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Punching Shear Strength of Steel Fiber Reinforced High Strength Concrete

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***Abstract*—This paper investigates the punching shear behavior of steel fiber reinforced concrete (SFRC) slabs. Experiments involved the testing of four SFRC and two control slabs against a punching load applied through a steel rod. The slabs were 600 mm square, 90 mm thick reinforced with 8 mm diameter steel rebars. SFRC was produced by mixing 1.2% and 1.4% hooked ended steel fibers in plain high strength concrete of 64.5 MPa grade. Effect of steel fibers on the punching shear cracking behavior and resistance of the slabs was investigated. The results show a significant increase in the punching shear capacity (34%) and considerable improvement in the cracking behavior. The failure of control slabs was brittle, while the SFRC slabs failed in a ductile manner. At serviceability limit state, significant reduction in the average crack width of the SFRC slabs was observed.**

***Keywords*—punching shear, steel fibers, reinforced concrete, slab, cracking**

I. Introduction

Punching shear failure of reinforced concrete (RC) slabs is a major concern for the structural designers of buildings and bridges [1]. This type of failure is more common in bridge decks supported by girders under the action of repeated wheel loads [2,3]. Shear failure, being brittle, is a matter of serious concern for bridge engineers. Once, the punching shear failure occurs, resistance of the structure is significantly reduced, which causes the separation of slab, and ultimately leads to the collapse of whole structure.

To increase punching shear capacity of slab, a variety of methods have been proposed such as: (i) providing traditional shear reinforcement using stirrups but this method is not applicable to slabs with shallow depth less than 150 mm [4]; (ii) using headed-studs but this needs much time in their installation [5]; (iii) using externally bonded metallic sheets [6,7] or fiber reinforced polymer (FRP) sheets [8,9,10]; though these serve the dual purpose of flexural as well as the shear enhancement but these are more effective in flexure and are time consuming.

The earliest use of fibers to strengthen materials dates back to the ancient time when clay bricks were reinforced with straw. Improvements in the tensile capacity of concrete have been observed from their use. However, as fibers are discontinuous and are randomly distributed throughout the cementitious matrix, they are not as efficient as conventional reinforcing bars in withstanding tensile stress. Thus, the main purpose of the inclusion of fibers in concrete is to arrest the crack propagation and increase the energy absorption capacity and ductility. Recently, the use of steel fibers to improve the punching shear resistance and cracking control of slab-column connections has proven to give good results [11,12,13,14,15,16,17]. Moreover, steel fibers also indicate high effectiveness in structures subjected to lateral loads such as seismic because of their ability of energy dissipation in the structures [18,19]. Nevertheless, so far, few researches have studied it exhaustively due to which the knowledge of punching behavior of SFRC slabs is limited.

The paper presents an experimental study of the effect of steel fibers on the punching shear resistance and cracking behavior of SFRC slabs. Two control and four SFRC small-scale singly reinforced slabs were tested against punching load.

II. Experimental Program

A. *Materials and Test Specimens*

Six square RC slabs of 600×600×90 mm size and reinforced with $\phi 8@100$ mm c/c bars (0.71% steel in both directions) were used in this study. The slabs were singly reinforced with rebars provided on the rear face of the slab. The reinforcement details of slabs are shown in Figure 1.

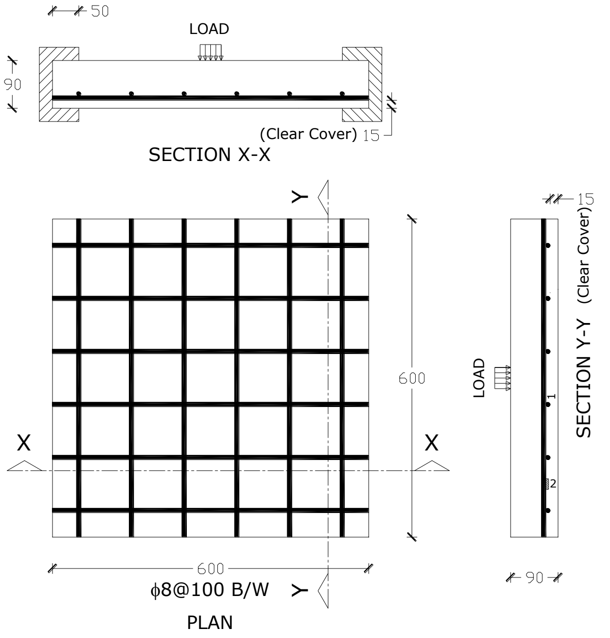

Figure 1. Reinforcement details of test slabs (All dimensions in mm).

