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Lifecycle performance assessment of steel fibre reinforced concrete ground slabs

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ABSTRACT

Steel fibres have been used in reinforced concrete ground slabs since 1970s. To keep the steel fibre reinforced concrete structures safe and sustainable, it is essential to correctly assess the performance of the structures during their lifecycle. This paper presents reliable finite element numerical simulations for predicting the performance of steel fibre reinforced concrete slabs under various loading conditions. The influence of reinforcement index (e.g. volume and aspect ratio) on the behaviour of concrete ground slabs is also investigated to simulate the deterioration of material properties and structural performance due to volume loss of steel fibres such as caused by reinforcement corrosion. Three-dimensional finite element analyses are performed for steel fibre reinforced concrete ground slabs. In numerical simulations, a smeared-crack model is used for reproducing the concrete cracking behaviour under loading. To study soil-structure interaction, the non-linear soil behaviour is simulated by tensionless elastic supports. Then, the ultimate load capacity and crack propagation pattern can be obtained from finite element numerical analyses. The results show that the numerical predictions obtained from finite element analyses agree well with the full-scale experimental data available.

1. INTRODUCTION

Fibre reinforced concrete (FRC) has an extraordinary potential for utilization in a mixed elements of structural building requirements. Generally, the stupendous investment for buildings and civil infrastructure has been in the area of ground slabs. The discrete fibres provide protection and confinement for the concrete deformations, thereby increasing its strength, ductility and durability, in addition to simplifying construction. The steel fibres can generally be engineered to offer the desired tensile strength and stiffness in a specific range, by controlling the shape and volume fraction. As such, the steel fibres can effectively replace conventional continuous longitudinal and transverse steel reinforcement. Studies have demonstrated several benefits of concrete-fill, including increasing flexural strength and stiffness and preventing cracks of the slab. The utilization of steel fibres in cement in place of common supports is valuable for most of the structures because of the less complex forming method. It could be fixed in any structural shape, requiring less effort to the assembling complexities. Also, it is promptly accessible in urban regions at generally minimal effort.

In the past two decades, notwithstanding, there has been an expanded trend in utilizing steel-FRC (SFRC) in pavements and ground bearing slabs (ACI 2002, Dong & Gao 2011). Furthermore, the behaviour of SFRC ground slabs as load bearing structures reinforced with steel bars for modern buildings and other structures has been investigated. Since 1989, a series of experiments have been undertaken on full-scale ground slabs by using the test facilities at the University of Greenwich in order to understand the behaviour of slabs. It is numerically demonstrated that the tensile force produced by drying shrinkage cracks is dangerously high (Beckett 2003, Beckett 2006). The results were used to improve the accuracy of the thickness design method given in the Concrete Society Technical Report 34 (Concrete Society 2003). A series of experiments were conducted by a group of international universities which lead to RILEM TC162-TDF as a design recommendation notes for SFRC structures (RILEM 2003). Meanwhile, a bulletin design of SFRC structures, Model Code FIB TG 8.3, was published in the field of ultra high strength fibre concretes (Fib 2009).

Recent experimental studies have been undertaken for the ground slabs to investigate the behaviour of loaded SFRC slabs with different volume of fibres (Plizzari 2007, Meda & Plizzari 2004, Sorrelli et al. 2006). These studies primarily focused on defining the mechanical properties of SFRC materials for analysis, which can be used in various conditions. Many numerical simulation models have been suggested on the basis experimental studies to model the behaviour of SFRC structures. The Finite Element (FE) method has been often employed to study the behaviour of SFRC ground slabs, including the associated soil nonlinearities. However, the accuracy of these models is not satisfactory. The analysis of SFRC ground slabs faces a complex problem due to the non-linearity and the nature of the structural materials. In order to tackle these problems, the approach used in this study is a material base modelling. The fibres and the concrete are not considered as two separate materials. Rather, it is defined as a material as fibre-reinforced-concrete. Then, if the mechanical properties of the fibre-reinforced-concrete were recognised, the modelling and analysing becomes as simple as common homogenous materials. Then, the mechanical properties of SFRC ground slabs are studied. The constitutive material relationship is used to translate the data into the commercial software ANSYS (Ansys 2012).

