SHEAR BEHAVIOR OF PRESTRESSED BEAMS WITH STEEL FIBER SELF-COMPACTING CONCRETE

Hemant B. Dhonde[1], Padmanabha Rao Tadepalli[2], Y.L. Mo[2], and Thomas T.C. Hsu[2]

[1] *Bechtel Corp., Houston, Texas, USA*
[2]*Department of Civil and Environmental Engineering, University of Houston, Houston, 77204-4003, USA*

ABSTRACT :

Seven prestressed concrete (PC) I-beams were designed to study the effects of steel fibers on the casting procedure, the control of end region cracking, and the increase in shear strength and ductility of beams. Three types of concrete were used in the seven specimens. One beam was cast using normal concrete to serve as the control specimen. While three of the remaining beams were cast using normal concrete reinforced with steel fibers, the others were cast with self-compacting fiber reinforced concrete (SCFRC). Strain gauges and temperature loggers were attached to the rebars in the beams to continuously measure the strains and temperatures respectively during the casting, curing and prestressing stages. It was observed that fibers effectively reduced the tensile strains due to thermal loading in the concrete matrix. Fibers contributed substantially towards enhancing the tensile strength and also prevented stress concentration in the end zones of PC beams. Concentration of stresses in the early stages of the beams often leads to development of cracks in the end regions. However, fibers were found to be more effective with regard to their performance in the end regions of beams with SCFRC than the ones with traditional fiber reinforced concrete (TFRC). After the fabrication of the beams they were subjected to concentrated vertical loads up to their maximum shear or moment capacity using four MTS actuators. During the load tests Linear Voltage Displacement Transducers (LVDTs) were used to measure displacements at several critical points on the web in the end zone of the beams. Several LVDTs were also placed under the beams at the points of loading to measure the actual total and net displacements of the beams. Strain gauges installed on the rebars inside the beams (used previously in the early-age measurements) were also used to monitor the rebar strains during the load tests. From the load tests it was observed that the load carrying capacities of the beams with self-compacting concrete were similar to the one with normal concrete. The shear capacities of the beams were observed to significantly increase due to the addition of steel fibers in concrete. Replacement of shear reinforcing bars with steel fibers also increased the ductility and energy dissipation capacity of the structure. Hence, prestressed beams with steel fiber self-compacting concrete are very appropriate to resist earthquake loading.

KEYWORDS: prestressed beam, self-compacting fiber reinforced concrete, shear reinforcement replacement, cracks prevention, ductility, energy dissipation

1. INTRODUCTION:

1.1 End Zone Cracking: At the end regions of a prestressed concrete beam, prestress forces, concrete hydration-thermal loading, creep and shrinkage are collectively responsible for generating end zone cracks. Past research has established that there were several possible causes of the end zone cracking such as the prestress forces, temperature differentials through the depth of the bridge, creep and shrinkage (Alabama Department of Transportation 1994). The conclusions of the Alaska Department of Transportation research were reported by Myers *et al.* (2001) as follows: 1. The cracking was not caused by a flexural failure, a diagonal tension failure, or a compression failure. 2. The observed cracks were initiated during fabrication, possibly due to elastic shortening induced by prestress transfer. 3. Thermal induced stresses originating from longitudinal restraint at the abutments have played a role in crack propagation (Myers *et al.* 2001).

Marshall and Mattock (1962) determined that an adequate amount of stirrup reinforcement should be provided to prevent the spread of horizontal cracks that develop when the prestress force is transferred. The authors suggested that girder-end cracking might be initiated by restrained shrinkage and thermal contraction provided by the form during curing, but no analysis of this was performed (Myers *et al.* 2001).

The maximum tensile stresses in the girder-ends due to prestress transfer were reported to be about 350 psi, which are approximately 40 % to 50 % of the tensile strength of traditional concrete (i.e. 550 to 750 psi). While these stresses by themselves may not be sufficient to cause cracking, when they are considered in conjunction with the residual tensile stresses due to hydration, thermal variation, creep and shrinkage, horizontal girder-end cracking is possible. Previous research has concluded that diagonal tension stress under service loads by itself may not be adequate to cause the end zone cracking (Myers *et al.* 2001).

