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BENCHMARK ANALYSIS OF FRACTURE SIMULATION FOR STEEL FIBER REINFORCED CONCRETE SLAB SUBJECTED TO PUNCHING SHEAR

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Abstract. The need for improved punching shear performance is constantly under review, particularly for slabs between stories or in indoor parking garages of collective buildings. As a part of this effort, the detailed finite element model for this slab was discussed. For the benchmark and parametric analysis of the failure tests conducted by *fib*, the overall punching shear load-vertical displacement relationship, local reinforcement strain, and concrete cracking pattern were investigated through a nonlinear finite element model. A square slab with a length of 2,550 mm and a thickness of 180 mm is modeled with a three-dimensional solid element incorporated with conventional rebars and hooked-end steel fiber inclusions. The two-step mechanical homogenization was conducted in order to extract the effective properties of this fiber reinforced concrete composites. Damaged plasticity was applied for the concrete nonlinearity. The punching shear load was applied to the central part of the slab in the vertical upward direction, until the radial cracks occured to failure in the simulation. In order to develop a possible ductility guarantee for the punching shear condition with relatively high uncertainty, the shear resistance performance of a steel fiber reinforced concrete slab was discussed in accordance to arbitrary fiber directions and different fiber aspect ratios.

1 INTRODUCTION

The *fib* Work Group 2.4.1 focuses on the analysis of fiber-reinforced concrete structures, conducting research on failure experiments and analytical techniques for various steel fiber-reinforced structures. The benchmark structure was a concrete slab reinforced with steel fibers and conventional rebar, subjected to punching shear, as conducted by the *fib* Work Group. The structure is a square concrete slab measuring 2,550 mm in width and 180 mm in thickness, reinforced with bi-directional conventional rebars and hooked-end steel fibers with an aspect ratio of 67. A 200 mm square column is located at the center of the slab. The method of applying the punching shear load involved arranging a steel reaction frame in a circular configuration on a strong floor, securing the specimen to the floor with Dywidag steel rods, and placing a hydraulic actuator at the position of the central column of the specimen to apply upward force. In this analysis, concrete, a two-phase composite material, was idealized as a homogenized matrix, with the steel fibers inside represented as randomly distributed and oriented within the matrix, imparting composite characteristics. This study is a benchmark analysis to predict the load-displacement relationship and corresponding strain levels of the slab subjected to punching shear. This includes the comparison of local crack initiation, propagation patterns, and failure modes that lead to the overall nonlinear behavior.

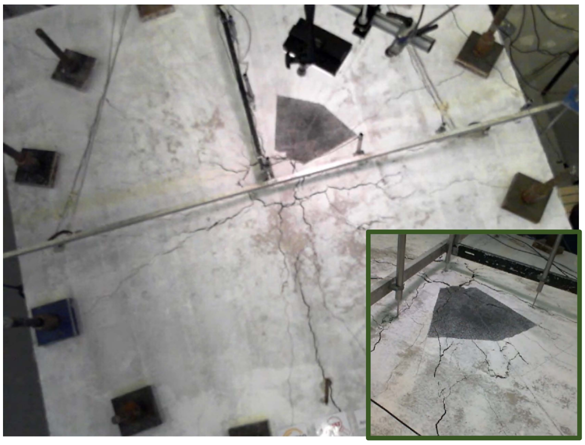


Figure 1: Crack pattern in the final stage of upward punching shear load [1]

