- Technical Paper -

PREDICTIVE METHOD ON THE SHEAR CAPACITY OF FIBER-REINFORCED PRESTRESSED CONCRETE BEAMS

Ken WATANABE*1, Zarni Win MYO*2, Koji MATSUMOTO*3 and Junichiro NIWA *4

ABSTRACT

This paper presents the experimental study on the shear carrying capacity of prestressed concrete beams having various types of steel fibers. Twelve specimens were tested on prestressed concrete beams with three different prestress levels and three different fiber volume fractions for each aspect ratio of steel fibers. The test results indicated that shear carrying capacities increased with increasing the prestress level in terms of concrete stresses at the bottom surfaces, the volume fraction and the aspect ratio of steel fibers.

Keywords: prestressed concrete, steel fibers, crack widths, shear carrying capacity.

1. INTRODUCTION

Concrete has low tensile strength and possesses a brittle manner. The brittle nature of concrete causes the collapse occurring shortly after the formation of the first crack. Adding short fibers to concrete aids in converting brittle characteristics to ductile one and enhances the shear strength and deformation characteristics under external load effects.

Prestressed concrete (PC) structures have been used in recent years. The use of steel fiber is particularly attractive for high-strength PC structures. PC also requires the high compressive strength at an early stage. In addition to its higher compressive strength, high-strength concrete has found to be more brittle when compared to the normal-strength concrete. Inclusion of steel fiber is the one way to solve the problem of brittleness and improve the shear strength of high-strength PC structures.

Experimental studies of PC beams reinforced with crimped ends fibers have been conducted and presented in last year [1]. The increase in the shear strength attributable to steel fibers depends not only on the volume content, but also on the anchorage conditions and the aspect ratio of steel fibers. Therefore, experimental studies were continued by using different types and the aspect ratio of steel fibers to determine the possible enhancement in the shear carrying capacity provided by steel fibers.

The main objective of this study is to determine the shear carrying capacity of prestressed concrete beams with different types of steel fibers and the effect of prestress level on the shear failure mechanisms. Therefore, the beams were designed to fail in a shear mode and the fibers were introduced to the beams at a different fraction up to 2.0% for the determination of the possible enhancement of the shear carrying capacity provided by steel fibers. Moreover, a series of three fiber reinforced PC beams with different stress distributions in terms of concrete stress at the extreme compression and tension fibers were conducted to evaluate their failure mechanisms and the shear carrying capacities.

2. TEST PROGRAMS

2.1 Material properties

Table 1 provides the details of the mix proportion used in the test program. Materials used in concrete were high early strength cement, fine aggregates and coarse aggregates. To achieve adequate fiber dispersion and workability, superplasticizer, 1.25% by weight of cement was used as the admixture for each concrete mix.

Reinforcements and cross-sectional details of the tested specimens are shown in Fig. 1. Two PC bars with the nominal diameter of 19 mm were used as longitudinal reinforcements. These dimensions correspond to a longitudinal reinforcement ratio of 3.2%. Two deformed steel bars with the nominal diameter of 6 mm were used as build-up steel bar. Their yield strengths were 1080 N/mm^2 and 355 N/mm^2.

Table 1 Mix proportion of concrete

W/C (%)	*W* (kg/m^3)	*C* (kg/m^3)	*S* (kg/m^3)	*G* (kg/m^3)	*SP* (g/m^3)
35.0	165	471	914	790	5890

W = water
C = high early strength cement, density = 3.14 g/cm^3
S = fine aggregate, density = 2.60 g/cm^3, FM = 2.62
G = coarse aggregate, density = 2.64 g/cm^3, FM = 6.89,
Maximum size of coarse aggregates, G_{max} = 20mm
SP = superplasticizer, density = 1.44 g/cm^3

*1 Assistant Prof., Department of Civil Engineering, Tokyo Institute of Technology, Ph. D., JCI Member
*2 Graduate student, Graduate School of Civil Engineering, Tokyo Institute of Technology, JCI Member
*3 Post doctoral fellow, Department of Civil Engineering, Tokyo Institute of Technology, Dr. E., JCI Member
*4 Prof., Department of Civil Engineering, Tokyo Institute of Technology, Dr. E., JCI Member

