PUNCHING SHEAR RESISTANCE OF STEEL FIBER REINFORCED CONCRETE FLAT SLABS

L. NGUYEN-MINH[1*], M. ROVŇÁK[2†], T. TRAN-QUOC[3], and K. NGUYEN-KIM[4]

[1, 3, 4] *Division of Structural Design, Faculty of Civil Engineering, HCMUT, Vietnam*
[2] *Institute of Technical and Technological Safety, University of Security Management, Slovakia*

ABSTRACT

This paper deals with behavior and capacity of steel fiber reinforced concrete (SFRC) flat slabs under punching shear force. A total of twelve small-scale flat slabs of different dimensions that consisted of nine SFRC and three control steel reinforced concrete (SRC) ones were tested. Effect of steel fibers amount on punching shear cracking behavior and resistance of the slabs was investigated. The results show a significant increase of the punching shear capacity and considerable improvement of cracking behavior as well as good integrity of column-slab connection of the slabs with fibers. The slabs without fibers failed suddenly in very brittle manner, while, the fiber reinforced ones collapsed in more ductile type. At serviceability limit state, a strong reduction of average crack width up to approximately 70.8% of the SFRC slabs in comparison with SRC ones was observed. In addition, based on experimental data obtained from the author's study and literature, the paper performed an evaluation of accuracy of existing models and formulas in previous studies that used to predict punching shear resistance of SFRC slabs. The results from the evaluation show that the existing formulas gave inaccurate results with a large scatter in comparison with the testing results, and thus, a new formula should be proposed for more accurate estimation of punching shear resistance of SFRC slabs.

Keywords: steel fiber reinforced concrete (SFRC); flat slab; punching shear resistance; crack; evaluation.

1. INTRODUCTION

Structural systems with reinforced concrete flat slabs are used commonly in practice. In such systems, the slabs are supported directly by columns without beams that helps to reduce considerably building height and increase used space. However, there is an important problem existing in this system that is punching shear failure of the slabs due to high concentration of stress in vicinity of slab- column connections. This failure type is very dangerous because of its brittle

[*] Corresponding author: Email: minhlong_nguyen@yahoo.com

[†] Presenter: Email: marian.rovnak@gmail.com

nature. Once, the punching shear failure occurs, resistance of the structure is significantly reduced, which causes separation of the column and slab, and then lead to collapse of the whole structure.

To increase punching shear capacity of flat slab, a variety of methods have been proposed such as: *i*) traditional shear reinforcing method using stirrups but this method is inapplicable to slabs with shallow depth less than 150 mm (ACI 318-2002); *2i*) new method using headed-studs but this one need much time for construction (Feretzakis 2005). Recently, new technique using steel fibers to improve the punching shear resistance and cracking control of slab-column connections has been proven to give good results (Alexander and Simmonds 1992; Theodorakopoulos and Swamy 1993; Harajli et al. 1995; McHarg et al. 2000, Naaman et al. 2007; Cheng and Montesinos 2010a). Moreover, steel fibers also indicate high effectiveness in structures sustained lateral loads i.e. seismic because of their ability to absorb energy dissipation of the structures (Megally and Ghali 2000; Cheng and Montesinos 2010b). Nevertheless, so far, it can be seen that researches related to this new method are only a few. This fact causes knowledge of behavior and punching shear capacity of SFRC flat slabs to be still limited.

Currently, several formulas exist which were proposed for estimation of punching shear capacity of SFRC slabs (Shaaban and Gesund 1994; Harajli et al. 1995; Choi et al. 2007). Formulas of Shaaban and Gesund and of Harajli were pure-empirical based on punching model of ACI 318. These formulas are simply and easy to use, but due to their experimental nature, the formulas can not determine mechanisms of punching shear transfer quantitatively that can lead to inaccurate results in comparison with tests results. Whereas, Choi's formula was derived semi-analytically by using a strength model which directly links failure criterion of FRC to punching shear capacity of slab-column connections. The formula was established based on assumption that yielding of tensile reinforcement occurs prior to punching shear failure. However, this assumption can be valid only in case of thin slabs (large span to thickness ratio) where behavior of slabs is dominated by flexural deformation. Moreover, effect of dowel action of tensile re-bars on the punching shear resistance of slabs is ignored in all of formulas that could decrease their accuracy in case of slabs with higher reinforcement ratios.

