Exploring the Performance of a Single Panel SFRC Slab under a Point Load with FE Analysis

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Abstract
This study explores the performances of a single round panel without conventional longitudinal reinforcement using a nonlinear finite element analysis (FEA) software, ABAQUS. Experimental data from an established work on a full-scale steel fibre-reinforced concrete (SFRC) panel with 1.0% fibre volume were validated using FEA. A constitutive model was used to interpret the tensile behaviour of SFRC panel, and concrete damaged plasticity (CDP) of ABAQUS deployed for both tensile and compressive behaviour of the panel. The model was relatively stiffer than the experiment. The experiment result has a failure load of 38.0 kN while the FEA failure load was 37.9kN, thou stiffer than that of the experiment. This shows the FEA simulate the behaviour of the round panel under central loading. The parametric studies were carried to investigate the impact of steel fibre on the tensile behaviour of SFRC round panel by varying the fibre volume (1%, 1.25%, 1.50%, 1.75%, 2.00% and 2.5%) and characteristic strength (30MPa, 40MPa, 50MPa and 60MPa). The results of the central displacements, yield and peak loads, strengths, ductility, strain, and crack patterns. The FEA results show that the more the fibre volume, the more the strength. The FEA was able to provide an essential performance profile of SFRC round-panel.

Keywords: Concrete, Steel-fibre, Point-load, Displacement, Round-panel

Introduction

Concrete has emerged over the years as the most used building material. It is very strong in compression and has about one-eighth of this strength in tension. The structural usage of it will require the inclusion of a material that has significant strength in tension (A. A. Abbas, Syed Mohsin, Cotsovos, & Ruiz-Teran, 2014; America Concrete Institute, 2002; J.A.O. Barros & Cruz, 2001; British Standard Institute, 1997, 2004; Crowther, 2009; T. S. Lok & Xiao, 1999). The inclusion of steel bars in the tension zone brought an improved solution which has led to the significant development in the construction industry and its acceptance in different structures elements including suspended slabs. Over the past years, these slabs were constructed by inserting rebar or welded mesh fabric in the concrete. An increasing trend to this construction method, is the replacement of some or all of the reinforcement with fibres (A. Abbas, Syed Mohsin, & Cotsovos, 2014; Ahmed, 2014; America Concrete Institute, 1999; ArcelorMittal, 2011; J.A.O Barros, Salehian, Pires, & Gonçalves, 2012; Beddar, 2004; Blanco, Pujadas, Cavalaro, de la Fuente, & Aguado, 2014; Cameron, 2002; Cerioni, Meda, & Plizzari, 2004; Chanh, 1990; Crowther, 2009; Destrée, 2001; J. Hedebratt & Silfwerbrand, 2008; McCraven, 2002; Mohsin, 2012; Rana, 2013; RILEM, 2002b; Singh, 2015; Swamy, 1974; Zollo, 1997). The replacement of rebars with fibres has proven to save construction time, lessen labour cost, improving safety on site by reducing chances of getting injured and ultimately leads to cheaper slabs when compared to the traditional reinforced concrete slabs. Various types of fibres (steel, glass, polyethene etc.) are available in the market with steel-fibres emerging as most used.

When plain concrete is subjected to loading, cracks are propagated on the tension surface. This damage first starts as a single crack when the tensile strength of the concrete has been exceeded and are thus mitigated by the introduction of fibres in the concrete matrix. With the improvement in the knowledge and understanding of steel-fibre usage in concrete in recent time, there has been a swift expansion in the construction of steel-fibre-reinforced concrete pile-supported slabs. (Beddar, 2004; British Standard Institute, 2006; Campione, 2002; Chanh, 1990; Ghaffar, Chavhan, & Tatwawadi, 2014; Jansson, 2011; Labib & Eden, 2004; Rai & Joshi, 2014).

