



Load-Carrying Capacity of SFRC Suspended Slabs with Different Support Conditions

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Abstract. Traditionally, steel fibres have been used in ground- and pile-supported concrete slabs. More recently, the structural use of steel fibres in suspended concrete slabs is on the rise. In the present research study, the structural behaviour of suspended steel-fibre-reinforced concrete (SFRC) slabs was investigated by means of non-linear finite-element analysis (NLFEA). The numerical models were calibrated (at the material level) and validated (at the structural level) using existing experimental data. NLFEA-based parametric studies were carried out to extend the range of V_f beyond the one considered in the experiential investigations. The aim was to determine the correlation between the slab load-carrying capacity and the corresponding fibre dosage increase. This is useful for design purposes and can provide guidance on the amount of fibres needed to achieve a certain prescribed load resistance level. It was found that the addition of steel fibres improved the load-carrying capacity and changed the failure mode to a flexural ductile one. Other critical structural performance indicators were also examined such as deflections, ductility, energy absorption and cracking patterns. So, in essence both the ultimate and serviceability limit states were investigated. Comparisons with current design guidelines were also made and recommendations for improvements proposed.

Keywords: Suspended slabs · Load-carrying capacity · Design · Ductility · Validation · NLFEA

1 Introduction

Concrete in its ordinary state comprise of cement, fine and coarse aggregate, water and where required, an additive. It has emerged the most used human-made construction material of all time (Beddar 2004). Significant improvement has been recorded both in the art and usage of concrete over the years compare to when it was first used for masonry work by the Roman in which pozzolanic mortar was used as binder. Normally, concrete is strong in compression (Ali A. Abbas, Syed Mohsin, Cotsovos, and Ruiz-Teran 2014; America Concrete Institute 2002; J.A.O. Barros and Cruz, 2001; British Standard Institute, 1997 2004; Crowther 2009; T. S. Lok and Xiao 1999) and possesses about one-eighth of this strength in tension. At the application of loads, the concrete member bends and cracks at the tension face. In suspended structural members, where tension is paramount in the design, the members are constructed using

concrete reinforced with longitudinal steel rebar or welded mesh fabric. An increasing trend, both in the UK and overseas, in the method of construction, is the replacement of some or all the reinforcement with fibres (A. Abbas, Syed Mohsin, and Cotsovos 2014; Ahmed, 2014; America Concrete Institute 1999; ArcelorMittal, 2011; J.A.O Barros, Salehian, Pires, and Gonçalves, 2012; Beddar 2004; Blanco, Pujadas, Cavalaro, de la Fuente, and Aguado 2014; Cameron, 2002; Cerioni, Meda, & Plizzari, 2004; Chanh, 1990; Crowther, 2009; Destrée, 2001; J. Hedebratt & Silfwerbrand, 2008; McCraven, 2002; Mohsin, 2012a; Rana, 2013; RILEM, 2002b; Singh, 2015; Swamy, 1974; Zollo, 1997).

1.1 Historical Background

Once cracking stresses are reached, an unreinforced concrete matrix fails in a brittle manner. This is due to its brittleness and lack of post-cracking resistance. Fibres have been found to enhance the ductility of concrete, by carrying stresses beyond matrix cracking and thus improve the structure's integrity and ability to accommodate deformations. The use of SFRC in construction of different types of structural system has recently been explored. This type of slab is generally designed as pile-supported or Elevated SFRC (Destree 2004)