To prevent the occurrence of end zone cracks, dense and intricate reinforcement of steel rebars amounting to 4.2 % by volume of concrete is provided in the TxDOT I-beams. However, observations show that such a heavy reinforcement cannot completely eliminate the cracking in the end regions. A potential alternative solution is to replace the conventional web reinforcement with steel fibers. This alternative solution could prevent the cracking at the end region, as well as allow easy placement of TxDOT traditional concrete.

1.2 Self-Consolidating Fiber Reinforced Concrete: Fiber Reinforced Concrete (FRC) requires a high degree of vibration to get good compactness. This increases the labor costs and noise pollution at the work site. Moreover, if the reinforcement is dense or the form is intricate in shape, it becomes even more difficult to place and vibrate the concrete. Unfortunately, when one tries to enhance the workability of FRC by adding more superplasticizers or intensifying the degree of vibration, segregation invariably occurs. Hence, the development of a Self-Consolidating Fiber Reinforced Concrete (SCFRC) should make for easier placement of concrete, save labor and avoid noise pollution. Self-Consolidating Concrete (SCC) offers several economic and technical benefits; the use of steel fibers extends its possibilities (Grünewald and Walraven 2001).

SCFRC appears to be a logical material for application to the end region of prestressed concrete I-beams. When steel fibers are added to the concrete mix, the tensile and shear resistance of the composite material is enhanced (Casanova *et al.* 1997, Beaudoin 1990). However, fibers are also known to impede the workability of plain concrete (Dixon *et al.* 1971). Moreover, the end zones are densely reinforced, making it necessary to use a highly workable concrete with steel fibers that would not only reduce or completely eliminate the traditional transverse reinforcement but also make it easier to place concrete.

Some research experiments as well as field applications have been successfully carried out on SCFRC. The mix design of SCFRC could be based on the mix design of an existing SCC mix (Petersson 1998). The workability of SCFRC is affected by fibers as they posses high surface area. The degree to which workability decreases depends on the type and content of fibers, the matrix composition and the properties of the constituents of the matrix on their own. The higher the fiber content in SCFRC, more difficult it becomes to uniformly distribute the fibers in the matrix (Grünewald and Walraven 2001). Concrete with satisfactory workability could be made self-consolidating even with a large fiber content of up to 1.3 % by volume (Ambroise *et al.* 2001).

The uniqueness of this research work lies in the application of SCFRC in full-scale prestressed concrete beams. Very few investigations are available in literature dealing with the use of fiber reinforced concrete in full-scale prestressed beams. Though it is a well-known fact that steel fibers enhance shear strength and ductility, it is still unknown how successful the steel fibers will be in full-scale prestressed concrete beams owing to the presence of very large prestress force in the beam. On the other hand, developing a fiber reinforced concrete and SCFRC mixes suited to cast real-scale beams pose another challenge in itself.

2.0 EXPERIMENTAL PROGRAM

The design and dimensions of the beams are shown in Table 1 and in Fig. 1. The details are reported in Hemant *et al*. (2007).

Table 1: Variable in Test Beams B0 to B6

Beams	Concrete Mixes	Steel Fibers	Transverse Steel North End	Transverse Steel South End	Concrete Cylinder Strength (ksi)
B0	TTFRC4	1.5 % SF	-0-	-0-	14.5
B1	TTC1	-0-	4.2 %	1 %	12.2
B2	TTFRC1	1 % SF	1 %	0.42 %	10.3
B3	TTFRC3	0.5 % LF	1 %	0.42 %	11.2
B4	SCFRC1	0.5 % LF	1 %	0.42 %	10.9
B5	SCFRC3	1 % SF	1 %	0.42 %	8.9
B6	SCC2-3	-0-	4.2 %	1 %	10.6

NOTE: TTC-TxDOT Traditional Concrete Mix
TTFRC-TTC + Fibers Mix
SCC-Self-Consolidating Concrete Mix
SCFRC- SCC + Fibers Mix
SF-Short Fiber ZP305
LF-Long Fiber RC80/60BN
TS - Transverse Steel