The analytical modelling approach of the SFRC ground slabs in this study is based on a new fibre-concrete material with a unique strain-stress curve in ANSYS. This approach is based on the concepts of composite material and strain compatibility. A parametric study is also conducted in this paper to examine the effect of the SFRC's strength, the slab deformation and the structural behaviour of SFRC ground slabs. This study firstly analyses the experimental results available for SFRC ground slabs. Then, from experimental results, FE numerical models for SFRC ground slabs are evaluated to find out the correct material properties used for numerical simulations. Finally, the numerical models are developed based on the new material definitions and characterisations for SFRC ground slabs.

2. PROPOSED MODEL

In this paper, an FE model is developed to predict the behaviour of SFRC ground slabs. This model accounts for cracking and plasticity of the steel-fibre-concrete and includes the effects of geometric nonlinearities. The numerical model is verified using experimental results from various sources such as Plizzari, et al. 2007, Falkner 1995, Beckett 2006, and Sorelli et al. 2006. This model is then used in a parametric study to examine the effect of a wide range of key steel fibre parameters on the behaviour and failure mode of SFRC ground slabs, including various volume fractions. Other parameters such as soil stiffness, slab thickness, concrete strength are also investigated for the SFRC ground slabs.

2.1 Model description

A typical SFRC ground slab situated on elastic soils is adopted for FE numerical simulation studies, with the dimensions of 3000mm×3000mm×150mm, as shown in Fig. 1.

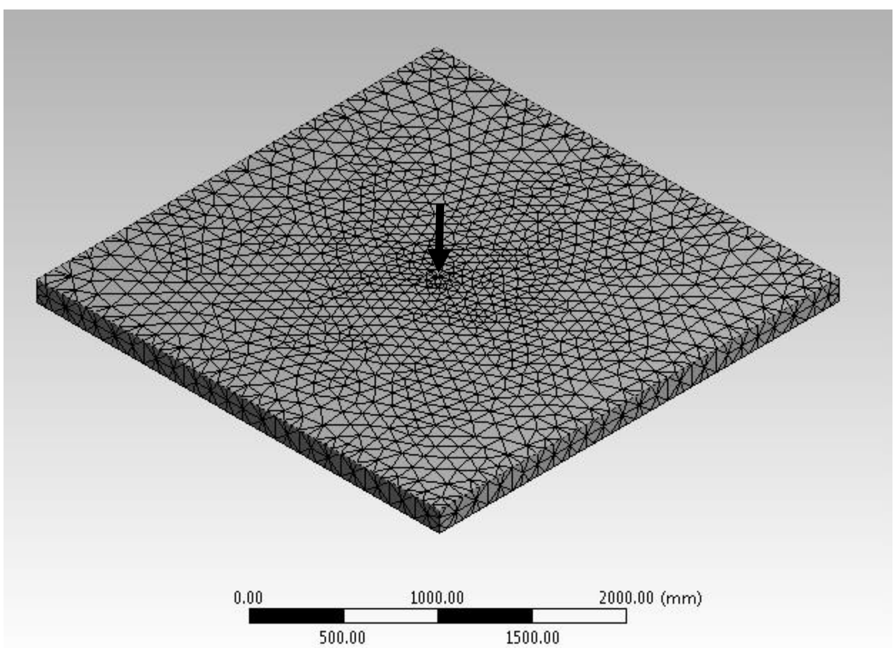

Fig. 1 Typical ground slab geometry, mesh and loading

The non-linear FE analysis program ANSYS WORKBENCH was used to model the flexural behaviour of SFRC ground slabs, accounting for both material and geometric nonlinearities. Change in geometry as the structure deforms is taken into account in the strain-displacement relationship and equilibrium conditions. This is considered in pre-crack stage as a small strain and finite displacement. Hence, once cracks initiate in concrete, the effect of steel fibres are considered in the numerical simulations. Large displacements typically result in change in the element shapes and orientations, and consequently affect the element stiffness matrix. A Tetrahedrons fine mesh is used where the load area has a finer mesh. This area supposed to be the failure region and both internal and edge loads are considered. This is accomplished by using the automatic meshing capability of the program.