In 1874, an American, A. Berard patented an idea in which grains of steel left-overs (waste) are mixed to the concrete to create a material that is more ductile (Berard 1874). Today, different types of fibres are used in the construction industry for structural and non-structural works. Examples are steel, carbon, polyethylene, natural fibres and so on, but the most researched on is the steel fibre. Earlier researches revealed the advantages of adding steel-fibres in concrete in structural members and these include [i] enhancing the post-cracking behaviour of the concrete regarding more ductility which leads to an increase in flexural strain capacity, [ii] the significant reduction in construction time (since they are conveniently cast in large pours compared to time to lay the traditional reinforcement); [iii] improve tensile strength and energy absorption and, [iv] reduction in crack-width giving rise to enhanced damage tolerance (T.-S. Lok and Pei 1998; Oslejs, 2008; RILEM, 2002a). Though, in some early works on SFRC provisions were made for rebar to resist peak moments over piles or supports, notably in the corner panel, and to control cracks due to early-age thermal stresses and then it was concluded that it will be better to not have steel-fibres only reinforced concrete (Chanh, 1990; IstructE 1999). However recent experimental works on full-size specimen have shown that there can be fibres-only reinforced concrete (J.A.O Barros et al. 2012; Destree 2004; Destrée 2007b; Destrée and Jürgen 2008; Jerry Hedebratt and Silfwerbrand 2014; Khan, Ansari, Saroj, Haider, and Kulkarni 2016; Lee, Cho, and Choi, 2017; Najim, Saeb, and Al-Azzawi, 2018; Ragi 2015; Vollum 2007)

Earlier studies carried out by (J. A. Barros, Cunha, Ribeiro, and Antunes 2005; Beckett 2004; Cameron 2003; Destrée 2001; H Thooft 1999) only consider a low range of volume fibres fraction and are restricted to certain types of structural arrangement due to time and financial limitations. These studies are mainly experimental, which does not have the advantage of implementing full parametric examinations such as the one carried out in this present research work. In time past, in order to control cracking and improve on the tensile strength of ground supported slabs, fibre were been added

(America Concrete Institute 2002; J.A.O. Barros and Figueiras, 2001; Beddar 2004; British Standard Institute 2006; Chanh, 1990; Chen, 2005; Crowther 2009; Eddy 2008; Edgington, 1973a; Ghaffar, Chavhan, and Tatwawadi, 2014; Jansson, 2011; Narayan, 2014; Swamy and Lankard, 1974; Zollo 1997). There have been tremendous works on numerical investigations on ground-supported slabs (Ali A Abbas, Pavlović, and Kotsovos 2004; J.A.O. Barros and Figueiras, 2001; Cerioni et al. 2004; Maya, Fernández Ruiz, Muttoni, and Foster, 2012) and minimal numerical investigation works on piled floors.

1.2 Design Methods

The existing design methods are either based on analytical material properties of SFRC established from tests on small beam specimens or empirically based on full-scale testing. General design guidelines are based on both elastic and yield-line analyses to calculate peak moments (Eddy 2008; The Concrete Society TR63 2007; Vollum 2007) alongside some national guides (America Concrete Institute 2002; British Standard Institute 2006; INRC 2007; Institute, 2011; NZS 2006). Proprietary design guidance were also 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) relies on the elastic moment coefficient of the Dutch Code NEN 6720 and is thus similar to TR 63 guidelines (Concrete-Society 2007). Only uniformly-distributed loads are considered, and conventional steel rebar is provided within the slab at the point of contact with the piles to resist hogging moments, but no rebar is provided in the interior of the slab (Viney 2007).

Yield line analysis is also incapable of providing information regarding deformations (deflections and slopes) or cracking, which are critical for suspended floors to ensure the safe operation of mechanical handling equipment (e.g. the lift truck is susceptible to slight tilts of the floor). Current design provisions are unsatisfactory as they adopt simple span/effective depth limits which were developed for flat slabs in buildings where the aim is to minimised cracking in finishes and partitions. Therefore, there is a need for appropriate limits to be derived to suit stringent surface regularity requirements in industrial floors. Current design guidance accounts only for uniformly distributed loads and concentrated load (whether single or multiple), often encountered in practice, are not considered. Although most floors are constructed using proprietary designs, the latter are excluded from the published guidance and require critical examination. The treatment of crack control due to restrained early-age and drying shrinkage is not precise, especially in the ArcelorMittal method which eliminates conventional reinforcement. Crack control measures are critical to piled floors since the slab is often cast in large pours with no internal joints (Beckett, 2004; Goodchild 2004). There is an acknowledged scatter in the thicknesses recommended by current design guidelines as they utilise a range of material and loading parameters, effective spans between piles and safety factors resulting in thicknesses that could differ by 25% or even more, with proprietary designs providing the smaller slabs sections as there will be no provision for cover. (Jerry Hedebratt, 2012; Hulett and Sketchley 2009). The performance of existing slabs is also a source of concern. There is a need for a unified and well-defined design method.

