Punching Shear Strength of Reinforced Concrete Flat Slabs with Macro Synthetic Fibers

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Abstract. Discrete macro fibers such as steel and synthetic have been recognized as an attractive material to improve concrete properties such as flexural toughness, shear strength, impact characteristics, deflection capacity and concrete ductility. In this paper, the effect of macro synthetic fibers on punching shear resistance and cracking behaviour of reinforced concrete slabs was investigated. A total of six reinforced concrete slabs were designed, instrumented and tested in displacement control mode, under monotonic center-point load in simply supported configuration. Synthetic fibers were added to the concrete slabs at dosage rates of 0.5% and 1% by volume. The results have shown a significant increase of the punching shear strength, energy absorption capacity and ductility of the slabs. The addition of 0.5% and 1% of macro synthetic fiber to the slab increased punching shear strength by 30% and 70% and increased energy absorbance by 40% and 80%, respectively.

1. Introduction
Punching shear failure is a type of failure in reinforced concrete slabs subjected to high localized forces. This type of failure is generally very brittle and occurs suddenly without warning. Punching failure can be prevented using traditional reinforcement methods such as shear stirrups, studs or drop panels. Integrating discrete macro fibers into concrete mix has been recognized as an effective method to improve the punching strength of concrete slabs [1-4]. The use of synthetic fibers increase the punching capacity, improve the energy absorption performance of the column–slab connection and transform brittle-type punching shear failure into a gradual and ductile shear failure [2,3]. These fibers are manufactured from polymer-based materials such as nylon, polyethylene and polypropylene. Synthetic fibers are added during or before mixing process. Synthetic fibers are highly durable, have lesser unit weight and unlike steel fibers, they are non-corrosive. Previous experiments in literature indicate that fibers contribution to punching shear strength lies in their bridging effect to limit crack propagation and minimize their width at critical sections. This bridging effect considerably enhances the post-cracking tensile strength at the tensile zone. It is believed that this improvement is basically attributed to synthetic fibers tensile and bonding strength with concrete. In recent years, many research papers are published focusing on punching shear strength in flat slabs containing steel fibers [5,6]. Utilization of steel fibers to enhance punching shear strength of flat plates has been introduced by Swamy and Ali, (1982) [5]. They reported enhancement in maximum shear load capacity between 23%
to 42% corresponding to adding steel fiber volume ratio contents from 0.6 percent (48 kg/m$^3$) to 1.2 percent (96 kg/m$^3$). In 1995, M. Harajli [6] tested twelve small-scaled slab-column specimens. His study results showed that adding steel fibers up to 2.0 percent (160 kg/m$^3$) of the total volume ratio increased the ultimate punching capacity by about 36 percent compared with plain concrete slabs. However, changing thickness had no noticeable effect on the ultimate punching capacity. In 2010 Cheng and Gustavo [7] tested 10 slabs. Their results have shown that the addition of steel fibers led to an increase in punching shear capacity and deflection capacity particularly when 1.5 % of fibers were used. Moreover, the results showed that slabs with lower flexural reinforcement ratio exhibited a change in failure mode from punching shear to flexural yielding. In 2012 L. Nguyen-Minh, M. Rovňák, and Toan Tran-Quoc [8] tested 12 flat slabs. The fiber content was (30, 45, 60 kg/m$^3$). They concluded that using steel fibers increases punching shear capacity up to 39%. It also reduces the average crack width up to 40% considering serviceability limit state. Furthermore, up to 36% reduction of deflection was observed. It was noticed that fibers shape and length to diameter ratio should be taken into account in calculations of the punching shear capacity. In 2016 Ahmed Abdel-Rahman, Nasr Hassan and Adel Soliman [9] tested 14 slab-column connections. Their results showed that using steel fiber increased both the failure load and energy absorbing capacity. It was found that the higher the steel fiber ratio was the higher the ultimate load carrying capacity of the specimens. Increasing the steel fiber by 1.5% enhanced the ultimate capacity of the specimens by 24%. In 2018 T.musse and E. liberati [10] tested 8 square slabs. The fiber percentage used was 0.9%, which is equivalent to 70.6 kg of fibers per cubic meter of concrete. Their results have shown that the use of fibers increased ultimate loads by 26% for the slab without shear reinforcement and increased approximately 12% for the slabs with shear reinforcement.