Steel-fibre in concrete started in 1874, when Berard patented an idea in which left-overs (waste) grains of steel are mixed to concrete which led to a more ductile material (Berard, 1874). In the present world, there are many types of fibres being used in the construction industry for variety of works. Examples are natural fibres and artificial fibres (steel, carbon, polyethene, and so on), but the most used and researched on is the steel fibre. The steel fibres come in various shapes, sizes and strength (Destrée, 2007a; Zollo, 1997). The benefits of adding of steel-fibres in concrete in structural members as reported in earlier researches include (i) enhancing the post-cracking behaviour of the concrete, (ii) the significant reduction in construction time, (iii) improve tensile strength and energy absorption and, (iv) reduction in crack-width giving rise to enhanced damage tolerance (Lok & Pei, 1998; Oslejs, 2008; RILEM, 2002a). However, provisions were made for additional reinforcement to resist peak moments over piles or supports, particularly in the corner panel (Chanh, 1990; IstructE, 1999). Also, recent experimental works on real-life full-size specimen justify the possibility of fibres-only reinforced concrete (J.A.O Barros et al., 2012; Destree, 2004; Destrée, 2007b; Destrée & Jürgen, 2008; Jerry Hedebratt & Silfwerbrand, 2014; Khan, Ansari, Saroj, Haider, & Kulkarni, 2016; Lee, Cho, & Choi, 2017; Najim, Saeb, & Al-Azzawi, 2018; Ragi, 2015; Vollum, 2007)

The absence of a generally accepted code or standard method for the design and analysis of SFRC slabs has led to development of design guidance based on elastic and yield-line analyses for suspended SFRC slabs (Eddy, 2008; The Concrete Society TR63, 2007; Vollum, 2007) and some national guidelines (America Concrete Institute, 2002; British Standard Institute, 2006; INRC, 2007; A. C. Institute, 2011; NZS, 2006). Likewise, manufacturers of steel-fibres came up with their design guidance as provided by Bekaert and ArcelorMittal, which are the principal suppliers of steel fibres (Dramix® and TAB-Structural system) in the UK. The Bekaert design method (Viney, 2007) uses the elastic moment coefficient of the Dutch Code NEN 6720 and is thus similar to TR 63 guidelines (Concrete-Society, 2007). The ArcelorMittal proprietary method, on the other hand, uses steel fibres to completely replace all traditional reinforcement (Destrée & Jürgen, 2008). Concrete is a composite material with pores and micro-cracks caused by shrinkage, expansion and thermal strains, which have been restrained by coarse aggregates and boundary conditions. During loading, the concrete matrix transfers part of the load to the fibres before any macro-crack is formed. With continuous loading, the micro-cracks will then start to expand and ultimately lead to a macro-crack which covers numerous micro-cracks (J. A. O. Barros, 2004; Bernardi, Cerioni, & Michelini, 2013; Kooiman, Veen, & Walraven, 2000; Richardson, 2008; Tlemat, Pilakoutas, & Neocleous, 2006).

This study aims at exploring the performance of a single panel steel-fibre reinforced concrete (SFRC) slabs under point-load with finite element analysis. The experimental work of R. de Montaignac, et al., (2011) Round Plate was explored. Parametric studies were carried out and their results compared to the numerical investigations and existing experimental data with current design guidance. This research work is limited to a single suspended slab over three supports at angle 120^0 apart.

Methodology

The post-cracking behaviour of SFRC structural elements was the thrust of their research works. The experimental work involves simply supported beams and round-plates consisting of six (6) specimens for each SFRC mix with varying amount of steel fibres (0.75-1.25%). The mechanical properties of the SFRC round-plate (labelled F35-1.0) chosen for this study in compression made was made from 1% volume fraction of fibres are compressive strength 46.9MPa, modulus of elasticity 33.5GPa and Poisson ratio of 0.23 while the post-cracking tensile strength of 2.6MPa was gotten from the uniaxial test. The hooked-end steel-fibre used in the concrete matrix has an aspect ratio of 67.2 and a length of 35mm. The strength of the steel fibre is 1200MPa.