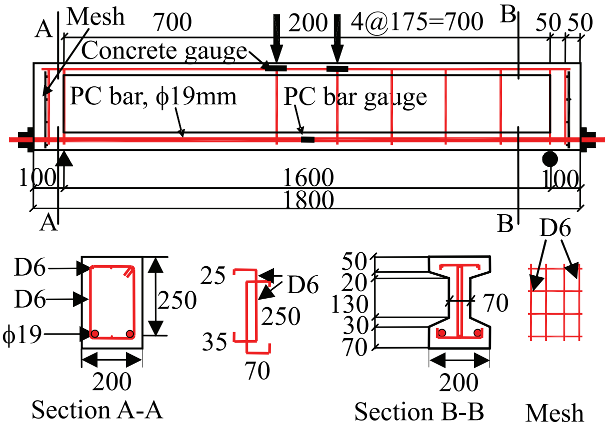


Fig. 1 Details of I-section PC beam, (Unit: mm)

Table 2 Properties of steel fibers

Length, L_f (mm)	Diameter, d_f (mm)	Volume (%)	Aspect ratio, L_f/d_f
30	0.75	0.5, 1.0, 1.5	40
30	0.60	1.0, 1.5, 2.0	50
60	0.90	0.5, 1.0, 1.5	65

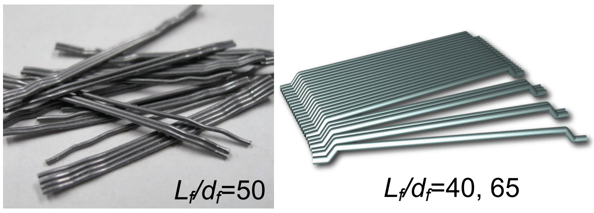


Fig. 2 Layout of steel fibers

Shear reinforcements consisting of deformed steel stirrups with the nominal diameter of 6 mm were provided in one shear span. Stirrups were not used in the test shear span.

Material properties and layout of steel fibers for each series of tests are provided in Table 2 and Fig. 2, respectively. In order to determine the effect of prestress level on the fiber reinforced PC beams, applied prestress level was adjusted to get the three different stress distributions. For these three beams, fiber volume fraction was kept constant at 1.0%.

2.2 Experimental setup

The test program consisted of twelve shear critical I-section PC beams having the same cross-section of width, b = 200 mm, height, h = 300 mm, shear span to effective depth ratio, a/d = 2.8, total length of 1800 mm and a span length of 1600 mm as shown in Fig. 1. One control beam specimen (with no fiber reinforcement) was cast to study the effect of parameters used in this study. The following terminology is used for the test beams: the former represents the prestressed concrete beam (PC), type of fiber (H for hooked ends and C for crimped ends fibers) and its aspect ratio, the latter shows the volume fraction of fibers contained in each specimen and the value of concrete stress at the extreme bottom fibers. Name of the specimens, all values of compressive strength (f'_c), tensile strength (f_t), concrete stress at top and bottom fibers (σ_u) and (σ_l) resulting from the tests corresponding to each specimen are listed in Table 3.

Table 3 Properties of each specimen

Name	f'_c (N/mm^2)	f_t (N/mm^2)	Concrete stress (N/mm^2)	
			σ_u	σ_l
PC-0.0(07)	63.6	3.7	-1.4	7.4
PCH40-0.5(07)	58.8	3.8	-1.3	7.1
PCH40-1.0(07)	59.6	4.3	-1.3	7.1
PCH40-1.5(07)	51.5	4.4	-1.5	7.9
PCC50-1.0(03)	50.1	3.9	-0.6	3.0
PCC50-1.0(07)	62.9	4.3	-1.4	7.6
PCC50-1.0(10)	57.1	4.3	-2.0	10.0
PCC50-1.5(07)	54.9	4.3	-1.4	7.3
PCC50-2.0(07)	55.9	4.8	-1.4	7.8
PCH65-0.5(07)	43.2	3.8	-1.5	8.1
PCH65-1.0(07)	40.2	4.2	-1.5	7.9
PCH65-1.5(07)	43.1	4.9	-1.4	7.4