The paper presents an experimental study of effect of steel fibers on the punching shear resistance and cracking behavior of SFRC slabs, in which, a total of twelve small-scale flat slabs of different dimensions was tested. Moreover, the paper provides evaluation of accuracy of existing formulas used to predict the punching shear capacity of SFCR flat slabs based on data of the authors and other researchers.

2. EXPERIMENTAL PROGRAM

2.1. Materials and test specimens

Testing slabs were made from concrete which contained Portland cement, natural sand, coarse aggregate, and plasticiment (**Table 1**). Dramix hooked steel fibers RC-80/60-BN were used in the test program. The length and diameter of individual fibers were 60 mm and 0.75 mm. The tensile strength and elastic modulus of fibers were 1100 MPa and 200 GPa. Cube specimens (150 mm) were used to determine the compressive $f_{c,cube}$ and splitting tensile strengths $f_{sp,cube}$ of concrete. The average concrete strengths $f_{c,cube}$ and $f_{sp,cube}$ were summarized in **Table 2**. Steel re-bars of 10 mm diameter were used as tensile reinforcement for slabs. The mechanical properties of re-bars were determined by tensile tests. The average yield stress f_y and ultimate tensile strength f_u of the re-bars were 492 MPa and 667 MPa. Their modulus of elasticity E_s was 210 GPa.

Table 1: Concrete mix proportions

Materials	**Quantity per 1 m^3**
Cement Holcim PC40	453 (kg)
Sand, 0-4 mm	624 (kg)
Coarse aggregate, 22 mm	1242 (kg)
Water	181 (l)
Sika Plastiment 96	5 (l)

A total of 12 slabs with different dimensions were tested. All slabs have same 125 mm depth and tensile reinforcement ratio ρ = 0.66%. The slabs were divided into three groups. Each group included three SFRC slabs and one control conventional reinforced concrete slab (**Table 2**). Fiber volume of individual slabs in the group was varied. The slabs in each group were cast at the same time from the same batch of concrete. Adequate compaction was achieved by using a poker vibrator. Observed slumps of SFRC and plain concrete were 122 mm and 96 mm. All slabs were cast and cured under similar conditions and tested after 28 days.