Research on punching shear strength of slabs with synthetic fibers however, is still scarce in the existing literature and thus more experimental work is needed which motivates the current study. The current paper presents and discusses experimental results obtained by testing to failure simply supported slabs containing macro synthetic fibers under center point loading.

2. Experimental program

2.1. Materials

The concrete mixture proportions and properties used in casting the six slabs are provided in Table 1. The concrete mix was designed to achieve a 28-day compressive strength of 30 MPa. Ordinary Portland cement was used with dune sand and aggregates having (5 mm, 10 mm, 20 mm) maximum size. CONCERA™ SA8476 was used as an admixture, it is a high efficiency polycarboxylate-based superplasticizer intended for the production of Control Flow Concrete, a highly flowable concrete utilizing conventional mix designs with extended slump-flow life and high resistance to segregation. Test slabs were reinforced with 12 mm diameter rebar of 420 MPa yield strength.

| Mix         | OPC | Aggregates | Dune Sand | Free W/C | Total water | Fibers | CONCERA |
|-------------|-----|------------|-----------|----------|-------------|--------|---------|
| Control     | 360 | 601        | 271       | 581      | 372         | 0.58   | 227     | 0.5     |
| 0.5% Fiber  | 360 | 601        | 271       | 581      | 372         | 0.58   | 227     | 4.6     |
| 1% Fiber    | 360 | 601        | 271       | 581      | 372         | 0.58   | 227     | 9.2     |

The macro synthetic fiber used in this testing program is “STRUX ® 90/40” (Figure 1) which is a commercial product used in many industrial applications. The main components of this polymeric fiber type are polypropylene and polyethylene. The length of individual fiber is 40 mm with aspect
ratio of 90. "STRUX® 90/40” role in concrete mix is purely mechanical and will not interfere with cement hydration. Table 2 shows "STRUX® 90/40” properties.

### Table 2. “STRUX® 90/40” Properties

| Parameter                   | Value          |
|-----------------------------|----------------|
| Specific gravity            | 0.92           |
| Absorption                  | None           |
| Modulus of elasticity       | 1,378 ksi (9.5 GPa) |
| Tensile strength            | 90 ksi (620 MPa) |
| Alkali, acid & salt resistance | High         |

2.2. Slab specimens and testing procedure

A total of 6 slabs were tested. All slabs are of the same thickness of 100 mm and tensile reinforcement ratio \( \rho = 0.9 \% \). The slab dimensions were the same for all six specimens, 1.5 m x 1.5 m with a 100 mm square column stub at the centre of the slab for load application. The slabs were divided into three groups with respect to their fiber content as follows: 2 plain concrete slabs with no fiber; 2 slabs with 0.5 % of macro synthetic fiber and 2 slabs with 1 % of macro synthetic fiber. The addition of fibers by up to 1% is commonly and practically used in industrial applications and previous studies. Duplicate slabs were tested to obtain average response and to assess the reliability and reproducibility of the test. Slabs were cast and cured under similar conditions and tested after 28 days. Measured slumps of synthetic fiber reinforced concrete and plain concrete were 160 mm and 145 mm, respectively. Table 3 provides details of slabs tested in this study.

### Table 3. Slabs details

| Slabs | Quantity | Dimension (mm) | Thickness (mm) | Effective depth (mm) | Steel ratio % | Fiber % | Compressive strength (Mpa) |
|-------|----------|----------------|----------------|----------------------|---------------|---------|---------------------------|
| Group 1 | 2        | 150 x 150      | 100            | 75                   | 0.9           | 0       | 28.0                      |
| Group 2 | 2        | 150 x 150      | 100            | 75                   | 0.9           | 0.5     | 29.0                      |
| Group 3 | 2        | 150 x 150      | 100            | 75                   | 0.9           | 1       | 29.45                     |

All slabs were tested under center point load. The load was applied monotonically in displacement control mode at a rate of 0.015 mm/sec. A vertically oriented hydraulic actuator connected to a steel reaction frame was used for application of the load to the slab specimens, as shown in Figure 2. All slabs tested were simply supported along four edges. Linear Variable Displacement Transducers (LVDTs) were placed under the slab in mid-span to monitor the deflection. At each load level, vertical deflection and crack patterns on the bottom surface of all slabs were recorded.
3. Results and discussions

3.1. Cracks and failure mode

Punching shear failure was primarily occurred in all the tested slabs. This was clearly evidenced by the column stub punch through the slab top surface and defined by the cracking patterns in the bottom of the slab surface. Visual observation of cracks intensity provides qualitative assessment of slabs punching behaviour. Slabs without fibers failed abruptly and with little cracking intensity in the punching area, and some parts of the bottom concrete cover fell apart (Figure 3a).