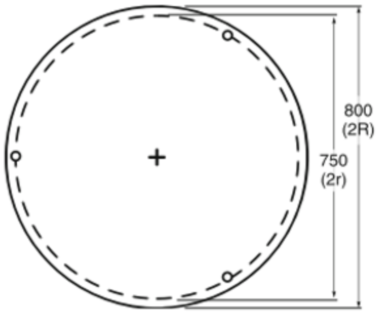

Figure 1: Dimensions of Round-Plate adapted from (de Montaignac, Massicotte, Charron, & Nour, 2011)

NLFEA were carried out in 3D using the ABAQUS and Lok and Xiao constitutive models. Taking advantage of the high-performance computer in University of East London, UK, the full size of the round-plate was modelled (i.e. 800 mm in diameter, 750 mm clear distance and 80 mm thick). Round steel sections were used to mimic the supports to prevent localised failure. A depiction of the plate model is shown in Figure 1. Calibration was done to validate the numerical model using the respective experimental data. The parametric study involves both the fibre volume (V_f) and concrete strength (f_{ck}) being changed. The experiment was conducted with 1% V_f. The slab was modelled using V_f values of 1%, 1.25%, 1.50%, 1.75%, 2.00% and 2.5%. Also, f_{ck} used in the experiment was 46.9MPa and for the parametric study f_{ck} used are 30MPa, 40MPa, 50MPa and 60MPa.

As earlier stated, the displacement-based loading was applied at the centre of the round plate. To guide against localised failure, a steel plate, 10mm thick was modelled for the loading rig. Based on the sensitivity analysis earlier done, a mesh elements size of 25 mm width was adopted, which produces the most suitable agreement with experimental data. To avoid distortion in the meshing, the wedge was used to restrain an uneven mesh pattern. The loading was applied gradually until failure using a displacement-based loading control. The following NLFEA results are at this moment discussed following sections.

Result and Discussion

Load-Displacement Diagrams

Figure 2 shows the Load-displacement curve for various values of V_f given that the f_{ck} for the experimental work was used. It clearly shows that as the fibre volume ratio increases, the peak load also increases. To further examined the response of the round-plate to apply loads, different amount of characteristic strength of concrete are considered. This is to determine the dependency of peak load with characteristic strength of concrete.