2 Case Studies

This paper presents two case studies on single SFRC elevated round-panel with different boundary conditions, which are based on the experimental investigations of de Montaignac et al (2011) and Soranakom et al (2007). The post-cracking behaviour of SFRC structural elements was the focus of the research work by de Montaignac et al (2011). Round-plates were examined (see Fig. 1) consisting of six specimens for each SFRC mix with varying amount of steel fibres [0.75–1.25%]. For this study, the SFRC round-plate [labelled F35-1.0] chosen was made from 1% volume fraction of fibres, has the mechanical properties with compressive strength 46.9 MPa, modulus of elasticity 33.5GPa, Poisson ratio of 0.23 and the post-cracking tensile strength of 2.6 MPa. The hooked-end steel-fibre used in the concrete matrix has an aspect ratio of 67.2 and a length of 35 mm. The strength of the fibre is 1200 MPa.

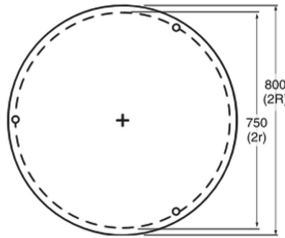


Fig. 1. Dimensions of round-plate adapted from (de Montaignac, Massicotte, Charron, and Nour, 2011)

The second case study examined the experimental work of Destree & Mandl (2008) as reported by Soranakom et al (2007), where load-displacement responses were established experimentally using SFRC round panels (see Fig. 2) with 1500 mm span and 150 mm thick, in inverse analysis to determine the properties of material (Young modulus, tensile stress, Poisson's ratio). The round panel was placed on a continuous simple support. The panel test was mainly for characterisation of the materials. One cubic meter of the SFRC were made of 350 kg Cement (type I), aggregate grading of 0–16 mm, 60 kg fly ash, 1.25% superplasticizer by volume, Undulated steel wire, TABIX 13/50 steel-fibres [1.3 mm diameter, 50 mm length and 900 MPa tensile strength and 0.50 water-cement ratio].

At 28 days, the average crushing strength of cube test was 43.7 MPa. The panels were loaded to failure. Their crack patterns are shown in Fig. 3 [a-c]. The load-displacement response is the core of the round panel tests, which is used for material characterisation purposes. The research works used inverse analysis to determine the properties of material of steel-fibre reinforced concrete [Young's modulus, Poisson's ratio and tensile stress crack width parameters] from the load-deflection response of the round-plate test [from which the load carrying capacity of the round-panel is known].

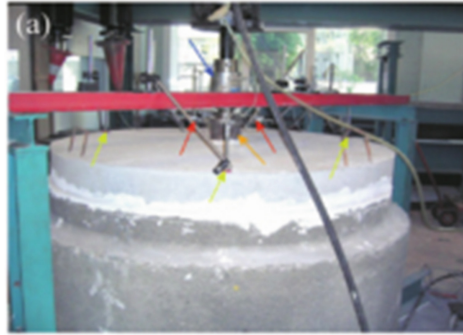


Fig. 2. Experimental setup of Destree & Mandl (2008)

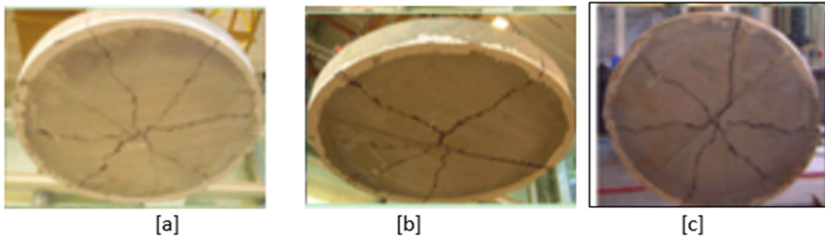


Fig. 3. Crack Patterns of Soranakom et al. round plate (2007)

3 Numerical Modelling

The FEA was carried out using ABAQUS to simulate the behaviour of the SFRC panels. ABAQUS has a materials library that has several models of the elastic and inelastic behaviour of various materials which include concrete, cast iron, metals, rock and soils. There are models embedded in it that can be used to model concrete and masonry structures. ABAQUS/Standard utilises the FEM to indirectly solve a system of equations at each solution “increment” for the analysis of framework, shell, and, solid models [ABAQUS, 2012].