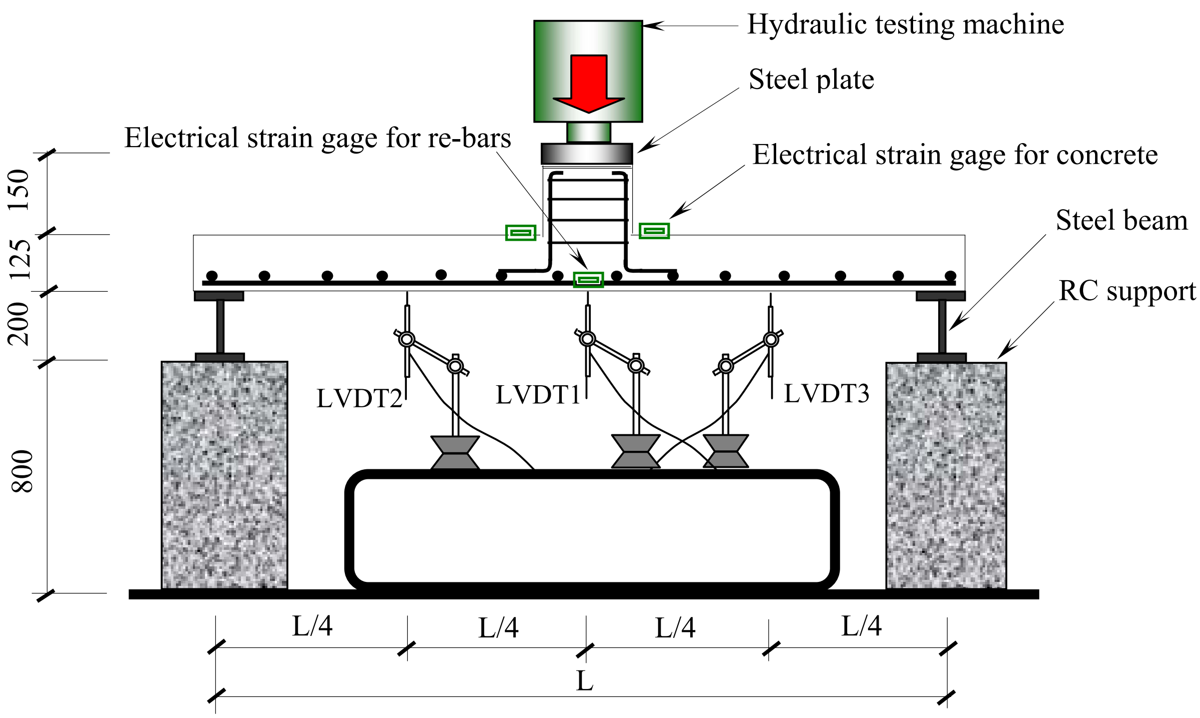


Figure 1: Details of tested slab and test arrangement

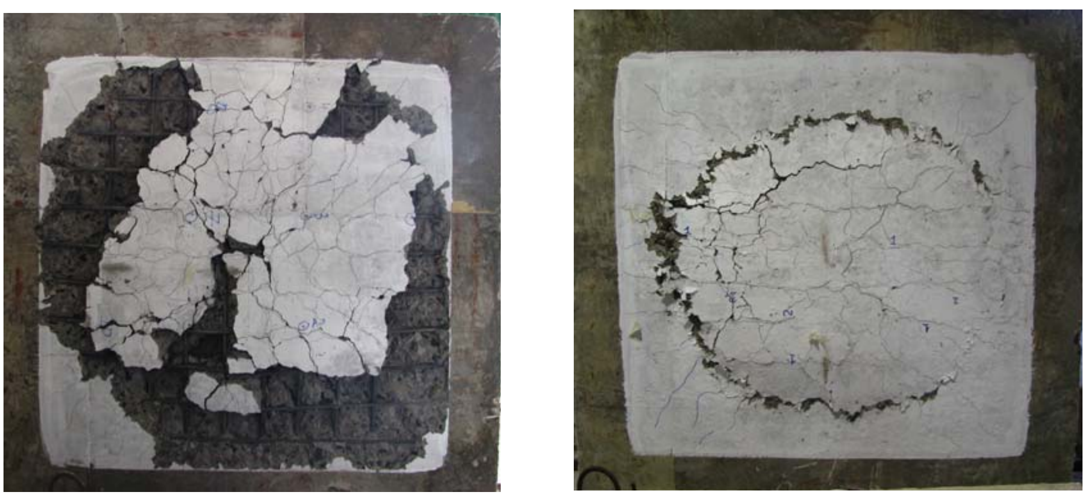
2.2. Test procedure and instrumentation

The slabs were tested under punching shear force. Three linear variable differential transformers (LVDTs) were used to determine deflection at mid-span and at a quarter of span of the slabs. One pair of electrical strain gages bonded on two of tensile re-bars were installed to measure their strain, and one pair on the top surface of slabs near column face to measure concrete strain. The slabs were loaded by a 1000 kN capacity machine under load control in increments of 10 kN up to failure. The loading rate was approximately 15 kN per min. At each load level, deflection, concrete and re-bars strain, and crack development were recorded. All instrumentation locations are shown in **Fig. 1**.

3. TEST RESULTS AND DISCUSSION

3.1. Failure of specimens

The crack patterns for typical slab are illustrated in **Fig. 2**. All slabs failed in punching shear (PS) (**Table 2**). The slabs without fibers failed in very brittle manner, where, concrete cover of bottom surface fell apart. The slabs with fibers failed in more ductile mode. In these slabs, cracks formed uniformly with smaller width due bridging effect of steel fibers. See that, steel fibers improve significantly concrete ductility and integrity of vicinity of slab-column connections.



a) without fibers b) with fibers

Figure 2: Typical failure pattern of testing slabs – bottom face

3.2. Load – displacement responses

Fig. 3 shows behavior of all slabs. In general, the behavior of slabs can be divided into two stages. The first stage also named "stage prior to cracking", in which, the behavior of all slabs was similar, and was approximately linear. In next stage (post-cracking stage), cracks were initiated and developed, which resulted in decrease of stiffness of the slabs and caused difference in the behavior of the slabs. See that, at a same loading level, displacement of SFRC slabs is lower than the one of slabs without fibers. It means that, steel fibers increase stiffness of slabs and this increase is directly proportional to fiber volume used in slabs.