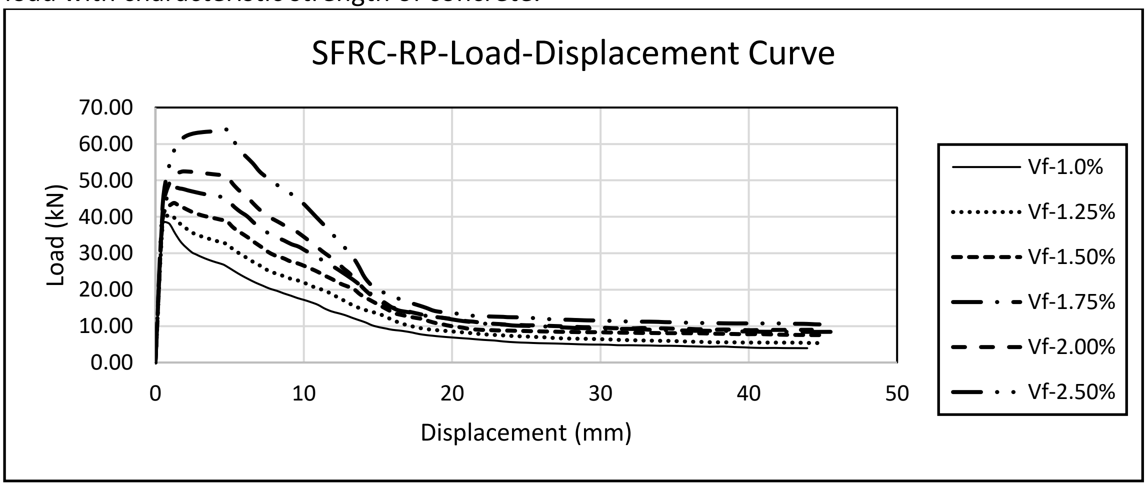

Figure 2: Load-Displacement Curve for a range of V_f

The result shows that round-panel with 1% fibre volume ratio yielded 38.21kN, while that of 2.50% fibre volume is 57.11kN in control. As the fibre volume is increased, there is a gradual increase in the yield load. There is also an increase in the stiffness as the fibre volume increases. The strength of the slab was also enhanced as the fibre volume increases. An 18% and 22% increment in strength was obtained in the slab when the fibre was increased to 1.25% and 1.5% respectively. Incidentally, all the FEA results for the displacement at the yield point give 0.51mm, which is 67% lower than the experimental result.

The load-carrying capacity of the slab was enhanced as the fibre volume is increased as shown in the load-displacement curves. This simply translates into, the higher the fibre volume, the higher the strength of the round plate to resist applied load. Both the experiment and FEA with 1% volume fibre failed at 38kN. As the fibre increases, the maximum load also increases. The FEA produces a slab that is less stiff as that of the experiment. This can be attributed to the stiffness in the FEA results. The strength and ductility ratios were also measured. There is a significant increase in the strength ratio and a decrease in the ductility ratio. Also, as the fibre volume fraction content increases (from 1.75% - 2.50%) a gentle plateau was observed that is relative to the peak load. The "plateau" was more obvious in beams with higher fibre volume ratio than in ones with small fibre dosage. This is due to the influence of the amount of fibre in the post-cracking phase of the slab. The yield and peak loads increase gradually as the f_{ck} increases.

Strength

The results show the panels after cracking occurred to demonstrate a sharp but controlled load reduction followed immediately by a post-cracking hardening phase which then changed gradually to smooth load reduction. After the matrix has cracked, a hardening response occurred when the peak load was approaching, followed by a gradual reduction in load as the crack width increases. The fibre volume ratios influence can be observed clearly as the fibre content increases. The Figure 3 shows the responses of the SFRC round panel at yield and peak loads in respect of different f_{ck}. The yield and peak loads increase gradually as the f_{ck} increases. This is due to the influence of the amount of fibre in the post-cracking phase of the slab.

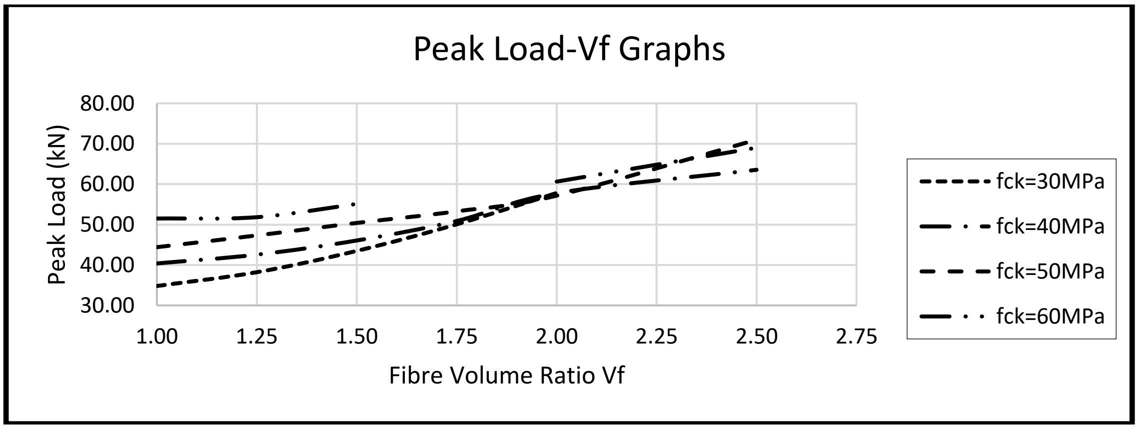

Figure 3: Peak load and Fibre Volume Ratio Graphs for f_{ck}

The displacements at yield loads are about the same for all the fibre volume ratios of different characteristic strengths are seen in Figure 4. This can be attributed to the fact that the linear part of the load-displacement graph (from zero to the point of yield load) is guided by the material properties of the SFRC matrix. In this part, the steel fibres place little or no role in the resistance of the load. They are resisted by the concrete matrix.