2 NUMERICAL HOMOGENIZATION

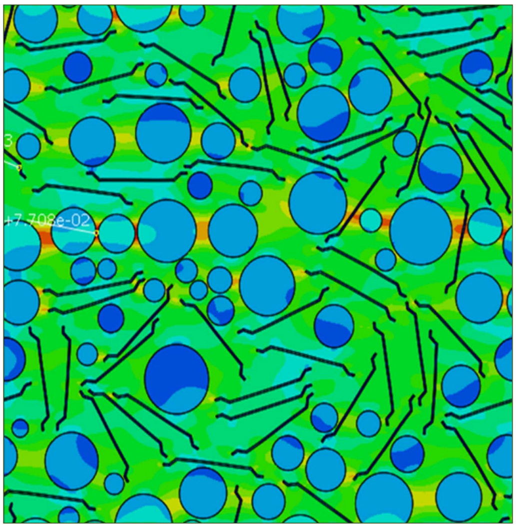
The Mori-Tanaka average stress theory was applied to derive equivalent material properties based on the volume fraction of rebar and steel fibers, as well as the material characteristics of the concrete and fibers. The effective stiffness tensor $\mathbf{C}_{eff}^{II}$ is given by:

$$\mathbf{C}_{eff}^{II} = \mathbf{C}_c + v_f \left(\mathbf{C}_f - \mathbf{C}_c \right) \mathbf{A} \tag{1}$$

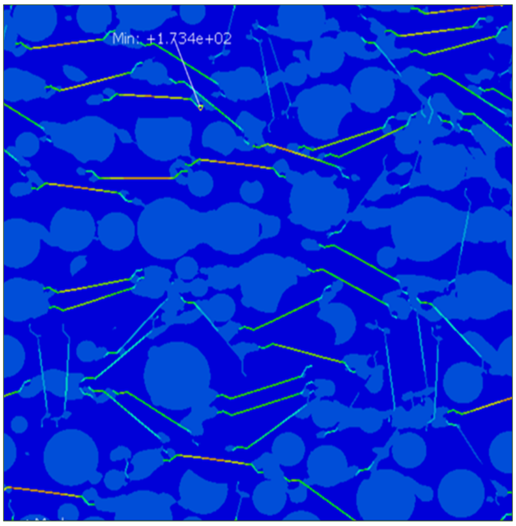
where, $\mathbf{C}_c$ is a stiffness tensor of the homogenized concrete, $\mathbf{C}_f$ is a stiffness tensor of the steel fibers, $\mathbf{A}$ is Eshelby tensor which accounts for inclusion shape and interaction with the matrix, and II is the step number. The Eshelby tensor $\mathbf{A}$ is complex and depends on the shape/orientation of inclusion, material properties, and the stiffness of the matrix. For the sake of simplicity, the Mori-Tanaka method gives the effective modulus of elasticity, E_{eff} for isotropic material as:

$$E_{eff}^{II} = E_c + v_f \frac{(E_f - E_c)}{1 + \frac{E_c}{E_f} \frac{1-v_f}{v_c}} \tag{2}$$

where, E_c is the elastic modulus of the concret matrix, E_f is the elastic modulus of the fiber inclusions, and v_f is the volume fraction of the inclusions. E_c sets base stiffness, representing the homogenized concrete from prehomogenization step for two-phase composites consisting of mortar and aggregates. The term $(E_f - E_c)$ adjusts the stiffness based on the difference between the matrix and inclusion moduli. The denominator accounts for the interaction between the inclusions and the matrix. Since this Mori-Tanaka method assume that inclusions are randomly distributed but uniformly oriented, the random orientation and shape of steel fiber inclusions need to be explored with aids of RVE finite element analysis as shown in Figure 2 and 3.



