manufacturer is 200 GPa. The manufactured tensile strength of GFRP bars with10 mm diameter is 249 MPa. However, based on the tensile result, the tensile strength is 428.049 MPa as shown in Table 3 which is a relatively comparable value.

Table 3: Tensile test results for GFRP bars

	Load (kN)	Stress (MPa)	Deformation (mm)	Strain (%)
Maximum	33.619	428.049	12.3	4.103
Break point	29.827	379.771	12.4	4.144
0.2% yield strength	30.539	388.835	9.8	3.28
Upper yield point	5.833	74.264	1.4	0.483

3.2. Flexural strength test

The flexural strength test was carried out based on BS EN 12390-5:2019 (2019). This test focuses only on concrete slabs or beams to resist failure in bending. The flexural bending test also known as the modulus of rupture is the ability of materials to resist under a certain load that is usually transverse loading until the structures fracture or yield.

3.2.1. First crack load

Table 4 shows the first crack load and the percentage difference of the sample compared to the control solid SFRC slab and two ribbed SFRC slab respectively.

Table 4: Percentage difference of first crack loads

Sample	First crack load, kN	Different % of the sample to Control solid SFRC slab	Different % sample to Two ribbed SFRC slab
Solid-SFRC	4.6	-	61.4
Rib – SFRC	2.85	38	-
Rib – SFRC - GFRP	5.3	15.2	85.9

The rib-SFRC-GFRP sample has a maximum initial crack load of 5.3 kN. This value indicates that the flexural strength of the two-ribbed SFRC slab is increased when reinforced with GFRP bars. The embedded GFRP bars' strength enables the slab to withstand loads of up to 6.95 kN. The first crack develops in the load-bearing centre of the slab. The first crack load difference between rib-SFRC slab and a solid-SFRC slab is approximately 15.2 percent. In addition, the first crack load of rib-SFRC-GFRP slab increases by approximately 85.9 % compared to rib-SFRC slab. According to the findings of [12], steel fibre has a significant effect on the tensile strength of concrete at 28 days. Even small amounts of steel fibre can affect the toughness of a material. As the concrete's abrasion resistance increases, the cracking resistance also increases.

3.2.2. Ultimate load capacity

The experimental study determined that the ultimate load capacity of the solid-SFRC slab is 5.01 kN, which is greater than that of the rib-SFRC slab. The variance of the solid-SFRC slab is 58 percent greater than the variance of the rib-SFRC slab. Nonetheless, the rib-SFRC-GFRP slab demonstrates the greatest ultimate load capacity when compared to the solid-SFRC slab and the rib-SFRC slab. The ultimate load capacity of two rib-SFRC-GRFP slabs was recorded to be 6.95 kN. Due to the ability of GFRP bars to strengthen the two ribbed SFRC slab while reducing corrosion and reducing the slab's self-weight, the slab is improved by 119.2 percent when GFRP bars are used. Table 5 displays the percentage variation in ultimate load for each SFRC slab sample.

Table 5: Percentage difference of ultimate of all slabs

Sample	Ultimate load, kN	Different % of sample to Solid-SFRC slab	Different % sample to rib-SFRC slab
Solid-SFRC	5.01	-	58
Rib – SFRC	3.17	36.7	-
Rib – SFRC - GFRP	6.95	38.7	119.2

3.2.3. Load vs deflection of SFRC slabs

The solid-SFRC slab, a rib-SFRC slab and rib-SFRC-GFRP slab were tested, and based on the results obtained from the experimental work, the graph of load vs deflection has been plotted as shown in Fig. 4 and the result of load vs deflection was summarized in Table 6.