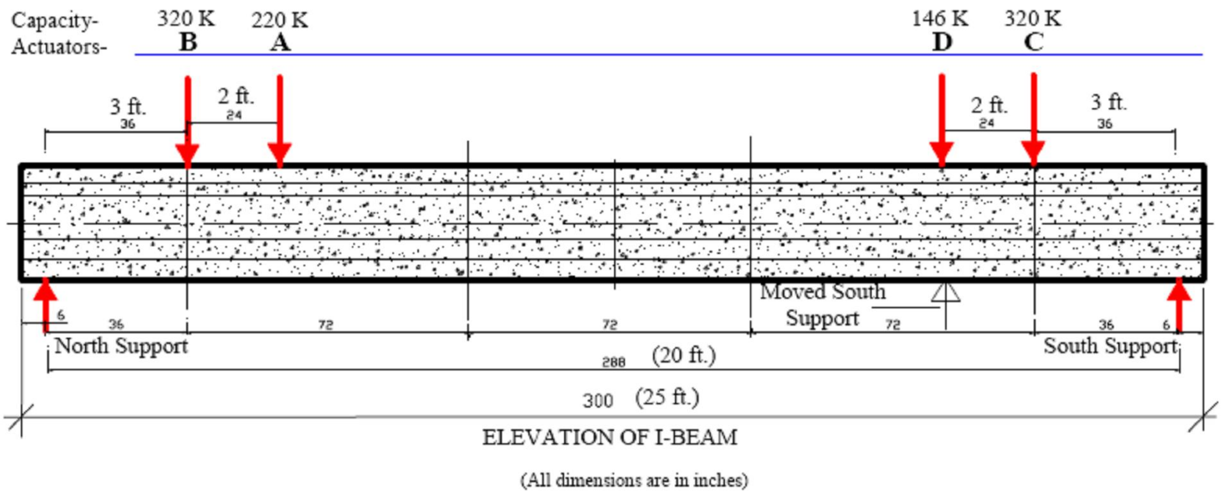

Fig. 1 Loading Points on Test Beam

2.1 Test Set-Up: In the load tests, the beams were subjected to vertical loading up to their maximum shear or moment capacity in a specially built steel loading frame as shown in Fig.2. Four actuators, attached to the steel frames, were used to provide vertical loads on the beams at north and south end. Fig. 1 presents the location of loading points on the test beams specimens.

The position of vertical loadings on the beam together with the support positions is shown in Fig. 1. The loads from actuators B and C were positioned at 3 feet from the north support and south support, respectively. The loads from actuators A and D were positioned at 2 feet to the south of actuator B and to the north of actuator C, respectively. Thus a constant shear span-to-depth ratio of 1.29 was maintained for all the beam tests. Actuator loads were applied through two 6 in. x 12 in. x 2 in. bearing plates and two-roller assembly, so as to ensure uniform and frictionless load transfer from actuators on to the beam surface. Lead sheets were also used between the load bearing plates and beam surface. All the bearing plates and rollers were hardened to maximum possible hardness, in order to minimize local deformations.

Fig. 2 Test Setup

After the south end failed, the south end support was moved 5 feet towards the north in order to avoid the failure zone at the south end and to provide a fixed support for testing the north end to failure. Fig. 1 shows the position of the moved south support by the thin-line arrow. The north end of the beam was then loaded by actuator B, programmed with a load control of 5 kips/min. Then, when the slope of load deflection curve approached the horizontal, the loading program was switched to a displacement control of 0.2 inches/hour. When the capacity of the north end of the beam was higher than the load capacity of actuator B, actuator A (2 feet from actuator B) was activated with the same displacement control procedure. The testing was stopped when the north end failed.

During the load testing, Linear Voltage Displacement Transducers (LVDTs) were used to measure displacements at several critical points on the web in the end zone of the beam. Several LVDTs were also placed under the beam at the point of loading to measure the actual total and net displacements of the beam . Strain gauges installed on the rebars inside the beams were also used to monitor the rebar strains during the load test. On an average, each beam was instrumented by about 30 LVDTs and 25 strain gauges to record the structural behavior of the beam. Data from these sensors were continuously monitored and stored by the HBM 'Spider-8' Data Acquisition System. Shear cracks formed on the beam web during the load test were regularly marked on the grid. The crack widths were measured using a hand-held microscope having a 0.001 in. measuring precision.