To deal with non-linearity and cracking development, the element stiffness matrix is continuously updated using the Newton–Raphson iterative procedure. At the end of each step, the program adjusts the stiffness matrix to reflect the nonlinear changes in the stiffness of the structure. The “Elastic Foundation Stiffness” (EFS) or “Elastic Support” is a useful method for specifying a spring stiffness per unit area that only acts in the direction normal to the face of the element in WORKBENCH, and the sub-base soils are considered as a tensionless-support in the study.

For the steel fibre reinforced concrete, an eight-node 3-D reinforced concrete solid (SOLID185) element was used. Each node has three degrees freedom, namely three translations in the nodal x, y, and z directions, respectively. The SOLID185 element is based on a constitutive model for the triaxial behaviour of concrete after William and Warnke (1975). For the crack monitoring the model is transferred to the ANSYS APDL and SOLID65 is adopted instead of SOLID185. The element SOLID185 includes a smeared crack analogy for cracking in tension zones and a plasticity algorithm to account for the possibility of concrete crushing in compression. The shear transfer coefficient is set in an open and a closed crack with values of 0.6 and 0.9, respectively. The concrete material is assumed to be initially isotropic, before cracking or crushing. Each element has eight integration points at which cracking and crushing checks are performed. Cracking or crushing occurs once one of the element’s principal stresses exceeds the tensile or compressive strength of concrete. Cracked or crushed regions are formed perpendicular to the relevant principal stress direction. Stresses are then redistributed locally. Therefore, the element is nonlinear and requires an iterative solution. The formation of a crack is achieved by the modification of the stress–strain relationship of the element to introduce a plane of weakness in the concerned principal stress direction.

2.2 Material parameters

The crushing algorithm is similar to a plasticity law. Once a section has crushed, any further application of load in that direction develops an increasing strain at a constant stress. Also, once an initial crack is formed, stresses tangential to the crack face may cause a second or third crack to develop at an integration point. For steel fibre reinforced concrete in compression, the uniaxial multi-linear isotropic stress–strain relationship was obtained before reaching the compressive strength f'_{cu} by using (Thomas et al. 2007)

$$f_{SFRC} = a(f'_{cu})^{\alpha 1} + b(f'_{cu})^{\alpha 2}\, I_R + c\, I_R \tag{1}$$

where f_{SFRC} is material property, i.e. cylinder strength, split tensile strength and modulus of rupture, of the steel fibre-reinforced concrete; *a*, *b* and *c* are regression coefficients; f'_{cu} is 28-day cube compressive strength of the matrix (plain concrete); and I_R is fibre-reinforcing index ($V_f L_f / \phi_f$), where V_f is the volume fraction of fibre, L_f is the length of fibre and ϕ_f is the fibre diameter. The coefficients α_1 and α_2 are assumed to take a value of 0.5 or 1.0 as used in the established method (Ou et al. 2012).

The behaviour of the SFRC materials is similar to the plain concrete in linear stage, and in post crack or non-linear stage the steel fibres become activated. This behaviour can be modelled as Ramberg-Osgood failure criteria, which has been used in many studies for modelling of dynamic composite behaviour, including Bogetti et al. (2012), Yuana et al. (2012), and Cousignéa et al. (2013). Based on this method, both compression and tensile stress-strain curves will be combined as one curve as strain-stress relation of the Ramberg-Osgood elasto-plastic model, expressed as

$$\frac{\gamma}{\gamma_y} = \frac{\tau}{\tau_y}\left(1 + \alpha \left|\frac{\tau}{\tau_y}\right|^{r-1}\right) \tag{2}$$

where γ = shear strain, τ = shear stress, γ_y = reference shear strain, τ_y = reference shear stress, α = constant $\geq$ 0, and r = constant $\geq$ 1.