3.1 Material Properties

Material properties for all elements are specified; however, high-quality material data were difficult to obtain, particularly for the more complex material models like material damage properties. The validity of the results is essentially limited by the accuracy and extent of the material data. Here linear elasticity and nonlinear plasticity of reinforcement steel and isotropic elasticity in combination with damaged plasticity model of concrete is discussed to depict a mechanical constitutive model.

3.2 Constitutive Model for SFRC in Compression

From various experimental and numerical results, the compressive strength of steel-fibre reinforced concrete [with volume fraction of fibre $\leq 1\%$] and that of plain concrete are about the same, but a higher percentage of fibre fraction tends to produce a slight increase in compressive strength but they are generally assumed to be the same (America Concrete Institute, 1999 [2002](#); J.A.O. Barros and Cruz, 1999, 2001; Joaquim A. O. Barros, Lourenço, Soltanzadeh, and Taheri, 2013; J.A.O Barros et al. 2012; British Standard Institute, [2006](#); Carr, 2000; Chanh, 1990; Chen [2005](#); Edgington, 1973b; Fall, 2014; Fathima and Varghese, 2014; Garcia and Borrell, 2010; Ghaffar et al. 2014; Ghosh, Bhattacharjya, and Chakraborty [2007](#); Hadi [2008](#); Jansson, 2011; Kooiman, 2000; T.-S. Lok and Pei [1998](#); Mohsin [2012b](#); N., 2009; Naaman and Gopalaratnam [1983](#); Neal [2000](#); RILEM, [2002b](#); Rossi, 1999; Swamy [1974](#); Van Chanh, 2004; Wang, Mindess, and Ko, 1996; Xie, Guo, Liu, and Xie, 2015; Zollo 1997).

3.3 Constitutive Model for SFRC in Tension

Different constitutive models for post-cracking behaviour of SFRC were considered, and Lok and Xiao ([1999](#)) model was selected as the most suitable to simulate the experimental result and mimic tension behaviour.

3.3.1 Lok and Pei ([1998](#))

The proposed constitutive model was based on the stress-strain relationship. Its tensile behaviour incorporates a bilinear strain softening. The model is defined by the properties of the composite material and that of steel-fibres. The first phase consists of a parabolic curve to point of first crack. Phase two [2] adopted a bilinear descending process to simplify the post-cracking phase. The main challenge of this model is that it is limited to low fibre dosage.

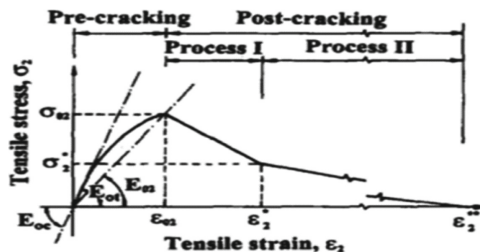


Fig. 4. Tensile stress-strain relationship adapted from Lok and Pei ([1998](#))

3.3.2 Barros and Figueiras ([1999](#))

In their work on “Flexural Behaviour of SFRC: Testing and Modelling, the outcomes of tests performed on specimens, using the 3-point bending test for steel fibre reinforced concrete (SFRC) were presented. The tensile constitutive model is depicted in Fig. 5.