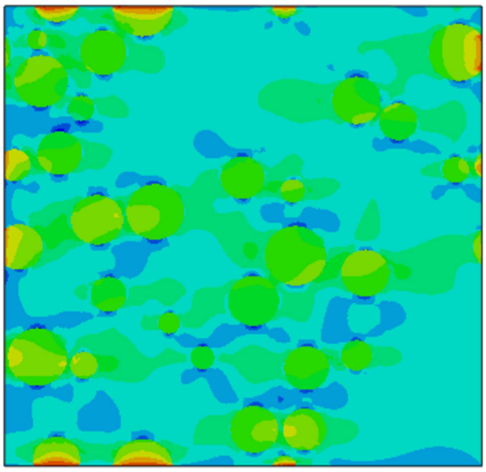
(a) Tensile crack in mortar



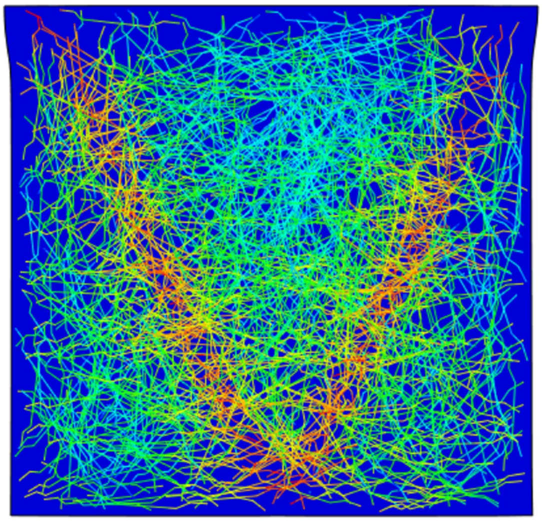
(b) Longitudinal stresses in steel fiber

Figure 2: Direct three-phase SFRC composite model (mortar-aggregates-steel fiber)

SFRC modeling techniques employ a two-step Mori-Tanaka homogenization approach: (1) concrete is first treated as a two-phase composite and homogenized into an equivalent concrete; (2) steel fibers are then incorporated into this equivalent concrete, ultimately determining the effective properties of the resulting SFRC.



(a) Heterogeneous mortar: stress contour



(b) Homogenized mortar with SF in compression

Figure 3: Two-phase (homogenized concrete-steel fiber) model: Two-step homogenization

In addition to the above, the tensile properties of SFRC are influenced by the interfacial characteristics between the concrete and the steel fibers, which can be expressed in terms of bond strength. At this stage, relative separation and interaction of the interface (zero-thickness surfaces) were represented using penalty conditions, along with mixed-mode damage as shown in Figure 4.

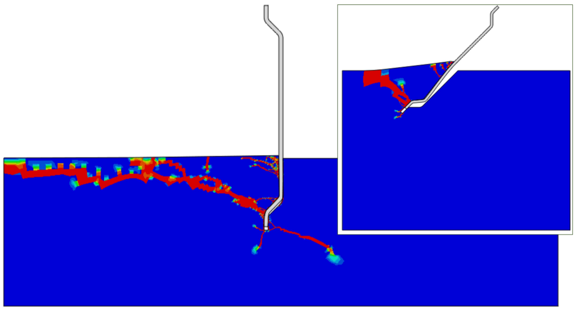


Figure 4: Pull-out simulation for single hooked-end steel fiber with zero-thickness interface elements in adhesive surfaces between steel fiber inclusion and base concrete

3 CALIBRATION ANALYSIS

Six round panels have been tested according to the ASTM C1550-10 recommendations [2], by recording the force-deflection and the crack patterns [3]. The slab has a diameter of 600 mm and a thickness of 60 mm. It is supported at three equally spaced points around its circumference, with an angular separation of 120° between each support. An LVDT is positioned below the slab to measure deflection at the center of the slab directly beneath the central load. The load is applied through a circular loading plate, and the load transfer mechanism is shown directly in line with the central axis of slab. In order to calibrate the flexural behaviors of SFRC panel, Figure 5 and 6 show the force-central deflection curve, and FE analysis and crack patterns.