The overall modulus elasticity of SFRC materials depends on the volume fraction(V_f), the aspect ratio of the fibres (L_f / ϕ_f), the module elasticity of both the fibres and the concrete matrix (Teng et al. 2004), expressed here as

$$E = E_m \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{3}$$

where *E* is the estimated modulus of elasticity, E_m is the original elastic and shear module of the concrete matrix, ξ is empirical parameter, and η is given by

$$\eta = \frac{E_f/E_m - 1}{E_f/E_m + \xi} \tag{4}$$

To estimate the compressive strength, a statistical study has conducted for the existing formulas (i.e. Haido et al. 2010, Bayramove et al. 2004, Thomas & Ramaswamy 2007). From the method by Haido et al. (2010), the compressive strength can be estimated from

$$f_{cf} = 14.169 V_f \frac{L_f}{D_f} + 0.984 f'_c \tag{5}$$

The general properties of the SFRC ground slabs from different experimental studies are given in Table 1, where the slabs were tested and loaded by a hydraulic jack placed in the slab centre or slab edge (Becket 2006, Plizzari et al. 2007, Sorelli et al. 2006). Most of compressive strengths were measured based on the cylindrical test, and some values of modulus of elasticity were obtained by laboratory tests. The steel fibres were hooked-end and crimp shapes with the same tensile strength. For the unmeasured compressive strength and elasticity modulus, the equations described above are used for estimation.

Table 1 The concrete properties, the fibre volume ratio and the soil stiffness of SFRC ground slabs from various experiments

Slab Name	Experimented By	Concrete	Compressive Strength (MPa)	Modulus of Elasticity (MPa)	Steel Fibre Details[$]	Soil Stiffness (N/mm^2)
SFRC40-E	Greenwich	$C28/35$	33[#]	28000[#]	0.50%/60	N/A
SFRC40-I	Greenwich	$C28/35$	33[#]	28000[#]	0.50%/60	N/A
P2	Plizarri et al	$C25/30$	30.4	24000[#]	0.37%/50	0.080
P3	Plizarri et al	$C25/30$	33.1	24500[#]	0.57%/50	0.080
P4	Plizarri et al	$C25/30$	35.2	25500[#]	0.37%/50	0.080
P5	Plizarri et al	$C25/30$	36.1	25500[#]	0.37%/50	0.080
SFRC-1	Sorelli et al	$C25/30$	30.0	24463	0.37%/50	0.078
SFRC-2	Sorelli et al	$C25/30$	32.0	23446	0.57%/50	0.078
SFRC-3	Sorelli et al	$C25/30$	25.0	24786	0.37%/50	0.078
SFRC-4	Sorelli et al	$C25/30$	27.0	19964	0.37%/50	0.078
SFRC-5	Sorelli et al	$C25/30$	24.0	17335	0.37%/50	0.078

E = Edge loading; I = Internal Loading; $: Fibre volume ratio (%) /Aspect ratio; #: Estimated from the proposed experimental formulas Eq. (3) and Eq. (5).

Table 2 Comparison of FE numerical simulation results with experimental data

Slab Name	First Crack Load Exp. (KN)	First Crack Load Num. (KN)	Difference (%)	Ultimate Load Exp. (KN)	Ultimate Load Num. (KN)	Difference (%)
SFRC40-E	120	102	15	380	392	3.1
SFRC40-I	380	363	4.5	>500	627	N/A
P2	45	44	2.2	246	240	2.4
P3	50	44	12	247	248	0.1
P4	50	49	2.0	265	271	2.2
P5	47	46	2.0	258	256	0.1
SFRC-1	N/A	62	N/A	265	253	4.5
SFRC-2	N/A	60	N/A	238	242	1.7
SFRC-3	N/A	94	N/A	258	262	1.6
SFRC-4	N/A	70	N/A	251	242	3.6
SFRC-5	N/A	N/A	N/A	226	228	0.1

E = Edge loading; I = Internal Loading; Exp. = Experimental results; Num.= Numerical Results.