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Test slabs were cast using concrete produced with ordinary Portland cement, natural sand, coarse aggregate, and a water reducing and retarding admixture, plastiment. Two volume percentages of 1.2% and 1.4% of hooked ended steel fibers were used in the test program (Figure 2). The length and diameter of individual steel fibers were 60 mm and 0.75 mm respectively.

All slabs were cast at the same time from the same batch of concrete. Adequate compaction was achieved by using a vibrator. Observed slumps of plain concrete and SFRC were 134 mm and 91 mm. All slabs were cast and cured under similar conditions and tested after 28 days.

The tensile strength and elastic modulus of steel fibers were 1100 MPa and 200 GPa respectively. Standard cylinder specimens (150 mm) were used to determine the compressive strength of concrete. Average concrete compressive strengths are summarized in Table I. The mechanical properties of rebars were determined by tension tests. The average yield stress of the rebars was 510 MPa and the modulus of elasticity was 205 GPa.

TABLE I. CONCRETE MIXES AND COMPRESSIVE STRENGTHS

Mix	Slab IDs	Percentage of fiber by volume (by weight)	Compressive strength of concrete (MPa)
M0	M0-S1, M0-S2	0.0 (0.00)	64.5
M1	M1-S1, M1-S2	1.2 (3.93)	73.5
M2	M2-S1, M2-S2	1.4 (4.58)	74.4

Figure 2. Steel fibers used in the study.

B. *Test Method*

The slabs were clamped on two opposite edges and tested under punching shear force which was applied through a steel rod. The shear load was applied at the center of the slab and therefore there were no slab rebars in the line of the load. This was done for predicting conservative punching shear loads. Three linear variable differential transformers (LVDTs) were used to determine deflection at mid-span and at a quarter of span of the slabs. The loading rate was approximately 20 kN per min. At each load increment, slab deflections and crack patterns were recorded.

The test setup employed for testing slabs in punching is shown in Figure 3.

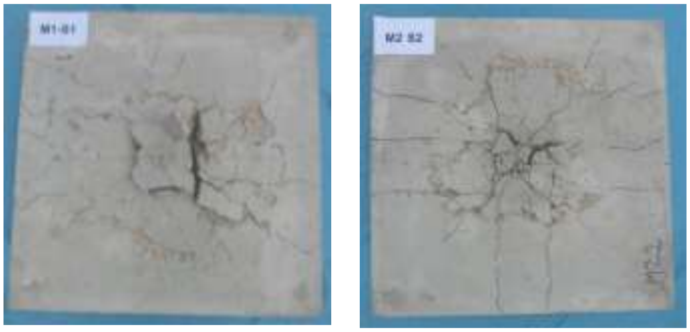
Figure 3. Test Setup.

III. Test Results and Discussion

A. *Failure Pattern*

The crack patterns on the back face of one of the slabs of each type are shown in Figure 4.

a) M0- Control (without fibers)



b) M1-With steel fibers (1.2%) c) M2-With steel fibers (1.4%)

Figure 4. Crack patterns in the back face of control and SFRC slabs.

The control slabs without fibers failed in a brittle manner, where, concrete cover of the back face fell apart and the penetrating rod made a smooth hole through the slab thickness. On the other hand, the SFRC slabs failed in a ductile mode. In these slabs, cracks on the back face were formed uniformly with smaller width in the beginning due to the bridging effect of steel fibers and growing with the increase in load. There was bulging of concrete at the back face (Figure 4b, c) because of the concrete mass held together due to the presence of steel fibers. This was responsible for spreading of cracks on the back face to a wider area. These factors contributed towards significant improvement of concrete ductility. At a load level of 40% of the ultimate load of control slab (approximately 32 kN), the control slabs without fibers showed an average crack width of 0.28 mm. Whereas at the same loading level, the average crack width observed in M1 slabs was 0.12 mm and that demonstrates the role of fibers in the reduction of the crack width for SFRC slabs.

B. *Load Displacement Behaviour*

Figure 5 shows the load-displacement variation for the test slabs. In general, there are three stages/zones of the load-displacement curves of all tested slabs. First zone is an almost linear relationship between load and displacement. This zone of load-displacement curve is called elastic zone and the first crack occurs at the end of this zone. It is observed from the figure that the addition of steel fibers has contributed to the enhancement in the initial stiffness which increases with the increase in the volume fraction of steel fibers as the curve becomes steeper for higher percentage of steel fibers. Second, the zone of the load-displacement curve from the end of first zone to the peak which is represented by a nonlinear relationship between load and displacement showing gradual degradation in the stiffness due to punching and cracking of concrete. The third zone is post-peak descending portion of the load-displacement curve. For control slabs, post-peak drop in load is sharp as compared to SFRC slabs because of the bridging action steel fibers which contribute after the formation of cracks.