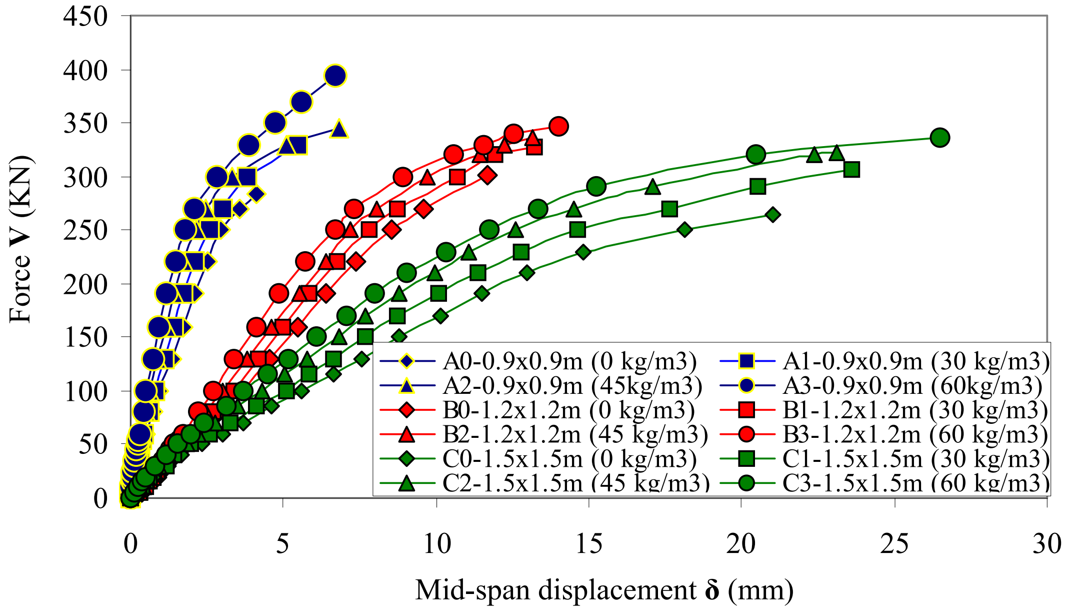


Figure 3: Load - displacement relationships of test slabs

3.3. Cracking behavior of slabs

The effect of fiber volume on the cracking behavior of the test slabs is shown in **Figs. 4**. At a loading level of $0.49V_u$ (approximately 130 kN), where V_u is punching shear capacity of slabs without fibers (264 kN) (**Table 2**), the slabs without fibers show an average crack width of 0.241 mm. At the same loading level, the average crack width observed in SFRC slabs was 0.141 mm and that represents a significant reduction of the crack width for SFRC slabs (approximately 70.8%). At higher load levels, the reduction significantly increases, and ranges in 41.5% to 89.5%.

3.4. Punching shear resistance

Table 2: Test results

Slabs	Dimensions	d (mm)	V_f (kg/m^3)	$f_{c,cube}$ (MPa)	$f_{sp,cube}$ (MPa)	V_{cr} (kN)	V_u (kN)	δ_u (mm)	Failure mode
A0	900×900×125	105	0	27.1	1.95	20	284	4.120	PS
A1		105	30	27.9	2.23	30	330	5.450	PS
A2		105	45	29.2	2.42	40	345	6.820	PS
A3		105	60	31.6	2.57	45	397	6.710	PS
B0	1200×1200×125	105	0	27.1	1.95	25	301	11.71	PS
B1		105	30	27.9	2.23	35	328	23.21	PS
B2		105	45	29.2	2.42	40	337	13.13	PS
B3		105	60	31.6	2.57	45	347	14.04	PS
C0	1500×1500×125	105	0	27.1	1.95	30	264	22.05	PS
C1		105	30	27.9	2.23	46	307	23.63	PS
C2		105	45	29.2	2.42	50	310	23.10	PS
C3		105	60	31.6	2.57	55	326	26.52	PS