In the Table 2, structural performance of SFRC ground slabs, such as loads for first crack and the ultimate loading capacity obtained by FE numerical simulations, is compared with the corresponding experimental data. Also, the relative errors between the predicted and experimental data are provided. From the results, the results of loads at first crack and ultimate capacity predicted by FE numerical simulations agree well with the corresponding experimental data.

3. STRUCTURAL PERFORMANCE

The results in Fig. 2 and Fig. 3 show the FE numerical results for load–deflection responses of SFRC ground slabs. Fig. 2 gives FE modelling results for the SFRC-1 ground slab under central load, which are compared with the experimental data (Sorelli et al. 2006). Fig. 3 provides similar results for FE numerical predictions and comparison with the existing experimental data for SFRC-2 ground slab. In general, very good agreement is observed between the experimental and the finite element analysis results both in linear range and non-linear stage. The difference between numerical and experimental data appears larger, which may be caused by the difference between the estimated values and the real values in the material properties after concrete cracking.

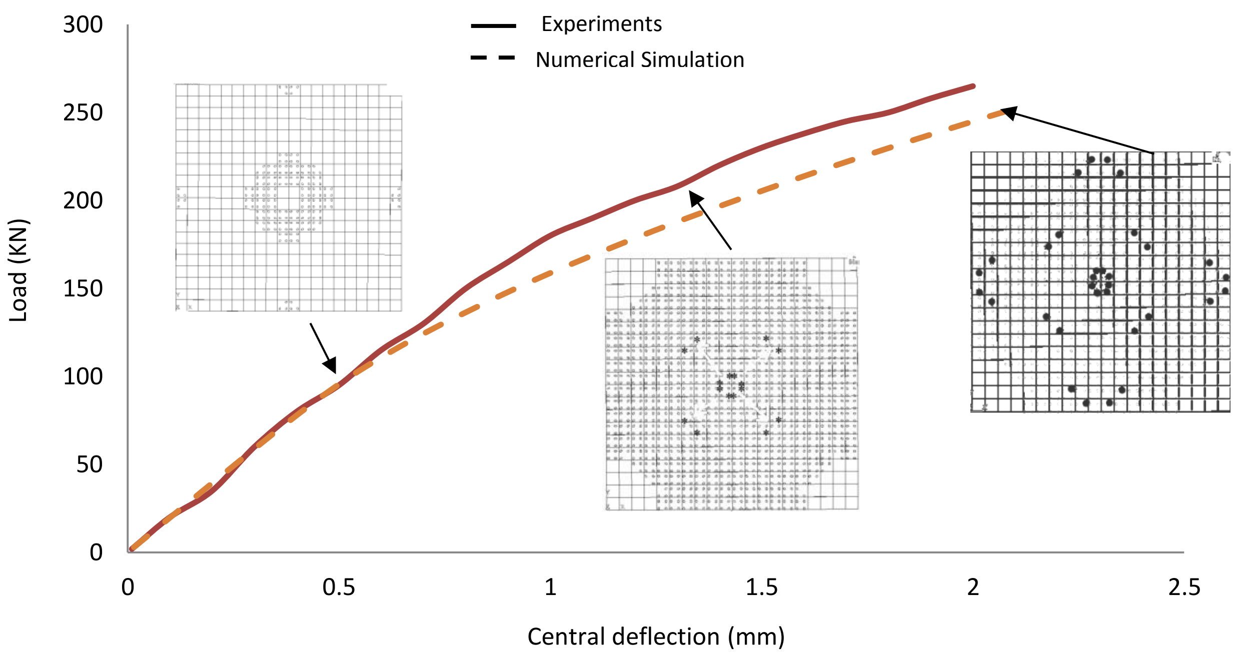

Fig. 2 Comparison of FE modelling results for the SFRC-1 ground slab under central load with the corresponding experimental data (Sorelli et al. 2006), load for first crack at 62 KN, the crack patterns given for 100 KN, 200 KN and ultimate loads.