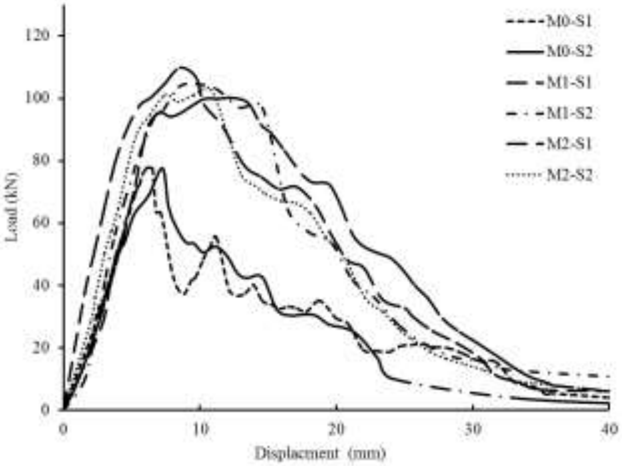


Figure 5. Load-displacement variation for punching of RC and SFRC slabs.

C. *Load Carrying Capacity and Energy*

Figure 6 shows the average ultimate punching load capacity of slabs. The percentage increase in load with respect to the control is also mentioned in the figure. It can be seen that there is a good improvement in the ultimate punching load capacity due to the addition of steel fibers. According to these results, the ultimate punching load capacity of SFRC slabs (M1, M2) increased by about 34% in comparison with control slab (M0). This increase in ultimate load capacity is due to the resistance provided by steel fibers against punching which help in distributing the punching load on a wider area and thus delaying the shear cracks.

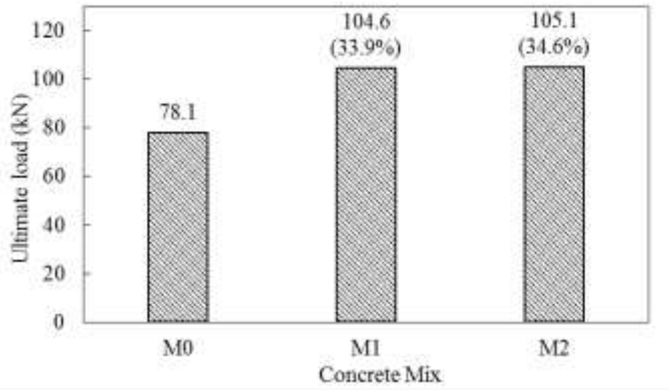


Figure 6. Ultimate load capacity of control and SFRC slabs.

Figure 7 shows the average energy absorption by plain concrete and SFRC slabs. The energy absorption capacity of the test specimens was evaluated based on the area under the punching shear load versus displacement response. The percentage increase in energy with respect to the control is also mentioned in the figure.

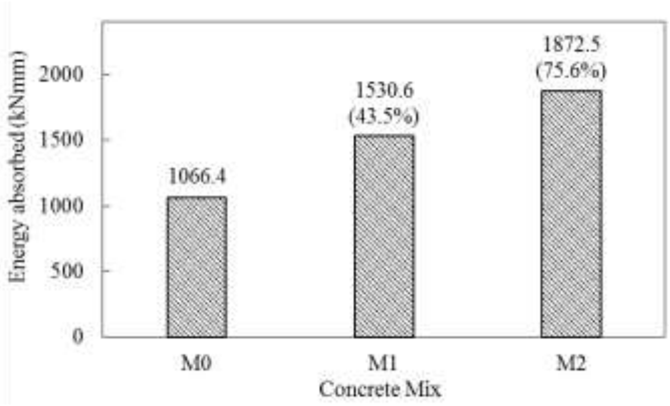


Figure 7. Energy absorption in punching of control and SFRC slabs.

As can be seen, the addition of fibers to the concrete led to an increase in energy absorption, particularly in the specimens with 1.4% steel fiber volume fraction by about 75%. For the fiber-volume fraction of 1.2%, the energy absorbed in punching of the specimens has increased by 43%. Thus the increase in the quantity of steel fibers has significant effect on the energy absorption in punching whereas similar effect is not evident in the ultimate shear load. This is due to role of steel fibers in the process of punching. The steel fibers have major role in the post-peak shear resistance by increasing the size of shear cone by holding concrete together and bridging the shear cracks.

IV. Conclusions

The addition of 1.2% steel fibers (by volume) in concrete lead to 34% increase in punching resistance of SFRC slabs and improved ductility. Further increase in steel fibers volume fraction to 1.4% had insignificant effect on the ultimate punching load but this lead to considerable increase in energy absorption. The average crack width of the slabs was reduced significantly in specimens with steel fibers compared to the control.

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