Unlike the slabs without fibers, slabs with fibers have failed in more ductile manner, the punching area became more defined and smaller than slabs with no fibers due to bridging effect of fibers (Figures 3b and 3c). Moreover, the crack intensity increased as the percentage of fibers increased. Furthermore, the slabs with 1% fiber have shown signs of flexural cracks which indicates that fibers increased punching shear capacity to a level where flexural yielding is induced (Figure 3c).

3.2. Peak Loads

Punching load and slab deflection were recorded during the test. Load-deflection curves for all slabs are presented in Figure 4. The results in Figure 4 show that fibers increased the punching load capacity of the slab. Adding 0.5% and 1% of macro synthetic fibers to the slab increased the peak punching load (P_u) by 30% and by 70% respectively relative to control slabs as shown in Figure 5. The average peak load of the duplicate slabs is reported in Figure 5 and summarized in Table 4.
3.3. Energy Absorbed

Energy absorption is defined by the total area under the load-deflection curve. The areas under the curves were computed. To perform consistent comparison, the area under the load-deflection curves was calculated up to 40 mm central deflection at which the control slabs completely failed. The ductility of control slabs was much lower than the slabs with fibers which failed at 75mm deflection. The computed absorbed energy ($E$) was normalized relative to the control slab ($E_c$) and illustrated in Figure 6. The result shows that macro synthetic fibers at 0.5% and 1% fibers increased the absorbed energy (relative to control) by 40% and 80%, respectively.

3.4. Comparison with previous studies

The results obtained from 62 full scale tests of slabs with steel fibers reported in the literature by Higashiyama [4] was compiled and used in the analysis. Minitab® 18 software was used to establish a linear regression model for the compiled results. The following regression model (equation 1) with a mean square error ($R^2$) of 0.89 was obtained as follows:

$$P_u = -361.2 -0.71t +4.13d +46.2\rho_s +58.6\rho_f +1.341L +1.155fc'$$  

Where: $P_u$ is the maximum punching load for the slab in kN. $t$ and $d$ are the slab thickness and effective depth, respectively in mm. $\rho_s$ and $\rho_f$ are the steel and fiber percentages respectively. $L$ is the loading plate length in mm, and $fc'$ is the compressive strength of concrete. The model developed for steel fibers in equation (1) was used to predict the punching shear capacity of slabs with macro synthetic fiber. Experimental and predicted values by the regression model are displayed in Figure 7.
The results show that the model for steel fibers predict the results with synthetic fibers reasonably well. Furthermore, the current test results fit within the previous studies done on steel fibers.

\[ R^2 = 0.8966 \]

![Figure 7. Experimental and predicted results for current and previous studies.](image)

4. Conclusion

This paper discussed the enhancement of punching shear strength in concrete slabs using macro synthetic fibers. A total of six slabs with thickness 100 mm were tested: 2 plain concrete slabs with no fiber, 2 slabs with 0.5% fibers and 2 slabs with 1% fibers. Slabs were tested under center point load in displacement control mode. The results have revealed a significant improvement in the punching shear capacity, energy absorption and ductility of the reinforced concrete slab. The addition of 0.5% and 1% of macro synthetic fiber to the slab increased punching shear strength by 30% and 70% and increased energy absorbance by 40% and 80%, respectively. Slabs without fibers behaved in a brittle way whereas slabs with fibers have failed in more ductile manner. The load-deflection curves of the tested slabs showed significant increase in ductility due to the addition of macro synthetic fibers. However, different slab geometries and boundary conditions shall be further considered in future studies to better assess and evaluate punching shear behavior of fiber reinforced concrete slabs.

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