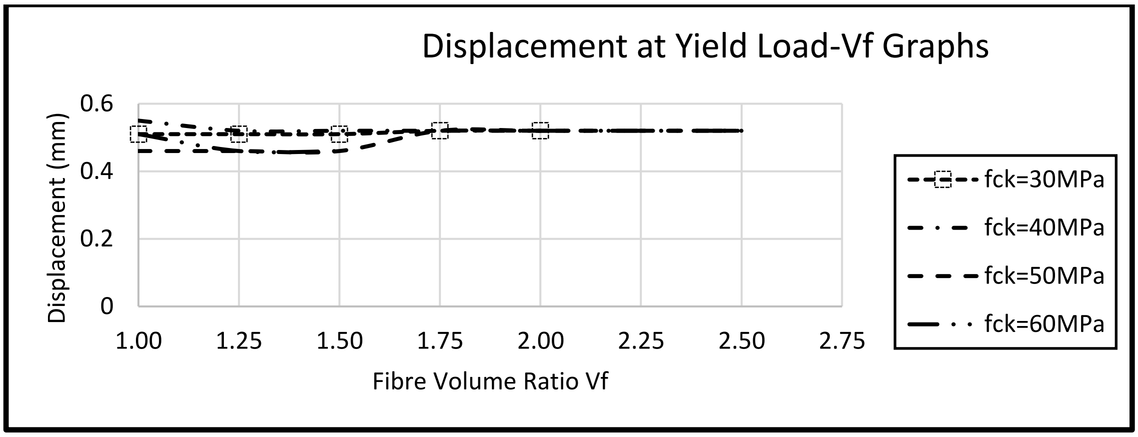

Figure 4: Displacement at Yield load and Fibre Volume Ratio Graphs for f_{ck}

At the peak load, the steel-fibre improves the resistance to load (Figure 5). There was a jump in the displacement from 1.50% to 2.00% in f_{ck} less than 50MPa. The peak load in 60MPa strength was a gentle slope from 1.00% to 2.50% fiber volume ratio.

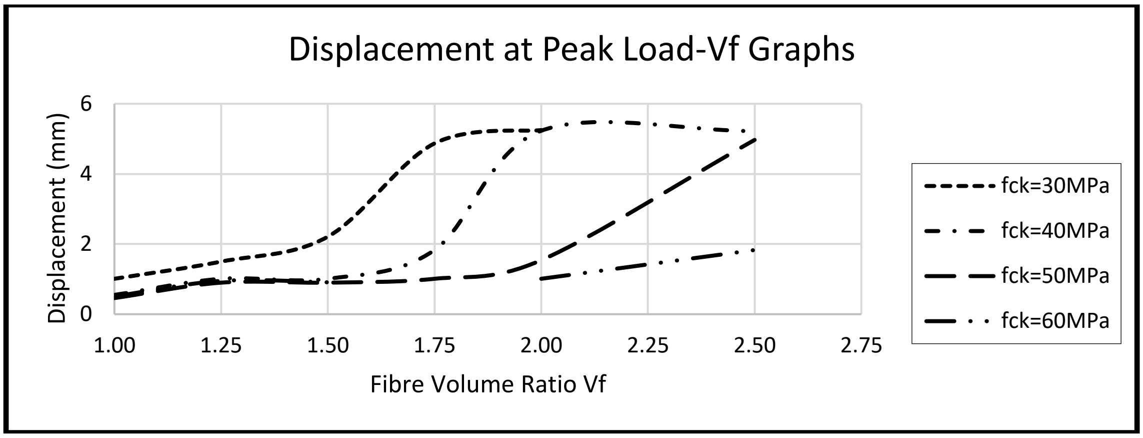

Figure 5: Displacement at Peak load and Fibre Volume Ratio Graphs for f_{ck}

Ductility

The ultimate displacement (δ_u) taken at the ultimate load (P_u) is used to measure the ductility of the Round-plate panels. The ultimate load (P_u) represents the (post-peak) residual strength at failure. A softening behaviour of the load-deflection response accompanies the rise in ductility. The residual strength was found to be sufficiently low (<85%) in all cases studied, suggesting that the softening is very significant. Consequently, to ensure practicality of these ductility levels, the residual strength was limited to a minimum of 85% of the load-carrying capacity (P_{max}). To truly utilise the resulting increase in ductility for the design purposes, it is vital to maintain the residual strength at a tolerable level.