Table 4 Comparison of test results

Name	P_{diag} (kN)	P_u (kN)	V_u=P_u/2 (kN)
PC-0.0(07)	186.6	233.1	116.6
PCH40-0.5(07)	185.2	241.2	120.6
PCH40-1.0(07)	161.8	263.8	131.9
PCH40-1.5(07)	164.2	250.5	125.3
PCC50-1.0(03)	147.9	196.7	98.4
PCC50-1.0(07)	196.2	295.3	147.6
PCC50-1.0(10)	207.7	274.8	137.4
PCC50-1.5(07)	163.0	263.1	131.5
PCC50-2.0(07)	178.3	274.7	137.3
PCH65-0.5(07)	145.7	198.3	99.2
PCH65-1.0(07)	153.5	250.2	125.1
PCH65-1.5(07)	169.8	202.1	101.1

2.3 Testing Procedure

All the beams were tested under a four-point bending system. A load cell was used to measure the applied load. Vertical deflections were measured at the mid-span and supports using displacement transducers. Electrical strain gauges were used to record the strain in concrete as well as PC bars at the mid span of the beam. A set of measurements was taken and also recorded the development and propagation of cracks. The test was stopped when the crushing of the concrete in compression and considerable loss of load carrying capacity was observed. The load at first diagonal crack, P_{diag}, peak load, P_u and the shear carrying capacity, V_u for all the specimens resulting from the tests are summarized in Table 4.

3. RESULTS AND DISCUSSION

3.1 Load-deflection responses

Figure 3 presents the effect of fiber addition, types of fibers and prestress level on the load versus mid-span deflections for each series of tests. The behavior of the curves can be divided into three major portions: linear elastic uncracked portion, linear elastic cracked portion and nonlinear cracked portion. At the beginning, all the beams behaved as the linear elastic