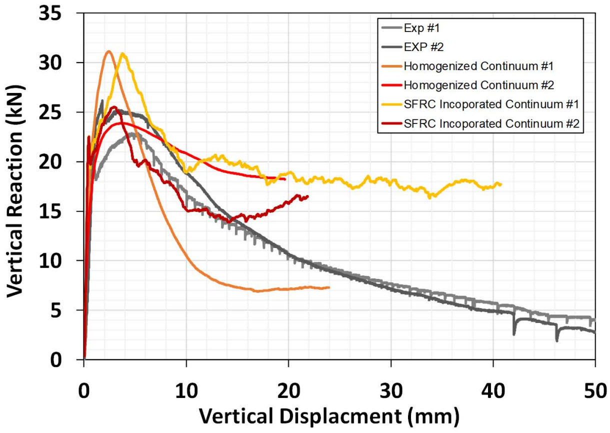
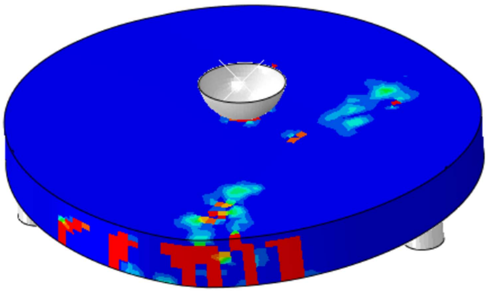
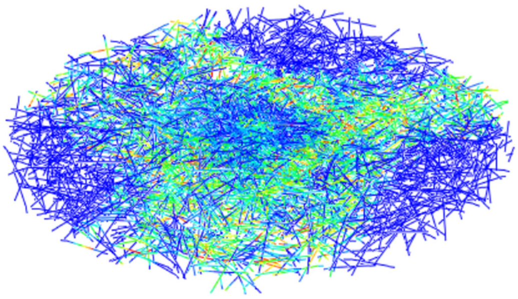


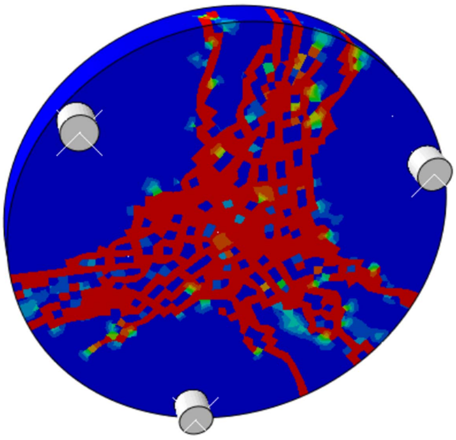
Figure 5: Load-deflection curve of SFRC circular slab under the upward punching shear load



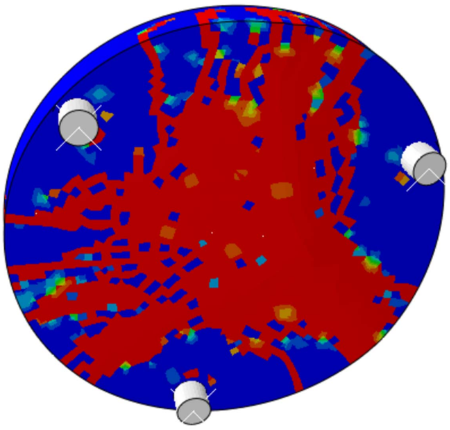
(a) Initial loading stage: Tensile crack



(b) Longitudinal stresses in steel fiber



(c) Intermediate loading stage: Tensile crack



(d) Final loading stage: Tensile crack

Figure 6: Failure patterns of SFRC circular slab under the upward punching shear load

4 BENCHMARK SIMULATION

The necessity of enhancing the punching shear performance of slabs, such as those in multi-unit buildings and underground parking lots, continues to be a subject of study. As part of these efforts, hybrid slabs combining conventional flexural reinforcement with steel fibers are being utilized to achieve more ductile behavior and reduce the risk of brittle failure. To validate previously conducted failure experiments [4] and perform parameter analysis, a nonlinear finite element analysis model was employed. This model examined the overall punching shear load-displacement relationship, local reinforcement strain, and concrete crack patterns. The materials used consist of C50-grade concrete with a water-to-cement ratio of 42%, incorporating hooked-end steel fibers with an aspect ratio of 67, added at a dosage of 60 kg/m³. The steel fibers have a tensile strength of 1,900 MPa. Nonlinear material behavior is modeled using compression softening and tension softening relationships for C50-grade concrete, along with a tensile hardening relationship for conventional reinforcement. The slab analyzed is a square slab with dimensions of 2,550 mm in length and 180 mm in thickness, as depicted in Figure 7. The slab incorporates conventional flexural reinforcement and hooked-end steel fibers in a finite element model. The concrete portion is modeled with 3D solid elements, and its nonlinear behavior is simulated using a compression damage model [5]. Figure 7 shows the application of an upward vertical punching shear load at the center of the slab, along with the potential patterns of radial cracking that may occur during loading up to failure.