The ductility of the Round-Plate panels can be determined based on the ductility ratio $\mu = {}^{\delta_u}\!/_{\delta_y}$ which shows that the addition of fibres leads to enhanced ductility ratio of the SFRC RP panels significantly. However, as the fibre volume fraction exceeds a crucial value, the addition of fibres beyond this value does not increase the ductility of the RP panel.

Deflected Shapes

A graphic presentation of the deflected shapes for the round-plate analysed at failure are given in Figures 8. The results are in agreement and have similar patterns with a substantial deflection at the round-plates' mid-span and a collapse along the weakest plane.

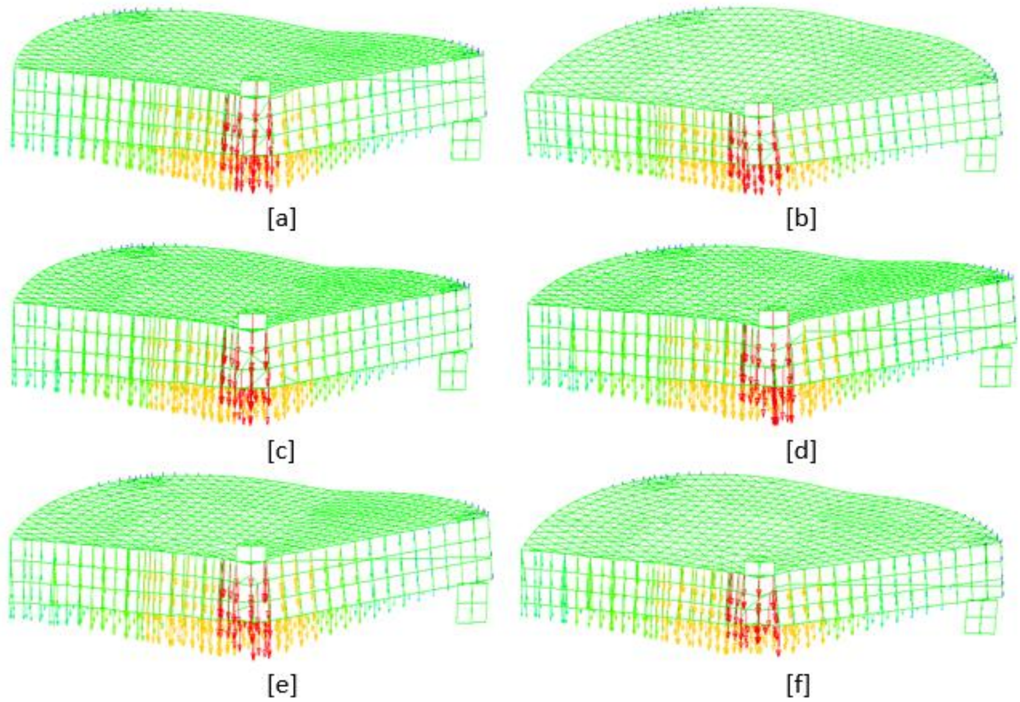

Figure 8: Deflected Shapes (y-y) for the round-plate with V_f = (a) 1.00% (b) 1.25% (c) 1.50% (d) 1.75% (e) 2.00% and (f) 2.50%

Comparative Study with Experimental Results Using Non-Dimensional Ratios

Comparisons are made between the round-plates analysed with various fibre volume and the experimental result serving as a control in this part. The normalisation of strength, ductility and energy absorption were obtained by dividing their values with the corresponding values of the experimental results. This will create a better understanding of the SFRC round-plates on isolated supports. Thus, conclusions were made on the potential of increase in fibres volume to be used for higher load bearing capacity in round-plates.