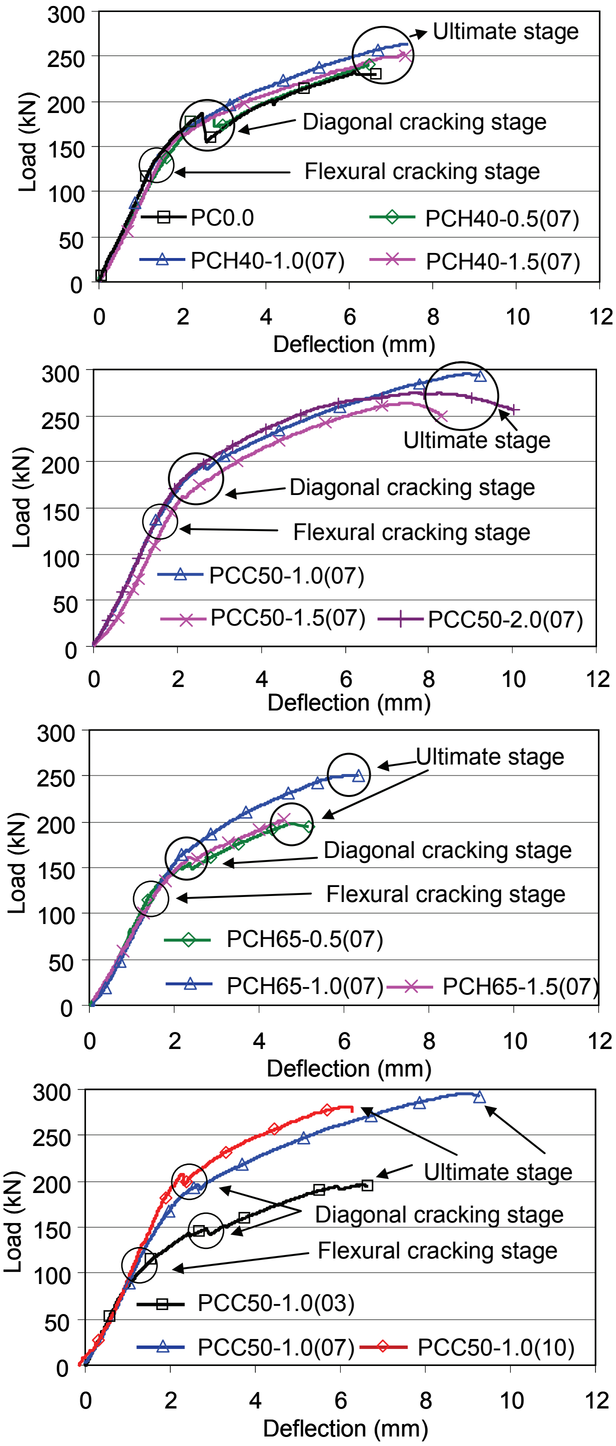


Fig. 3 Load-deflection curves

until the first crack occurred in the mid-span. The initial stiffness of the beam was slightly decreased with the initiation of the first crack and drastically decreased with the formation of the diagonal crack in the shear span. For this reason, a sharp drop of load was observed in a control beam when the diagonal crack occurred in the shear span. After the diagonal cracking stage, the resistance of the beam was mainly provided by prestress and continued to resist the additional loads until ultimate stage. However, a sharp drop of load gradually disappeared in fiber-reinforced PC beams with increasing the fiber volume fraction. It was also found that fibers became effective after the shear cracking and they continued to transmit the shear stresses along the inclined crack and then resist the beams at higher load levels. Prestress level also affected on the load carrying capacity of the beams. The load at the first diagonal crack increased with increasing prestress level and improved the ultimate shear carrying capacities of the beams. Therefore, addition of steel fibers and increase in prestress level not only enhanced ultimate shear carrying capacity of tested beams but also increased the stiffness and hence reduced the deflections for a given load level.

3.2 Crack patterns

Figure 4 shows the patterns of the cracks resulting from the tests at the various stages of loadings up to failure. For all the beams, flexural cracks appeared in the constant bending moment zone in the early stage of loadings. With the further increase in load, additional flexural cracks formed in the mid-span and new cracks were developed in the shear span. As the load increased further, a diagonal crack occurred in the shear span and propagates towards the loading point. In later stage of loading, the web cracks in the shear span were widened and the concrete near the crack tip in the compression zone was crushed.

The presence of steel fibers in the concrete greatly affected the observed cracking patterns. After initiating the first diagonal crack in the control beam, the width of the diagonal crack increased rapidly with increasing the applied load level. However, the fiber reinforced beams showed a decrease in the crack propagation and widening of the existing diagonal cracks. Thus, the presence of fibers in the concrete improves the transmission of shear stresses across the two crack surfaces. By comparing the cracking behaviors until the ultimate stage, the increasing number of both flexural and shear cracks were observed in the fiber reinforced beams as shown in Fig. 4. The failure in all specimens was due to the diagonal crack penetrating deep into the compression zone along with crushing and spalling of concrete in the web region. Steel fibers have the influence over the number of cracks and crack-widths due to the increased stress redistribution taking place along the all possible cracks within the whole span. Owing to this property, when the new cracks widen, a decrease in propagation and widening of critical diagonal crack was achieved due to the stress transferring mechanisms of steel fibers and improved the shear carrying capacity in the presence of steel fibers.

Prestress level also affected the cracking behaviors of the test beams. The number of cracks increased with increasing prestress level. The effect of prestress level was more significant after the diagonal cracking stage. At this stage, the resistances of the beams were mainly provided by the bridging action of steel fibers on the flange and the prestress. Finally, the applied loads were dropped and the beams reached the ultimate stage by crushing of the concrete at the web or crushing on the flange at the loading point. From these results, the increase in prestress level improved the shear carrying capacity of fiber reinforced PC beams