The crack propagation patterns and the load at the first crack are also discussed and shown in Fig. 2 and Fig. 3. To achieve this goal, at first the value of first crack should be read from the WORKBENCH results, then this force applies to the same slab in APDL model to monitor the cracks and crashes. The process is repeated for different force values to find out the pattern of crack propagation. The lighter hatches in the figures are the micro cracks which used for the first and second force loadings. This indicates there is no failure crack. The darker dots are the main cracks which happen in nonlinear stage. As shown in Fig. 2 and Fig. 3, the patterns of crack propagation are well related to the applied loads. For the SFRC-1 ground slab shown in Fig. 2, the first crack appears when the central deflection reaches 0.3 mm and the corresponding applied load is 62 KN. For the SFRC-2 ground slab shown in Fig. 3, the first crack occurs at the central deflection of 0.33mm and load at 60 KN. As the applied load increases, the cracks in concrete slabs propagate from the loading areas to the edges, eventually reaching the ultimate bearing capacity.

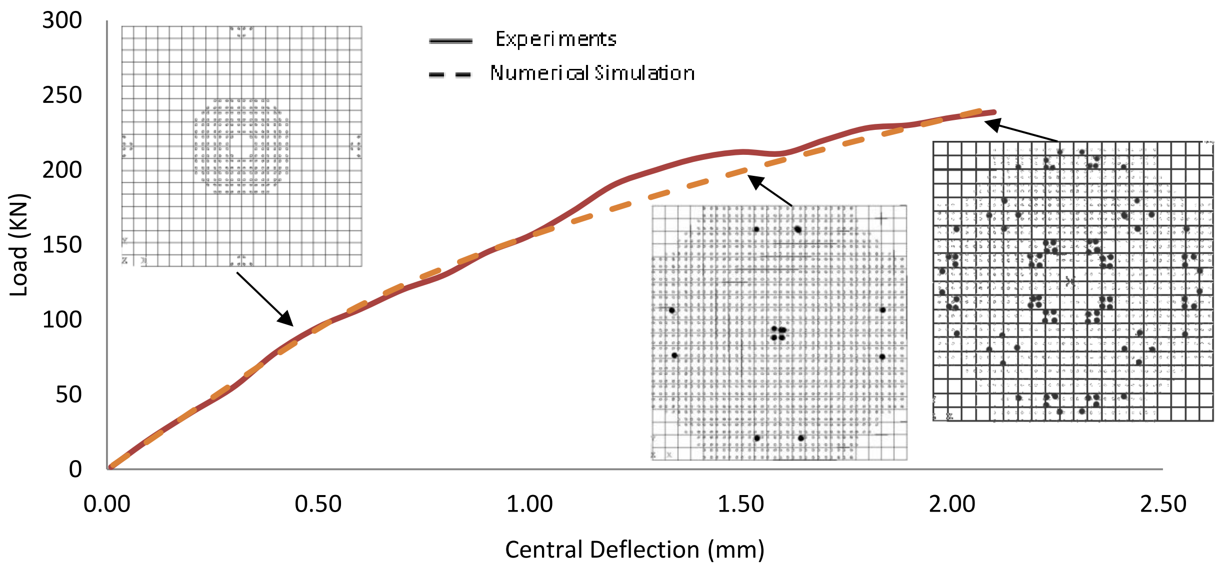

Fig. 3 Comparison of FE modelling results for the SFRC-2 ground slab under central load with the corresponding experimental data (Sorelli et al. 2006), load for first crack at 60 KN, the crack patterns given for 100 KN, 200 KN and ultimate loads.