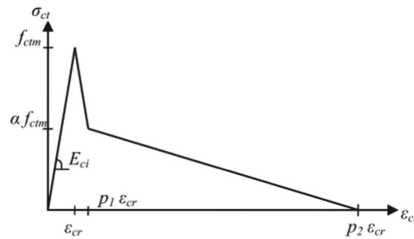


Fig. 5. Proposed tensile stress-strain diagram adapted from (Barros and Figueiras, 1999)

The fracture energy model was used to evaluate the post-peak tensile behaviour, and a numerical model was developed. A bilinear tensile stress-strain relationship was used to depicts the strain softening behaviour of the beam. The model is based on stress-strain relationship of the SFRC

3.3.3 RILEM TC 162-TDF (2002)

In a 3-point bending test on several beams, the RILEM TC 162-TDF Recommendation (2002) proposed a stress-strain relation for SFRC with compressive strengths up to C50/60. The design of SFRC according to the $\sigma - \epsilon$ method [Fig. 6]

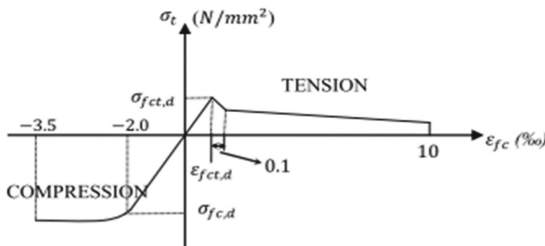


Fig. 6. Stress-Strain Diagram adapted from (RILEM, 2002)

3.3.4 Lok and Xiao (1999)

Based on their previous works which resulted in the accurate prediction of the steel-fibre reinforced concrete (SFRC) flexural response from a constitutive model, unambiguous expressions for the first crack and the ultimate flexural strength are derived in the work.

There was good agreement when the Predictions obtained by using the simplified ultimate strength expression are compared with results obtained from both the above analytical procedure and experimental data. The approaches serve as an effective tool for flexural strength assessment of SFRC.

The three constitutive models were used in the analysis of a simply supported SFRC beam with the results displayed in Fig. 8.

The Lok and Xiao (1999) constitutive model is chosen for works done based on its agreement with experimental results and also due to its incorporation of high volume fibre fraction (0-3%) while Barros and Figueiras (1999) model have a maximum volume fibre fraction of 1%.

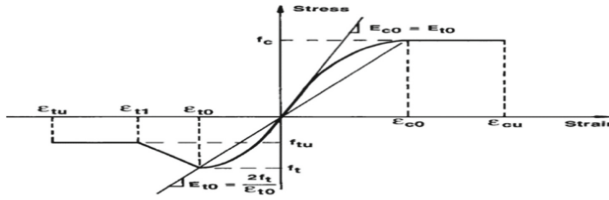


Fig. 7. Stress-Strain constitutive model adapted from (Lok and Xiao, 1999)