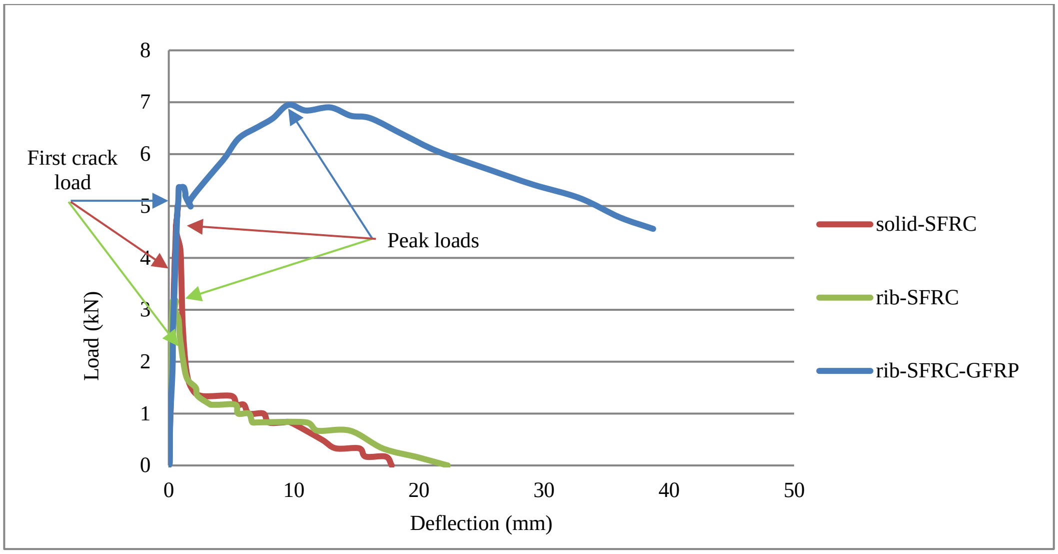

Figure 4: Load versus deflection of the samples

Table 6: Results of load vs. deflection (magnitude and values)

Sample	Maximum Load, kN	Maximum Deflection, mm	Range curve behave elastic, kN
Solid-SFRC	5.01	0.68	0-4.5
Rib – SFRC	3.17	0.64	0-2.8
Rib – SFRC - GFRP	6.95	9.57	0-5.25

The rib-SFRC-GFRP slabs behave very differently than the other slab. This slab behaves linearly up to 5.25 kN (elastic range from A to B) before the onset of the first cracks after point B. The load decreases to 5.09 kN possibly due to the appearance of the first cracks in the slab. This slab resists the greatest load during the elastic state compared to the other slab. Due to the young modulus of elasticity and the strength of the GFRP bars embedded in the slab, this is the case. Thus, the GFRP bars began to yield, the load was increased until the maximum load the slab could sustain occurred in the plastic deformation region (B-C), and the slab experienced rupturing (D) prior to failing.

Failure of the solid-SFRC slab and the rib-SFRC slab is primarily due to brittle cracking and not the plastic mechanism depicted in the B-D graph pattern. Moreover, the rib-SFRC-GFRP slabs failed due to the plastic mechanism (B-D) because GFRP bars were present. The load behaviour in the ascending branch of all tested slabs is characterised by three load stages: initial crack load, service load, and ultimate load.

In general, SFRC slab behaviour can be divided into two stages. Prior to the onset of cracking, the behaviour of all SFRC slabs was approximately linear and identical. The subsequent stage is the post-cracking stage, during which cracks were initiated and developed, resulting in a decrease in the slabs' stiffness and a change in the behaviour of SFRC slabs. Compared to two ribbed SFRC slabs with a lower steel fibre content, the control solid-SFRC slab with a high steel fibre content increased in stiffness. However, the stiffness of the rib-

SFRC-GFRP slab is the greatest due to the presence of steel fibres and GFRP bars.

3.2.4. Theoretical and experimental result of deflection

Table 7 compares the deflection of the control solid-SFRC slab, rib-SFRC slab, and ribbed SFRC slab reinforced with GFRP (rib-SFRC-GFRP) bars based on experimental and theoretical results. The experimental result for the deflection of a rib-SFRC-GFRP slab is 88 percent greater than the corresponding theoretical result. The obtained result is unexpected due to the large percentage difference. In the presence of GFRP bars, which have relatively higher tensile strength but lower stiffness, deflections are likely to be greater than for equivalent steel-reinforced units. According to (Wiater & Siwowski, 2020) the deflection of concrete slabs reinforced with GFRP bars increases significantly more rapidly after cracking than concrete slabs reinforced with steel bars. In addition, to determine the deflection theoretically, the deflection formula of the slab is shown in Equation 1.

Table 7: Comparison of experimental and theoretical results

Samples	Mid Span Deflection (mm)		Difference (%)
	Experimental	Theoretical	
Solid-SFRC	0.72	0.766	6.0
Rib – SFRC	0.64	0.6	6.67
Rib – SFRC - GFRP	9.57	1.15	88