Reinforcement corrosion will significantly affect life cycle performance of concrete structures (Chen & Alani 2013, Chen & Xiao 2012). In order to investigate the long term performance deterioration of SFRC structures affected by the loss of steel fibre volume in concrete, which may be caused by steel corrosion, the effects of steel fibre volume ratio on the behaviour of SFRC materials are shown in Fig. 4. The SFRC-2 ground slab is considered here, and the material properties such as tangent modulus, compressive strength, tensile strength, and ultimate load are estimated from the equations described above. The value of fibre volume ratio reduces from 2.5% to 0.0%, as indicated in Fig. 4. As expected, as fibre volume ratio reduces, all material properties and structural performance get deteriorated.

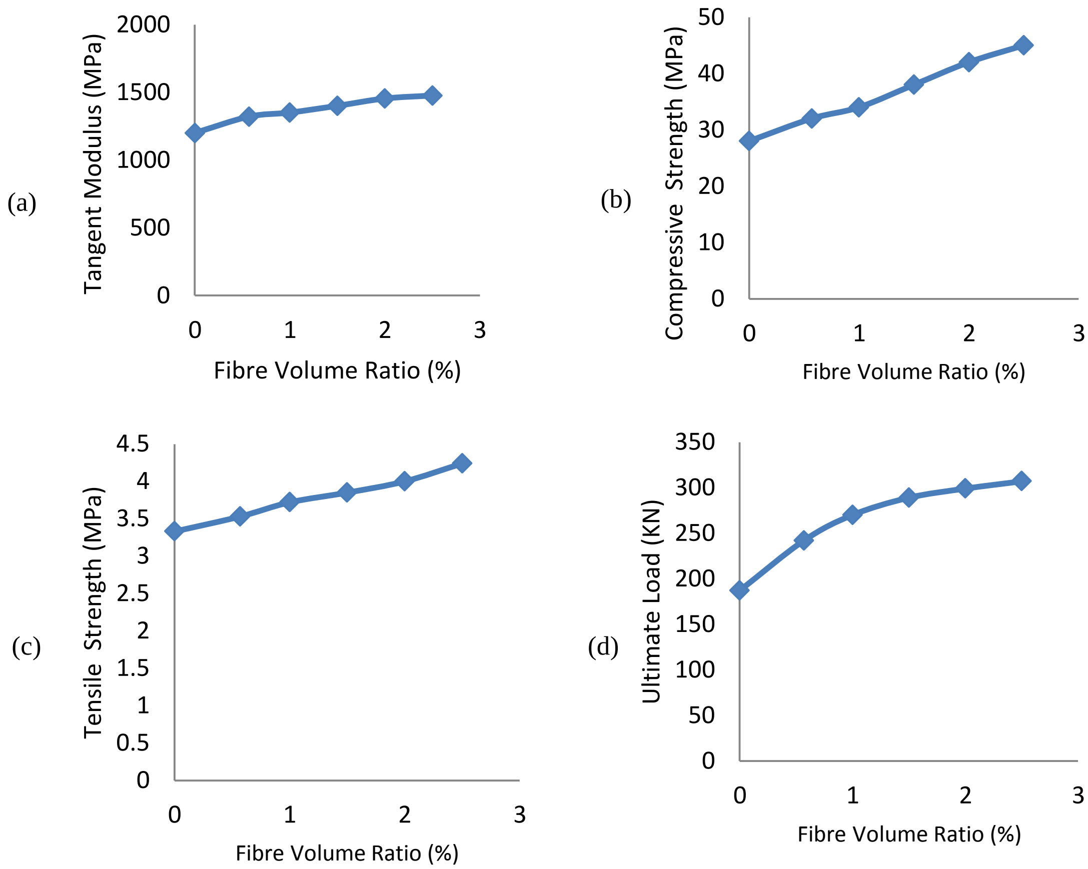

Fig. 4 Effects of fibre volume ratio on SFRC material properties and structural performance: (a) Tangent modulus, (b) Compressive strength, (c) Tensile strength, (d) Ultimate load.