The punching shear resistance of test slabs is shown in **Table 2**. See that, steel fibers increase considerably punching shear capacity of slabs and this increase is directly proportional to fiber volume. Adding from 30 to 60 kg/m^3 steel fibers to concrete, increase the punching shear resistance from 16.2 to 39.8% for slabs in group A. For slabs in group B, this increase ranges in 9.0 to 15.3%, and in 16.3 to 23.5% for the ones in group C. The increase of punching shear capacity of SFRC slabs is because of steel fibers help to bridge cracks in the whole concrete volume and transfer tensile stress through two opposite faces of cracks until the fibers are totally pulled-out or broken. For this reason, in stage of initiation and propagation of cracks, tensile zone of SFRC slabs still sustains load. This increases concrete tensile strength and indirectly leads to increase the punching shear resistance of slabs. **Fig. 5** shows clearly effect of fiber volume on the punching shear capacity of test slabs.

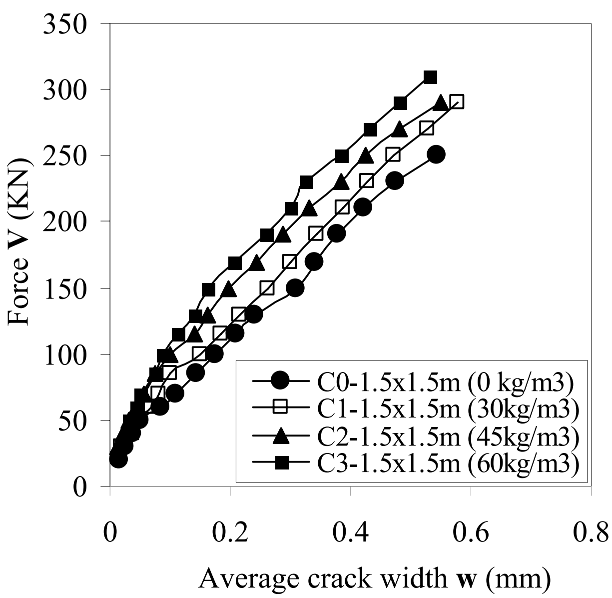


Figure 4: Typical load-crack width relationships of test slabs

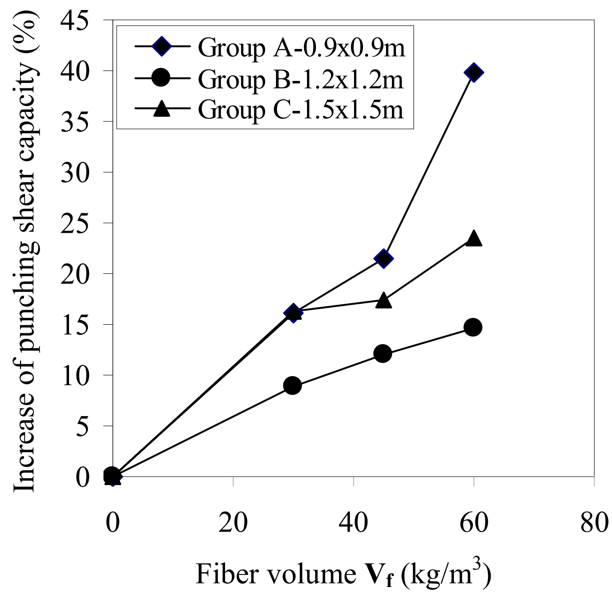


Figure 5: Effect of fiber volume on increase of punching shear resistance of slabs