5 CONCLUSIONS

This study employs finite element analysis to predict the load-central deflection relationship and strain levels of conventional flexural reinforcement in slabs under punching shear loading conditions. It includes the validation of local crack initiation and propagation patterns, as well as failure modes that contribute to the overall nonlinear behavior. To address the relatively high levels of unexpected uncertainty in punching shear conditions and to ensure potential ductility, it is necessary to develop an analytical model that can evaluate the shear resistance performance of concrete slabs reinforced with conventional flexural reinforcement and randomly oriented hooked-end steel fibers in the future.

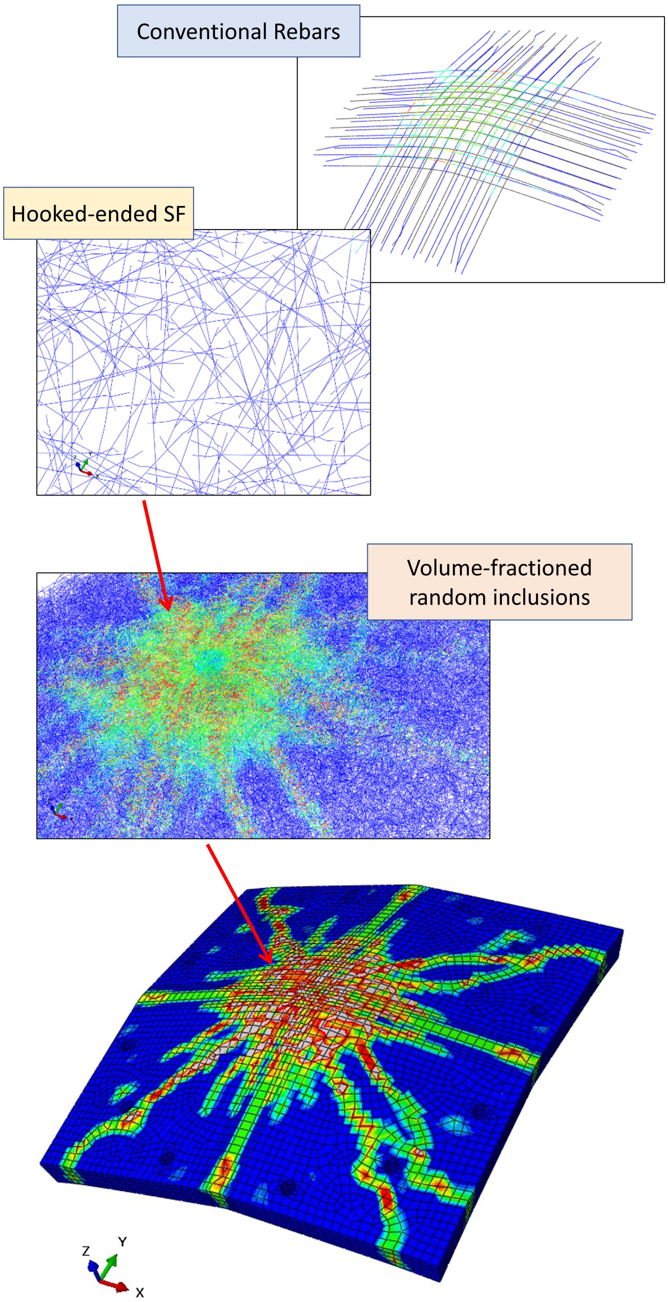


Figure 7: Modeling detail for steel fibers, conventional rebars, and failure pattern of the slab at the final loading stage.

6 ACKNOWLEDGEMENT

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