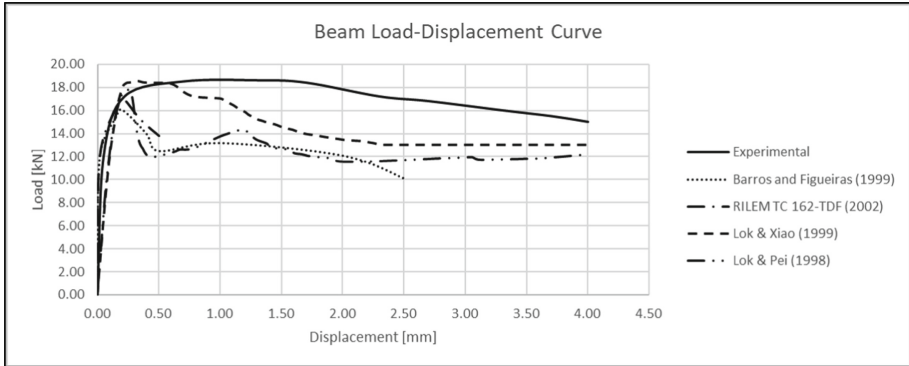


Fig. 8. Load-displacement curve based on different constitutive models

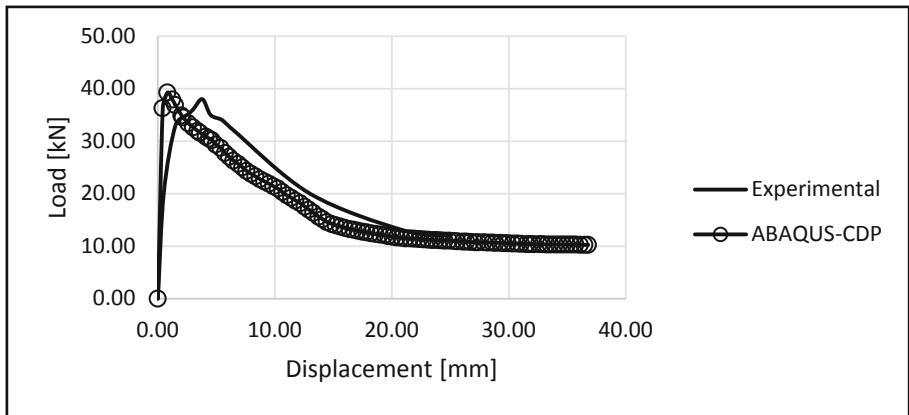


Fig. 9. Load-Displacement Curve de Montagnac et al Round-Plate (2011)

3.4 Validation and Calibration Using Experimental Data

For the ABAQUS-CDP, the plasticity parameters are given as follows: $\psi = 40^\circ$, $\varepsilon = 0.1$, $f_{b0}/f_{c0} = 1.16$, $K=0.667$ and $\mu= 0.006$. The compression and tensile stresses and damaged parameters provided at 80% tensile damaged. The displacement loading of

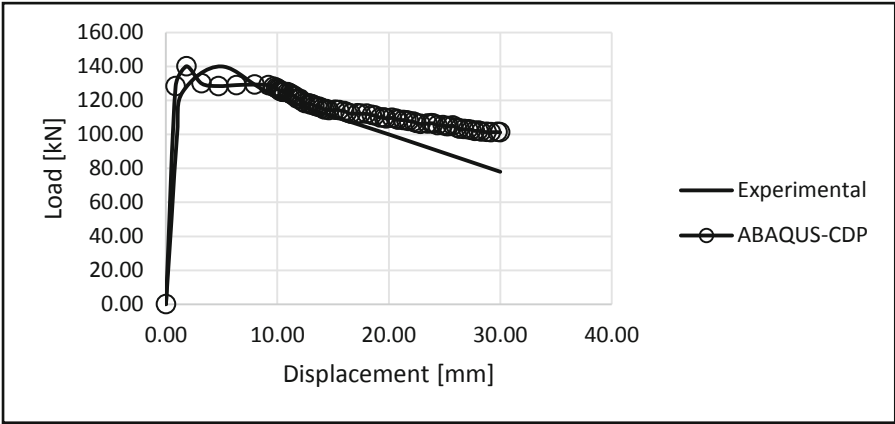


Fig. 10. Load-Displacement curve for Soranakom et al Round Plate (2007)

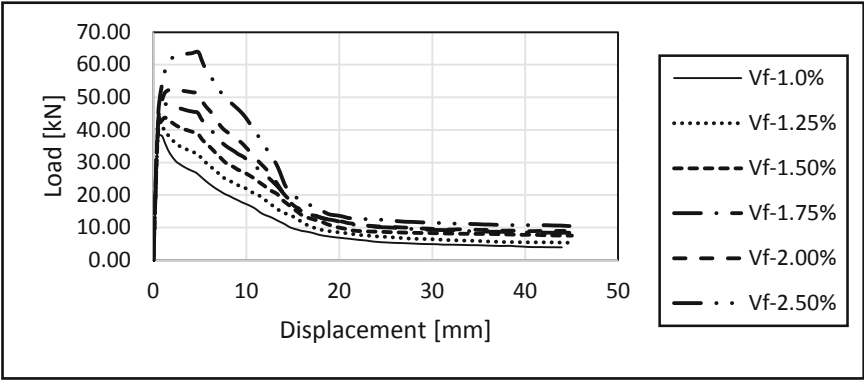


Fig. 11. Load-displacement curve for a range of V_f

4 mm was applied at the centre of the beam at a slow incremental rate of 0.04 mm. This is to reduce convergence challenges. The convergence criteria based on the residual forces tolerance is maintained at 5%. The bond stress used for this analysis is 3.0 MPa and 25 mm mesh size.