4. EVALUATION OF EXISTING FORMULAS

This section provides evaluation of accuracy of existing formulas used to predict the punching shear capacity of SFCR flat slabs proposed by Harajli (Harajli et al. 1994), Shaaban and Gesund (Shaaban and Gesund 1994) and Choi (Choi et al. 2007) using results of 73 test slabs of previous (Swamy and Ali 1982; Alexander and Simmonds 1992; Theodorakopoulos and Swamy 1993; Harajli et al. 1994; McHarg et al. 2000; Cheng and Montesinos 2010a) and authors's tests. These 73 experimental results were obtained from the punching shear tests of SFRC flat slabs with different concrete strength (from 12.4 to 59.4MPa), effective depth of slab (from 39 to 139mm), span to effective depth ratio (from 8 to 20), tensile reinforcement ratio (from 0.26 to 1.46%), fiber volume (from 0 to 2%), fiber length to diameter ratio (from 0 to 100), and fiber types. The slabs were all simply supported. They cover a relatively wide spectrum of the material and geometric properties of SFRC slabs used in practice. All of these slabs failed in punching shear. Average value (Mean), standard deviation (STD) and coefficient of variation (COV) of predicted to experimental punching shear capacity ratio $V_{u,pred}/V_{u,exp}$ of individual formulas are defined and presented in **Fig. 6**.

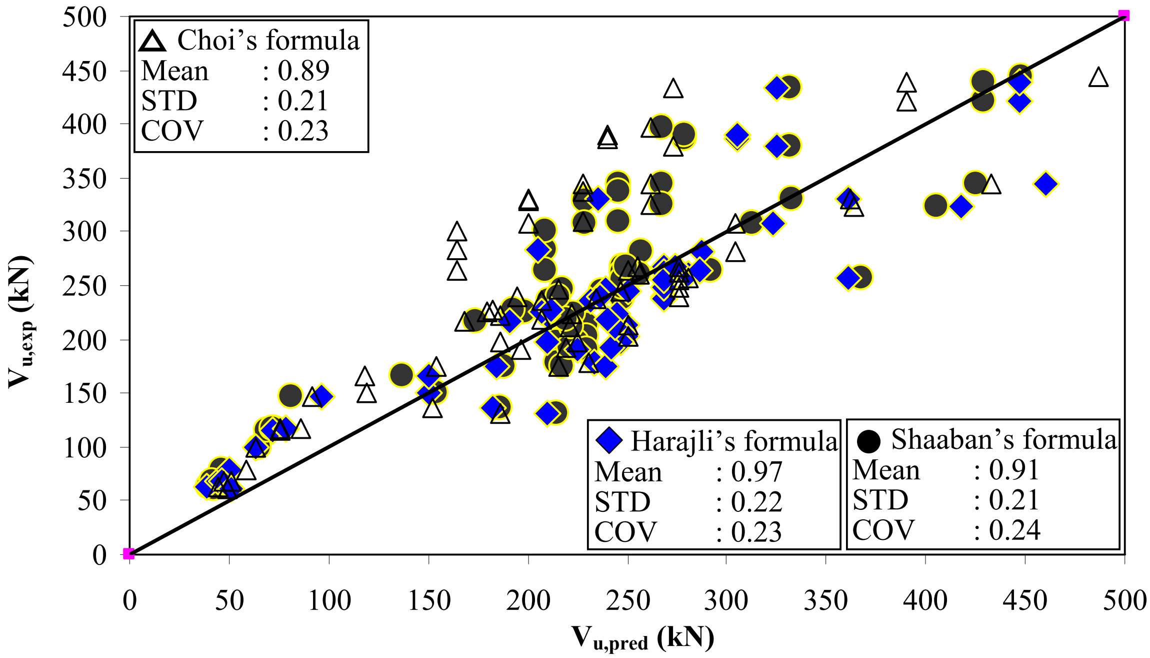


Figure 6: Comparison between theoretical and experimental punching shear capacities of slabs

Fig. 6 show that existing formulas give inaccurate results and with large scatter in comparison with test results. In many cases, the formulas yield results much higher than experimental ones that indicated un-safety of the formulas from the point of view of reliability.