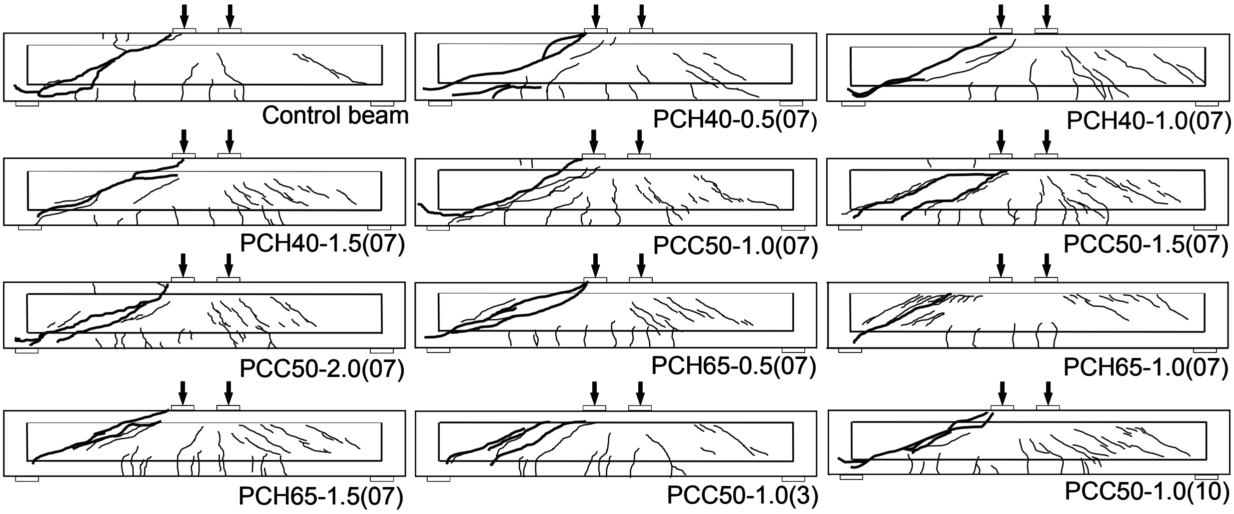


Fig. 4 Crack patterns of test beams

when prestress level in terms of lower fiber stress, σ_l was increased from 3 to 7 N/mm^2. However, the improvement in shear carrying capacity was not observed when σ_l was increased to 10 N/mm^2.

3.3 Effect of the major parameters

The beneficial effect of fiber volume fraction on the shear carrying capacity is shown in Fig. 5. The number adjacent to each specimen represents the compressive strength of concrete resulting from the tests. For all series, an increase in fiber content resulted in an increase in the shear carrying capacity up to 1.0%, while it did not increase the shear capacity at the ultimate stage for the beams with 1.5 and 2.0% of fibers. This phenomenon can be explained by the fact that when the fiber content exceeded 1% by volume, placing and finishing the fresh concrete mix was difficult, which resulted in an inadequate mix with high void ratio. It was also noted that increasing the volume fraction of fibers; it led to balling, segregation, that is, fibers clamped to each other without coarse aggregates in the concrete mix resulting to the decrease in the compressive strength as well as the shear carrying capacity of the beams.

Figure 6 shows the effect of aspect ratio on the shear carrying capacity for each series with the same fiber content in volume. The results indicated that shear carrying capacity increased progressively when aspect ratio was increased from 40 to 50. It is seen that the total number of steel fibers in concrete increased with increasing aspect ratio resulting the increased stress redistribution taking place along the all possible cracks within the whole span. However, the beams with aspect ratio of 65, shear carrying capacities were decreased drastically. It can be explained by the fact that homogeneous distribution and orientation was decreased with large value l_f/d_f especially for the beams with thin web-widths regardless of the type of fibers.

As shown in Fig. 7, the increase in Prestress level resulted in an increased in shear carrying capacity of the beams with σ_l= 3 and 7 N/mm^2. In case of comparatively large value of σ_l= 10 N/mm^2, the slope of the concentrated stress flow became steeper and weak while the stress flow curvedly transferred from