The flexural behaviour of the round panel was modelled using ABAQUS Concrete Damaged Plasticity (CDP) nonlinear model. To really capture the panel, the full panel was modelled using 3D brick model with 25 mm mesh. The loading on the round panel was modelled using static analysis and displacement based loading. The compressive and shear stresses are assumed to develop within the elastic range thus guided by the elastic properties of the material [young's modulus and Poisson's ratio]. The tension behaved elastically until it cracks and then conform to the tensile-strain (Loks and Xiao 1999) relationship afterward. Figures 4 and 5 show the Load-Displacement curve for de Montaignac et al. (2011) and Soranakom et al. (2007) round plates. The young's modulus controls the rising elastic response of the curve from the origin up to the first

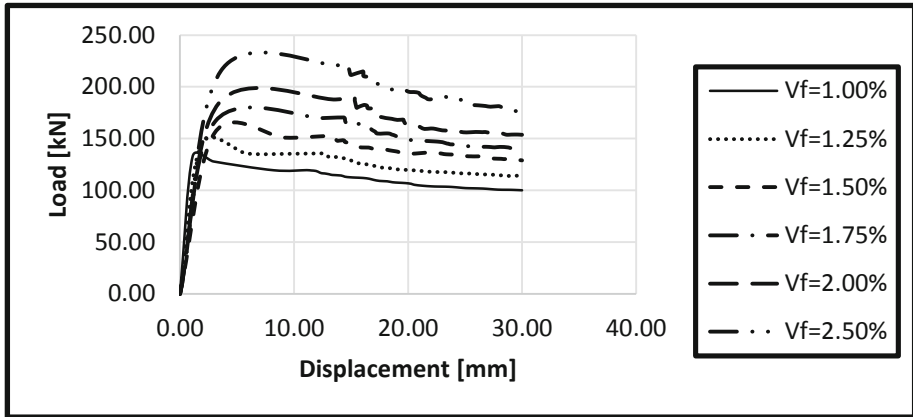


Fig. 12. Load-displacement curve for a range of V_f for Round-Panel

crack. The point that the load-displacement curve diverges from the linear elastic response correlates to the tensile strength parameter f_t . The maximum load is governed by the first softening of the slope and the f_t while the post cracking response is governed by the tensile stress-strain parameters (Loks and Xiao 1999). The load-displacement curve was plotted in Fig. 5, which shows the experimental result with an ultimate load of 138.6kN. The NLFEA gave an ultimate load of 140.09kN. This is 1.08% higher than the experimental value. The response of ABAQUS CDP was in agreement with the experimental results, thou stiffer. This shows the conservativeness of the model. At the peak load, the concrete cracked and the fibre held the composite together while undergoing to softening behaviour.

4 Results and Discussion

4.1 Parametric Studies

The FEA is used to extend the experimental studies and cover the full practical range of the key parameters, i.e the fibre volume ratio and the characteristic strength of the SFRC. The result of the experimental round-plate SFRC with $V_f = 1.00\%$ is used as a control. The experimental work examined the effect of adding fibres to suspended panels up to 1.5%. This case study extended the fibre volume ratio to full range as practically obtainable in the industry, 2.5%.

4.2 Case Study1: 3-Point Support

For the round-plate with three supports, the load-displacement curves for the varying volume fibre fraction are shown in Fig. 6. These are also interpreted in Table 1, namely: the load at first crack [P_y] signifying the yield load and its associated displacement [δ_{max}] the maximum load [P_{max}] signifying the load-carrying capacity and associated displacement [δ_{max}], the ultimate load [P_u] signifying the residual strength

(taken as the lesser of the load at failure or 85% of the maximum load to ensure its practical usefulness) and associated displacement $[\delta_u]$ and the ductility ratio μ defined as $\mu = \delta_u/\delta_y$. For comparison purposes, the SFRC with $V_f = 1.00\%$ is taken as the control specimen. The maximum load is the measure of the strength of the slab while the ultimate load is a measure of the residual strength. Likewise, the displacement at yield and ultimate loads are δ_y and δ_u respectively. The ductility of the slab is measured as the ratio of δ_y to δ_u .