3.2.5. Strain distribution of the ribbed SFRC slab with GFRP bars

Figure 5 displays the distribution of strain for the SFRC and GFRP bars. The load versus strain curve reveals that the GFRP bar and SFRC behave differently at first. In tension up to 69.84 m/m, the strain distribution of GFRP bars behaves in a linear elastic manner. In compression, as opposed to tension, the strain distribution of SFRC behaves linearly elastically at -45.81 m/m and 4.67 kN. The negative value was due to the ability of the steel fibres to sustain the loads by holding the concrete matrix together in the earlier stage of loading before the emergence of the first crack. This occurs due to the distinct characteristics of SFRC and GFRP bars. Where the concrete has a high compressive strength but a low tensile strength. While the GFRP bar is strong in tension. In addition, the GFRP bars continue to behave plastically in tension from 204.48 m/m at 5.36 kN to 1553.93 m/m at 6.69 kN before reaching the breaking point. Before reaching the breaking point, the SFRC begins to behave in tension from 94.69 m/m at 5.840 kN to 709.12 m/m at 6.9 kN. This altering behaviour is due to the combination of steel fibres and concrete, where the steel fibre improves the concrete's properties and makes the SFRC compression and tension-resistant. This demonstrates that the performance of the rib-SFRC-GFRP slab is superior to that of the rib-SFRC slab and the control solid-SFRC slab in terms of strength, ductility, and toughness.

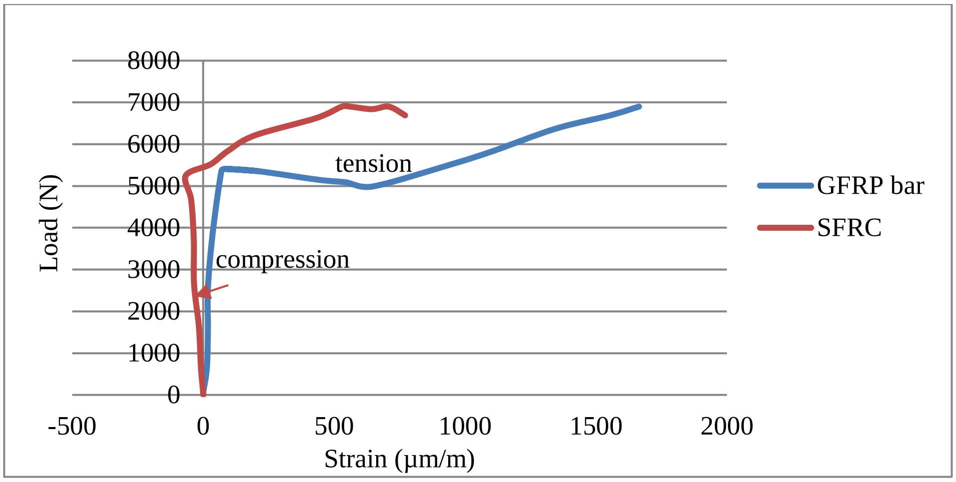

Figure 5: Load – strain curves of SFRC and GFRP bar

3.2.6. Energy absorption

The area under the load-deflection curve can be used to calculate energy absorption. The area under the curve for the two ribbed SFRC slab reinforced with GFRP bars is 1,333.82% greater than for the two ribbed SFRC slab without GFRP bars. According to Table 8, the area under the curve of two ribbed SFRC slabs with GFRP bars is 243.75 kNmm. This result demonstrates that the two-ribbed SFRC slab with GFRP bars has a high energy absorption because it has a larger area under its curve than the other slabs. Consequently, the flexural strength of the two ribbed SFRC slab with GFRP bars is also greater, and the stiffness of the two ribbed SFRC slab with GFRP bars is greater as a result of the slab's highest first-load cracks.

Table 8: Different % of energy absorption

Samples	Energy Absorption (kNmm)	Different % with Control Solid SFRC Slab	Different % with Two ribbed SFRC Slab
Control Solid SFRC slab	25.25	-	48.52%
Two ribbed SFRC Slab	17.00	32.7	-
Two ribbed SFRC Slab with GFRP bar	243.75	865.35	1333.82

The addition of steel fibres significantly improves the energy absorption or tensile strength of concrete. All of the specimens of plain concrete failed immediately after the first cracks appeared. The energy absorption capacity of fiber-reinforced concrete is approximately 10 to 40 times that of conventional concrete. The steel fibre with a hooked end absorbs more energy than its straight counterpart. The greater the energy absorption of a component, the greater its ductility. The definition of ductility is the capacity to absorb inelastic energy without sacrificing load capacity. For the safe design and strengthening of any structural element, ductility is crucial. The two ribbed SFRC slab with GFRP bars has the highest ductility in this study, followed by the control solid SFRC slab and the two ribbed SFRC slab.