The ultimate limit states of structures during their service life are influenced by the structural resistance deterioration, which can significantly reduce the structural reliability (Chen & Alani 2012, Chen & Bicanic 2010). The results in Fig. 5 show the load-deflection behaviour predicted by FE numerical simulations with various steel fibre volume ratios. Here again, the load-deflection curves could be divided into three stages. The first stage is linear behaviour of the slab before the first crack, and indicates the SFRC materials have similar properties to plain concrete at this stage. After the first crack, the non-linear behaviour starts as the fibres activates. The final stage is after the secondary cracks, and the cohesiveness between the fibres and the concrete plays an important role. As expected, as the fibre volume ratio decreases, the performance of SFRC ground slabs deteriorates.

For common concrete, the tensile stresses can be ignored in the concrete after concrete cracked. However, for SFRC materials, there are remarkable tensile stresses in the concrete across cracks, which improve the resistance of the slab and reduce cracking. Also, steel fibres in concrete between cracks contribute to the flexural rigidity of the concrete, resulting in stiffening the concrete ground slabs.

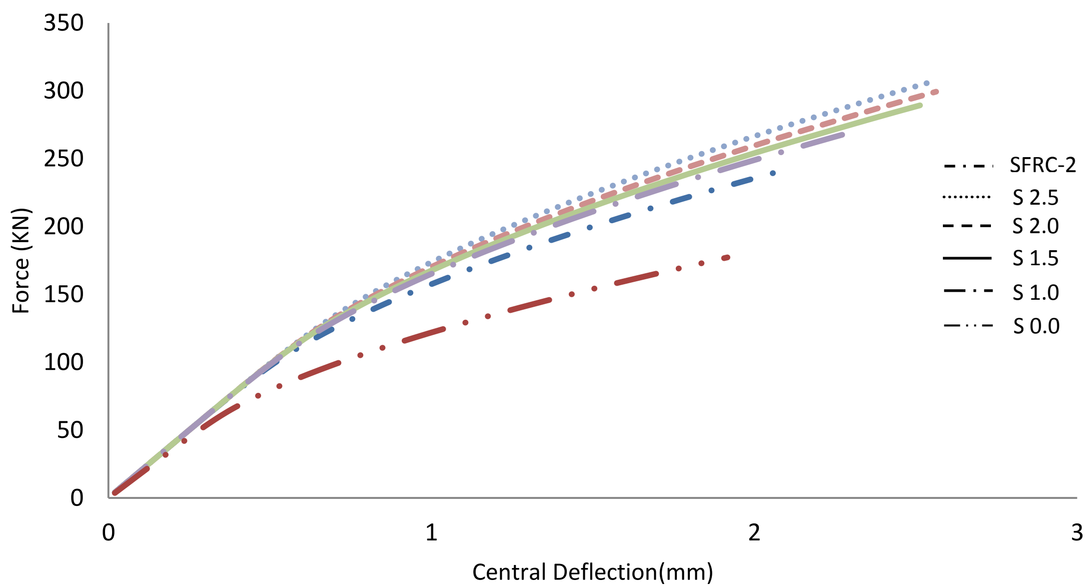

Fig. 4 Effects of steel fibre volume ratio on the load-deflection behaviour

4. CONCLUSIONS

A numerical model for modelling steel fibre reinforced concrete ground slabs is proposed for predicting long-term material properties and structural performance. Non-linear finite element numerical analyses are performed, and the numerical results are then examined with the corresponding experimental data available from various sources. On the basis of the results obtained from the numerical examples, following conclusions are drawn: a) The proposed numerical model can reliably predict the material properties and structural behaviour under loading for steel fibre reinforced concrete ground slabs; b) The proposed model can also correctly evaluate the crack propagation in the concrete slabs under loading; c) The steel fibre volume ratio has significant influence on the material properties and structural performance of steel fibre reinforced concrete, reducing material properties as steel fibre ratio decreases; d) The life cycle structural performance such as ultimate loading capacity of steel fibre reinforced concrete slabs is significantly affected by the reduction of steel fibre volume in concrete due to steel corrosion.

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