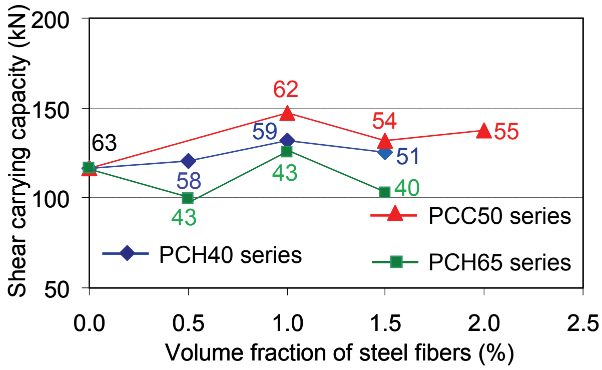


Fig. 5 Effect of fiber volume

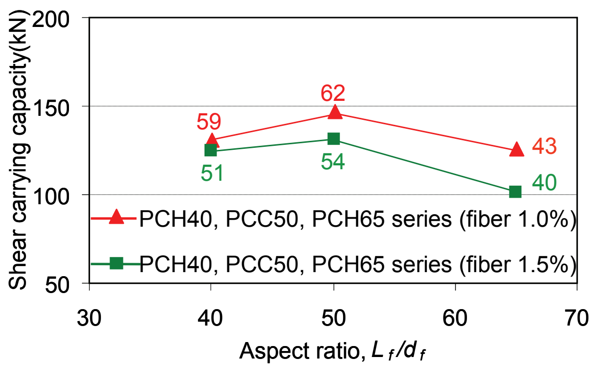


Fig. 6 Effect of aspect ratio

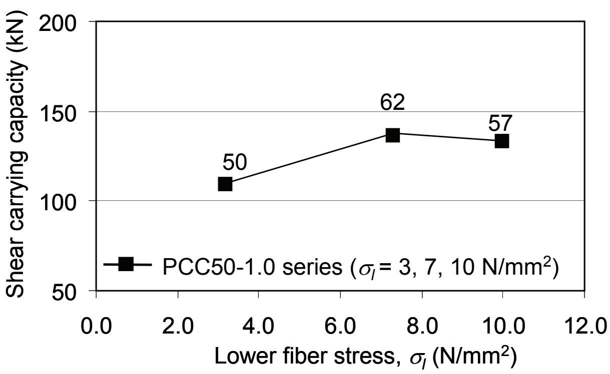


Fig. 7 Effect of prestress level

the loading point to the support and the member at this region becomes critical [2]. From these results, the increase in prestress level in terms of concrete stress at the bottom fiber increases the shear carrying capacity of PC beams with steel fibers.

4 Prediction model for shear carrying capacity

In prestressed concrete beams containing steel fibers, the ultimate shear carrying capacity (V_u) is assumed to be:

$$V_u = V_{PC} + V_F \tag{1}$$

where V_{PC} is the shear force carried by prestressed concrete and V_F is the shear force carried by steel fibers through pullout forces along the inclined crack.

4.1 Shear carrying capacity of concrete, V_{PC}

In order to get the high accuracy for predicting the shear carrying capacity of PC beams, the simplified truss model proposed by Lertsamattiyakul [2] was adopted in this study. Figure 8 shows the configuration of simplified truss model. In the evaluation of member forces due to applied shear, forces on each member cannot be easily calculated by using the balances of forces at each node (simplified truss model is indeterminate). Therefore, each of the member force caused by external applied shear is assessed based on the Castigliano's second theorem. On the other hand, the resistance capacity of each diagonal compression member can be obtained from compressive strength of concrete incorporating the compressive softening parameter, the cross sectional area of each member and its inclination. By comparing the value of member forces to member resistances for each member, V_{PC} can be determined when one of the diagonal compression members become critical. The critical member refers to the member among four diagonal compression members where the ratio of member force to member resistance becomes greatest or equal to 1.0.

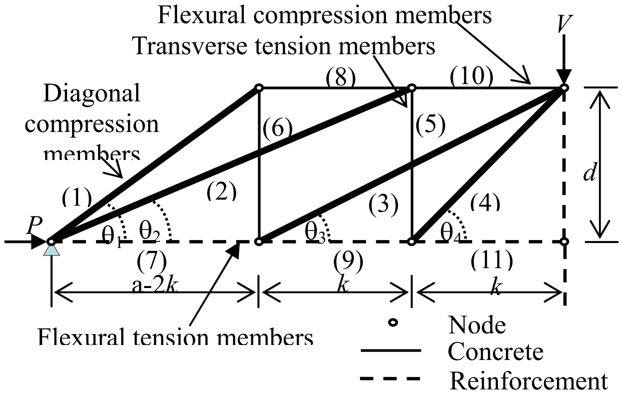
4.2 Shear force carried by steel fibers, V_F

For the beams that had steel fibers in their concrete mix, the effect of steel fiber was estimated from the following equation [3]:

$$v = 0.41\tau_{bF} V_f \frac{L_f}{d_f} \tag{2}$$

in which v is the contribution of the fiber pullout mechanisms to the shear stress (N/mm^2), τ_{bF} is the average interfacial bond stress between the fiber and corresponding concrete, taken as 4.15 N/mm^2 in the absence of any pullout tests, V_f is the volume of fibers expressed as (%), L_f is the fiber length (mm) and d_f is the fiber diameter (mm).