Table 1. Results for SFRC round plate

	V_f %	P_y [kN]	$[\delta_y]$ [mm]	P_{max} [kN]	$\frac{P_{max}}{P_{max*}}$	δ_{max} [mm]	Pu [kN]	δ_u [mm]	$\frac{P_y}{P_{ye}}$	$\mu = \frac{\delta_u}{\delta_y}$	$\frac{\mu}{\mu_c}$
Control	1.00	38.21	0.51	38.21		0.51	32.48	1.75		3.43	
	1.00	38.21	0.51	38.21	1.00	0.51	32.48	1.75	1.00	3.43	1.00
	1.25	39.08	0.51	40.51	1.06	1.01	34.43	3.28	1.02	6.43	1.87
	1.50	40.31	0.51	43.24	1.13	1.53	36.75	3.22	1.05	6.31	1.84
	1.75	41.68	0.52	47.73	1.25	1.71	40.57	6.15	1.09	11.83	3.45
	2.00	42.77	0.52	52.44	1.37	2.13	44.57	6.32	1.12	12.15	3.54
	2.50	57.11	1.16	63.91	1.67	4.82	54.32	6.62	1.49	5.71	1.66

*Pmaxc represent the control peak load

In the SFRC with $f_{cu} = 30$ MPa, the result shows that round-panel with 1% fibre volume ratio yielded 38.21 kN, while that of 2.50% fibre volume is 57.11 kN 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 load give 0.51 mm.

4.3 Case Study2: Continuous Support

In the case of the round-panel with continuous support along the edge, the load-displacement curves for the varying fibre volume fractions are shown in Fig. 6. These are also interpreted in Table 2, namely: the load at first crack $[P_y]$, its displacement $[\delta_u]$, the maximum load $[P_{max}]$, its displacement $[\delta_{max}]$, the ultimate load $[P_u]$, its displacement $[\delta_u]$ and the ductility ratio $[\mu]$. The load-displacement curves of the slab with different amount of fibre volume ratio shows that the maximum loads were reached for $vf = 1.00-1.50\%$ before 3 mm central displacement while for $vf = 1.75-2.50\%$, they were reached after 3 mm. These resistances are due to the amount of fibres in the concrete matrix. For all the specimens under study, the first crack was noticed before 5 mm displacement. The fibre volume ratios influence can be observed clearly as the fibre content increases.

Table 2. Results for SFRC round plate

	V_f %	$[P_y]$ [kN]	$[\delta_y]$ [mm]	P_{max} [kN]	$[\delta_{max}]$ [mm]	$\frac{P_{max}}{P_{maxc}}$	$\frac{P_y}{P_{yc}}$	Pu [kN]	$[\delta_u]$ [mm]	$\mu = \frac{\delta_u}{\delta_y}$	$\frac{\mu}{\mu_s}$
Control	1.00	132.91	1.11	132.9	1.11			113.0	14.5	13.06	
	1.00	132.91	1.11	132.9	1.11	1.00	1.00	113.0	14.5	13.06	1.00
	1.25	143.79	1.85	143.8	1.85	1.08	1.08	122.2	17.5	9.46	0.72
	1.50	155.51	3.03	155.5	3.03	1.17	1.17	132.2	26.8	8.84	0.68
	1.75	166.82	3.10	170.4	14.36	1.28	1.26	144.8	23.7	3.05	0.23
	2.00	184.19	3.40	189.7	15.24	1.43	1.39	161.2	21.1	2.36	0.18
	2.50	215.64	3.60	221.8	14.74	1.67	1.62	188.5	22.1	2.42	0.19

It can be seen that the load-carrying capacity $[P_{max}]$ of the round-panels were improved by the increment in steel fibres. The enhancement was evident in all the round-panels as the values of fibre volume increases which lead to higher strength. The curves also show that stiffness was enhance with fibres between 1.00–1.50%. The round-panels deflects more with 1.750–2.50% fibre volume.

5 Conclusions

It was found 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. Likewise, the strength increases by $\sim 7\%$ over the previous result of the round-panel with isolated supports and $\sim 11\%$ for the round-plates with continuous support under monotonic loading. This also leads to a rise in ductility and strength enhancement.

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