The inaccuracy of formulas of Harajli or of Shaaban could be proceeded from their experimental nature that can not determine mechanisms of punching shear transfer quantitatively. Moreover, these formulas do not account effect of length, shape, and ratio of length and diameter of fibers in the punching shear resistance of slabs. In fact, these factors effect strongly to bond strength of steel fibers in concrete, then to concrete tensile strength that influences punching shear capacity of SFRC slabs. While, bad agreement between punching shear resistance predicted by formula of Choi and experimental ones can be due to the assumption about yielding of tensile reinforcement, based on that the formula was established. As discussed above, this assumption can be valid in the case of thin slabs (large span to thickness ratio) where behavior of slab is dominated by flexural deformation. However, in the case of slabs with small span to thickness ratio where its behavior is governed mostly by shear deformation, the assumption should be reconsidered. In addition, all of formulas do not also calculate contribution of dowel action of tensile re-bars to punching shear resistance of SFRC slab-column connections. This can decrease accuracy of the formula, especially, in the case of slabs with higher tensile reinforcement ratios.

5. CONCLUSIONS

Based on the results obtained from study, the following conclusions can be drawn:

1. Steel fibers improve the punching shear resistance of the slabs considerably. Using steel fibers with fiber volume of 30 to 60 kg/m^3 increase the punching shear resistance of the slabs from 9 to 39.8% and this increase is directly proportional to fiber volume.
2. Steel fibers reduced significantly average crack width of the slabs up to approximately 70.8% at serviceability limit state. Moreover, steel fibers increase stiffness of the slabs and improve concrete ductility and integrity of vicinity of slab-column connections.
3. The results from the evaluation indicated that the formulas gave inaccurate results with a large scatter (COV is approximately 24%) in comparison with the experimental results.
4. A new formula should be proposed for more accurate estimation of punching shear resistance of SFRC slabs, in which, the effect of length, shape, and ratio of length and diameter of fibers as well as contribution of dowel action of tensile reinforcement should be considered.

ACKNOWLEDGMENTS

The paper was funded by Ho Chi Minh University of Technology of Vietnam SR (Project No. T-KTXD-2010-18), University of Security Management of Slovak Republic and BEKAERT Indonesia Co.

REFERENCES

ACI Committee 318 (2002). Building code requirements for structural concrete (ACI 318-02). 87(3), pp. 350-361.

Alexander SDB and Simmonds SH (1992). Punching shear tests of concrete slab–column joints containing fiber reinforcement. ACI Structural Journal. 89(4), pp. 425–432.

Cheng MY and Parra-Montesinos GJ (2010a). Evaluation steel fibers reinforcement for punching shear resistance in slab-column connections-part1: Monotonically increased load. ACI Structural Journal. 107(1), pp. 101–109.

Cheng MY and Parra-Montesinos GJ (2010b). Evaluation steel fibers reinforcement for punching shear resistance in slab-column connections-part2: Lateral displacement reversals. ACI Structural Journal. 107(1), pp. 110–118.

Choi KK, Reda Taha MM, Park HG, and Maji AK (2007). Punching shear strength of interior concrete slab–column connections reinforced with steel fibers. Cement & Concrete Composites. 29, pp. 409–420.

Feretzakis A (2005). Flat slabs and punching shear: reinforcement systems. Msc. Thesis, University of Dundee, UK.

Harajli MH, Maalouf D, and Khatib H (1995). Effect of fibers on the punching shear strength of slab–column connections. Cement & Concrete Composites. 17, pp.161–170.

McHarg PJ, Cook WD, Mitchell D, and Young-Soo Y (2000). Benefits of concentrated slab reinforcement and steel fibers on performance of slab–column connections. ACI Structural Journal. 97(2), pp. 225–234.

Megally S and Ghali A (2000). Punching shear design of earthquake resistant slab-column connections. ACI Structural Journal. 97(5), pp. 720–730.

Naaman AE, Likhitruangsilp V, and Parra-Montesinos GJ (2007). Punching shear response of high-performance fiber-reinforced cementitious composite slabs. ACI Structural Journal. 104(2), pp. 170–1779.

Shaaban AM and Gesund H (1994). Punching shear strength of steel fibers reinforced concrete flat plates. ACI Structural Journal. 91(3), pp. 406–414.

Swamy RN and Ali SAR (1982). Punching shear behavior of reinforced slab–column connections made with steel fiber concrete. ACI Structural Journal. 79(6), pp. 392–406.

Theodorakopoulos DD and Swamy N (1993). Contribution of steel fibers to the strength characteristics of lightweight concrete slab–column connections falling in punching shear. ACI Structural Journal. 90(4), pp.342–355.