Strength Ratio

Figure 9 shows the ratio between each round-plate maximum load and that of the round-plate used in the experiment($^{P_{max}}/_{P_{maxc}}$). The graph shows that there is an enhancement in the strength of the round-plate as the fibre volume ratio increases.

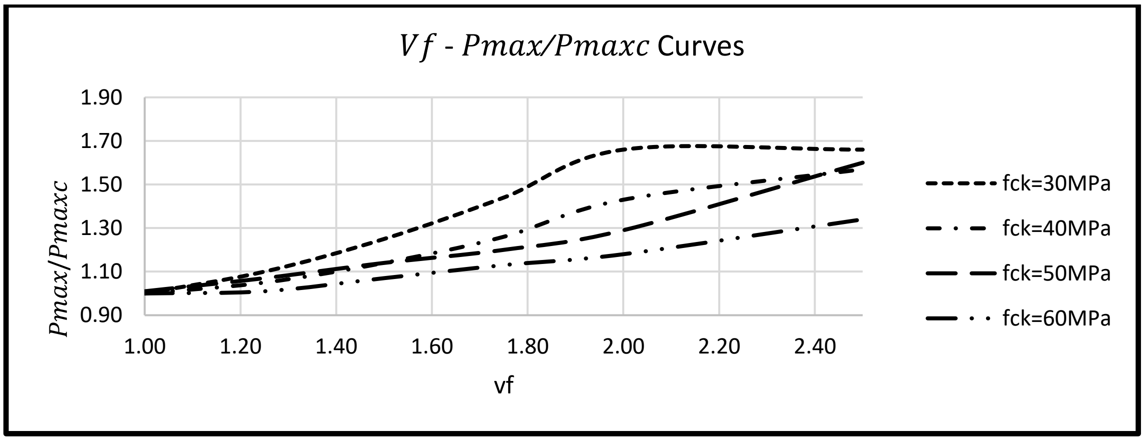

Figure 9: Graph of V_f against P_{max}/P_{maxc} for f_{ck}

The ratio between each round plate's yield load and that of the experimental round-plate $[{P_y}/{P_{ye}}]$ is represented in Figure 10. The upward trend of the graph was consistent in this figure, meaning that as the fibre increases, the yield load also increases.