The prediction method developed in the study accounts for the effect of other influential parameters such as: fiber orientation factor, bond strength and bond factor for each type of fibers to determine the shear carrying capacity of the beams. The main concern of this study is the shear force carried by steel fibers



where k is 0.5*md* if *m* > 1.0 and 1.0*md* if *m* ≤ 1.0
The number in parenthesis ( ) shows member number

Fig. 8 Details of simplified truss model (half model)

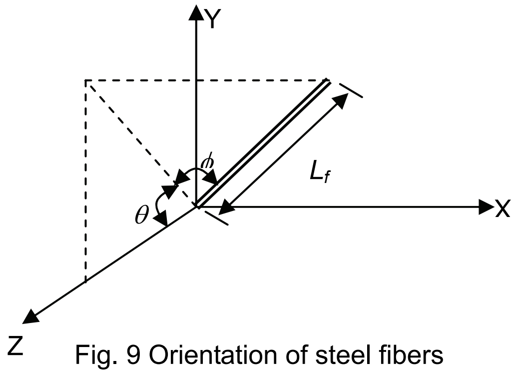


Fig. 9 Orientation of steel fibers

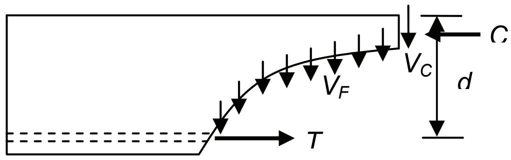


Fig. 10 Contribution of steel fibers to shear

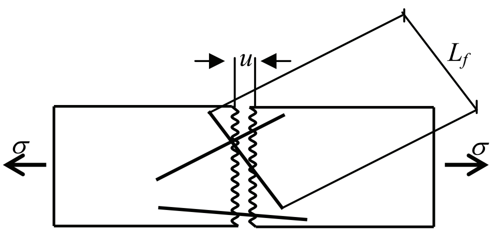


Fig. 11 Pullout length of randomly oriented fibers

through pullout forces along the inclined crack. Since the fiber pullout force mainly depends on the number of steel fibers per unit area (N_f). The number of fibers crossing a unit cross sectional area has been determined by using the following equation [4]:

$$N_f = \alpha \frac{V_f}{A_f} \tag{3}$$

where $A_f=\pi d_f^2/4$ is the cross sectional area of fibers, α is the probabilistic fiber orientation factor and V_f is the volume fraction of steel fibers. In the present study, fibers have an equal probability of being oriented in any direction as shown in Fig. 9. Therefore, the equation for calculating the value of α was adopted as follows [4]:

$$\alpha = \frac{\int_0^{\frac{\pi}{2}}\int_0^{\frac{\pi}{2}} L_f \cos\theta \ \cos\phi \ d\theta \ d\phi}{\left(\frac{\pi}{2}\right)^2 L_f} = \frac{4}{\pi^2} \quad (4)$$

The contribution of steel fibers to shear after the formation of shear crack is expressed in Fig. 10 where V_c is the shear force across the compression zone and V_F is the vertical component of fiber pullout force along the inclined crack. Depending on the location of steel fibers along the crack, the total bond area of steel fibers across section was computed. Considering a unit crack surface with crack width value of u in Fig. 11 and assuming a pure fiber pullout on the side of the shorter embedment length of any fibers crossing the crack, more and more fibers are fully pullout with increasing the crack opening value of u. Finally, the stress drops to zero when $u=L_f/2$. Therefore, the total bond area of fibers across the section has been obtained by assuming the average pullout length value of fibers to be $L_f/4$ (since the pullout length of fibers ranges between 0 and $L_f/2$) as shown in the following equation:

$$A_b = N_f \pi d_f \frac{L_f}{4} \quad (5)$$

And the total force developed by fiber is

$$F_b = A_b \tau_{bF} \quad (6)$$

where τ_{bF} is the average interfacial bond stress between the fiber and corresponding concrete. The bond stress τ_{bF} of hooked ends and crimped ends fibers used in the present study was estimated in Eq. (6), which was adopted from the experimental results of frictional slip between fiber and the corresponding concrete [5].