3.2.7. Material consumption effect of steel fiber and GFRP bars

The control solid-SFRC slab has the largest cross-sectional area compared to the two ribbed SFRC slabs with or without GFRP bars. As the cross-sectional area increases, so does the amount of material employed. The volume of concrete used, and the weight of steel fibres are 266 kg/m^3 and 5.93 kg, respectively. Increasing the percentage of steel fibres increases both the ultimate load and the load at which cracking begins (Chang & Seo, 2012; Wiater & Siwowski, 2020). Consequently, the control solid SFRC slab can withstand a load of up to 5.01 kN before it fails. Compared to the rib-SFRC slab, this value has 36.7% greater strength. In addition, the two ribbed SFRC slab is weaker than the control solid-SFRC slab because its material consumption is less than that of the other slab samples. The volume used for steel fibre and concrete is 5.03 kg and 222 kg/m^3 respectively. Nonetheless, the rib-SFRC slab can withstand a load of up to 3.17 kN before failing.

In addition, the rib-SFRC-GFRP slab uses the same volume of concrete and steel fibre as the rib-SFRC slab but achieves the highest strength among the other slabs. This is because the GFRP bars added to the slab act as reinforcement materials in addition to the SFRC itself. Before being embedded into the slab during the casting process, a total of 6.8 metres of GFRP bars were cut and arranged according to the BRC shape of B3 size.

Figure 6 illustrates the steel fibre bridging the cracks of all slab samples and demonstrates the steel fiber's effectiveness. The effectiveness of steel fibres is contingent on the type of steel fibre used, the aspect ratio of steel fibre, the quantity of fibre, and the orientation of fibre. Observations made during the testing of all samples indicate that steel fibre performs well by absorbing tensile stress and delaying or delaying the matrix's failure. As the only reinforcement in the control solid-SFRC slab and rib-SFRC slabs, steel fibre contributes to the increase in stiffness of the slabs.

Figure 6: Steel fiber bridging the cracks of concrete

3.2.8. Mode of Failure

The mode of failure was investigated for the control solid-SFRC slab, the rib-SFRC slab, and the rib-SFRC-GFRP slab. All the slab samples exhibited a nearly identical mode of failure. Not only do steel fibres delay the deformations of cracking within the slab, but they also convert the brittle punching shear failure to a gradual and ductile shear failure. Figure 7 shows the failure mode of all samples under loading. Several types of failure are observed following the three-point flexural examination. The flexural crack appeared just beneath the loading point as a result of the slab's reduced stiffness. The cracks begin at the midspan of the slabs and then spread across their width. As the load on the slabs increases, the number of cracks also increases. When the GFRP bars fail, the flexural failure of a two-ribbed SFRC slab with GFRP bars occurs. In addition, shear failures occur in slab samples. The shear failure is observed in the slabs' thickness. Peeling failure of concrete also occurred when slabs were subjected to loads approaching failure. The first cracks to form are flexural cracks, followed by the critical shear crack. As the primary component of this slab is steel fibre, debonding between the steel fibre and concrete occurred prior to the slabs reaching their failure load. At the main cracks, which are flexural and shear cracks, steel fibre debonding occurs. The problem of debonding can be resolved by covering the entire bottom slab surface with fibre sheeting.

(a) (b) (c)

Figure 7: Mode of failure of all samples; (a) solid-SFRC, (b) rib-SFRC, (c) rib-SFRC-GFRP

4. Conclusion

This study demonstrates that steel fibre reinforced concrete (SFRC) can be a valuable structural material with its own potential and advantages for use in the modern construction industry. In terms of ultimate load capacity, deflection curve, strain distribution curve, and failure behaviour, the behaviour of rib-SFRC-GFRP slab differed from the rib-SFRC slab and the control solid-SFRC slab. Results indicate that both GFRP bars and steel fibres within the concrete play a crucial role in absorbing the subjected load. The experimental data indicates that the load capacity of two ribbed SFRC slabs with GFRP bars is less than 10 kN. Therefore, this study demonstrates that the combination of both GFRP bars and steel fibre can serve as concrete reinforcement. In addition, the two-ribbed SFRC slab with GFRP bars fails in flexural, shear, and cracking modes. Based on the experimental performance and analysis of rib-SFRC-GFRP slabs, the following conclusions are drawn:

i. The rib-SFRC-GFRP slab bars has higher ultimate load capacity of 119.2 percent and a higher deflection of 92.3 percent than rib-SFRC slab.
ii. The rib-SFRC-GFRP slab bar possesses greater strength, ductility, and toughness than the control solid-SFRC slab and the rib-SFRC slab.
iii. The use of steel fibres and GFRP bars enhanced the energy absorption and stiffness of SFRC slabs.
iv. The rib-SFRC-GFRP fails in flexural and shear modes.

Overall, it can be concluded that the combination of the two materials; i.e. the steel fibres and the GFRP bars showed a promising potential for application in the ribbed slab structure that uses less concrete material in comparison to the conventional solid slab commonly used in construction.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

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