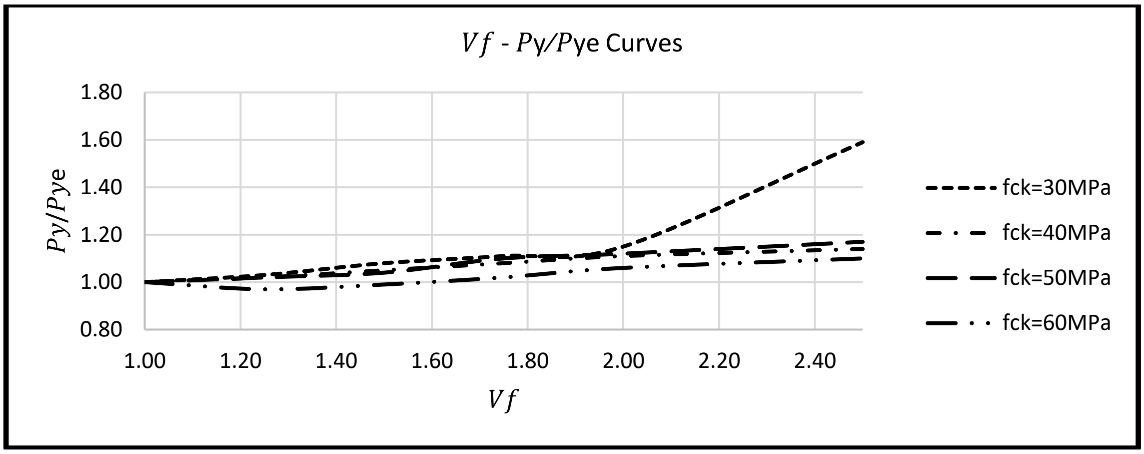

Figure 10: Graph of V_f against P_y/P_{ye} for f_{ck}

Ductility Ratio
The ductility ratios of the round-panels analysed were normalised by dividing them by the corresponding ratio of the control round plate (i.e. $\mu/\mu e$) and the results were plotted against the fibre volume fraction as shown in Figure 11. For the round plate with f_{ck}=30MPa, the ductility ratio reaches a maximum with fibre volume fraction of 1.75%. As the strength of SFRC matrix increase, the ductility ratio also increases.

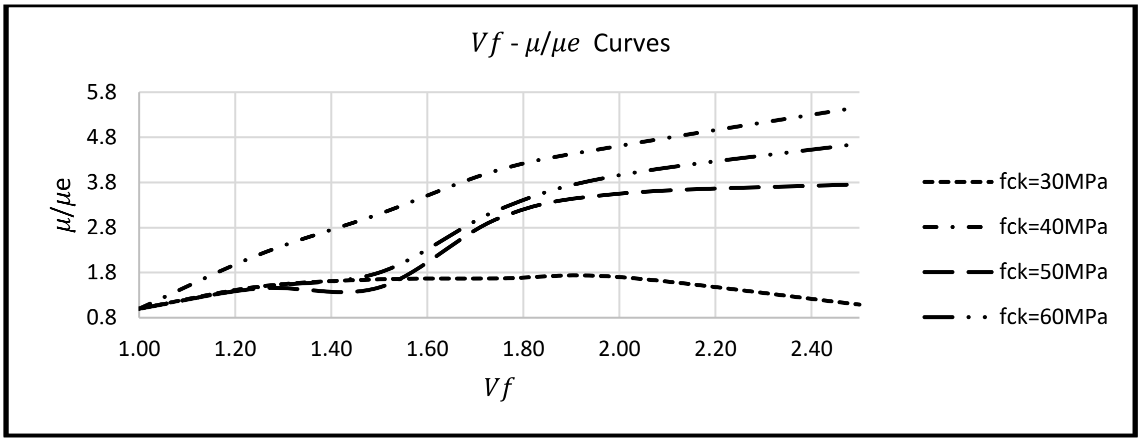

Figure 11: Graph of V_f against μ/μe for f_{ck}

Conclusions
The exploration was on round-plates with three (3) isolated supports under monotonic loads. The flexural behaviour of the round-panels was studied with fibre volume ratio V_f =1.00%. It comprises of change in fibre volume ratios and the characteristic strength of the SFRC. It was observed that the characteristic strength f_{ck} has no effect on the flexural strength f_{tu} of the matrix. This is because the flexural strength is based on certain parameters (fibre volume ratio, bond stress, length and equivalent diameter of fibre).

The exploration shows that the load-carrying capacity of the round-plates was enhanced as the volume of steel fibres increases. Likewise, the strength increases by ~7% over the previous result of the round-panel with isolated supports and ~11% for the round-plates with continuous support under monotonic loading. Also, additional fibres lead to increase stiffness which resulted in a reduction to deflections of the round-panels. The benefits of adding steel fibres are seen both at the serviceability and ultimate limit states. Reduction in crack formation was also achieved. Structurally, increase in fibres changes the failure mode to ductile failure from brittle failure, which is required in the structural design. As the fibres volume increases, ductility was improved. Interestingly, the different characteristic strengths produce an increase in ductility and strength, which shows that the higher the characteristic strength of the SFRC matrix, the higher the ductility and strength. Three cracks formed along the weakest plane, from the point of load application, which are the spaces in-between two adjacent supports.

Conclusively, it can be established that the load-carrying capacity of the plates are enhanced by the addition of steel fibres and ensures a more ductile structural response (thus avoiding a brittle failure mode), which is preferred in design. This also leads to a rise in ductility and strength enhancement.

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