$$\tau_{bF} = 0.6(f'_c)^{\frac{2}{3}} \quad (7)$$

In order to allow for different pullout resistances offered by different anchorage conditions of steel fibers, it was essential to use the bond factor d_b into the calculation. Based on the large series of pullout tests [6], d_b was assigned a relative value of 0.5 for round fibers, 0.75 for crimped end and hooked end fibers. By substituting the Eq. (3) and (5) into Eq. (6), the stress carried by fibers at cracking is given by:

$$v = \alpha \tau_{bF} d_b V_f \frac{L_f}{d_f} \quad (8)$$

Shear force carried by steel fibers, V_F can be computed as the values of v multiplied with width of the beam (b_w) and effective depth (d) of the beam.

The validations of modified model with

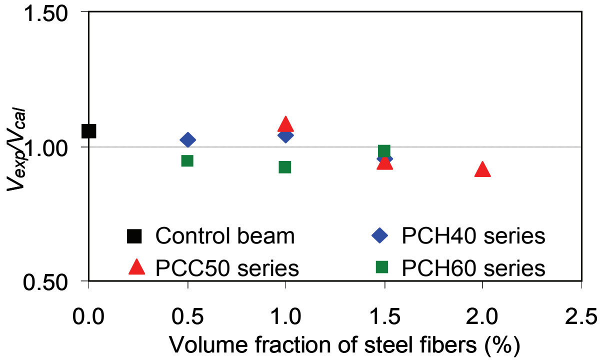


Fig. 12 Validation of test results

experiments are shown in Fig. 12. By comparing the observed and predicted shear carrying capacities on the fiber volume for each series, the solutions based on the proposed model correlate well with both series of tests, having a mean ratio of 0.98.

5. CONCLUSIONS

(1) The addition of steel fiber in prestressed concrete beams improved the shear carrying capacity. The enhancement on the shear carrying capacity was more prominent when when 1.0% of steel fibers into the concrete mix.

(2) Depending on the absence or presence of steel fibers, a control beam fails in the brittle manner; however, fiber reinforced beams eventually collapsed from the several localized deformations at one or two major cracks.

(3) According to the comparison of test results, the method that proposed in this study can predict the shear carrying capacity of fiber reinforced prestressed concrete beams.

References

[1] Myo, Z. W.: Shear Carrying Capacity of Prestressed Concrete I-beams Reinforced with Steel Fibers, Proceedings of JCI, Vol. 32, No. 2, pp. 1309-1314, 2009.

[2] Lertsamattiyakul, M.: Simplified Truss Model for Shear Carrying Capacity of Prestressed Concrete Members, PhD thesis, Tokyo Institute of Technology, 2005.

[3] Swamy, R. N., Jones, R. and Chiam, A. T. P.: Influence of Steel Fibers on Shear Resistance of Lightweight Concrete T-Beams, ACI Structural Journal, Vol. 90, No. 1, pp. 103-114, 1993.

[4] Sorousian, P. and Lee, C.: Distribution of Fibers in Steel Fiber Reinforced Concrete: ACI Materials Journal, Vol. 87, No. 5, pp. 433-439, Sept-Oct. 1990.

[5] Marti, P., Pfyl, T., Sigrist, V. and Ulaga, T.: Harmonized Test Procedure of Steel Fiber Reinforced Concrete, ACI Materials Journal, Vol. 96, No. 6, pp.676-685, Nov-Dec. 1999.

[6] Naranyan, R. and Kareen, P.: Effect of Fiber Addition on Concrete Strengths, Indian Concrete Journal, Vol. 58, No. 4, pp. 100-103, Apr. 1984.