The seven test specimens, B0 to B6, involve four variables: type of concrete mixes, type and volume of steel fibers (short fiber or long fiber), and transverse steel (at north end and at south end). These variables are listed in Table 1. The cylinder strengths of the concrete used in the test beams were also recorded. These concrete cylinders were cast and steam cured along with the beams in Victoria, Texas. It should be noted that the strengths indicated in this table are not measured at 28 days but on the day of the beam test. It can be seen from the table that the compressive strengths of the concrete varied between 8.9 ksi and 14.5 ksi. This variation in the concrete strengths may be useful in explaining the variation of behavior of different beams to be reported hereafter.

3.0 EXPERIMENTAL RESULTS

Shear and flexural failure of beams B1 and B6 were sudden and catastrophic. All other fibrous beams demonstrated ductile and less catastrophic failures. Table 2 shows the ultimate strengths at failure for each of the two ends of the beam specimens. It can be seen that only the north ends of beams B1 and B6 failed in flexure. This is due to the fact that the beam-ends had a high percentage of shear reinforcement (4.2 %) contributing to the high shear capacities. Thus, these beams reached their flexure capacities before reaching their shear capacities. For all other end regions, the ultimate shear capacity governed the failure.

3.1 Ultimate Shear Strengths: The effect of steel fibers on the shear strength of test beams can be observed by examining Table 2. First, the shear strength of the south ends of beams B1 made of TTC1 mix was 294 kips, while that of B6, made of SCC2-3 mix was 290 kips. It can be seen that the concrete mixes (TTC1 vs. SCC2-3) has negligible effect on the shear capacity of the beams. Slightly lower shear strength of beam B6 may be attributed to its lesser compressive strength when compared to beam B1.

Second, the comparison of the south end shear strength of beam B1 with those of beams B2 and B3 shows that the shear capacity of the beams can be significantly increased due to the addition of steel fibers in concrete, even though the compressive strength of concrete and the amount of shear steel in the south ends of beams B2 and B3 were lower than those in the south end of beam B1.

Third, the south end shear capacities of beams B4 and B5 with steel fibers (276 and 248 kips) were less than that of beam B1 (294 kips). This may be due to the fact that beams B4 and B5 had much lower concrete strength (10.9 and 8.9 ksi) in comparison to the concrete in beam B1 (12.2 ksi). Also, the transverse steel was mush less (0.42 % vs. 1 %). Finally, the south end of beam B0 had a shear capacity of 375 kips, much higher than that of 294 kips for beam B1, even though beam B0 had no traditional shear reinforcement. In short, the significance of steel fibers in contributing to the shear strengths is evident.

A very interesting observation can be made from Table 2 concerning the reduction of shear strength at the north end in comparison with the south end of the beams. North ends of beams B2, B3, B4 and B0 had lower shear strengths than their corresponding south ends, even with greater amount of transverse reinforcement. This reduction in shear strength could be explained with the help of two probable reasons, acting together or independently, as explained below:

Table 2: Ultimate Shear Strengths of Beams B0 to B6 at North and South Ends.

Beam (Mix)	Failure Type	Ultimate Shear Capacity V (kips)	Ultimate Moment Capacity M (kips-ft.)	Max. Shear at Ultimate Moment (kips)	Max. Moment at Ultimate Shear (kips-ft.)
B1-North (TTC1)	Flexure	-	**1048**	**329**	-
B1-South (TTC1)	Shear	**294**	-	-	**882**
B2-North (TTFRC1)	Shear	**330**	-	-	**1078**
B2-South (TTFRC1)	Shear	**349**	-	-	**1151**
B3-North (TTFRC3)	Shear	**253**	-	-	**759**
B3-South (TTFRC3)	Shear	**342**	-	-	**1079**
B4-North (SCFRC1)	Shear	**265**	-	-	**795**
B4-South (SCFRC1)	Shear	**276**	-	-	**828**
B5-North (SCFRC3)	Shear	**257**	-	-	**771**
B5-South (SCFRC3)	Shear	**248**	-	-	**777**
B6-North (SCC2-3)	Flexure	-	**1077**	**325**	-
B6-South (SCC2-3)	Shear	**290**	-	-	**897**
B0-North (TTFRC4)	Shear	**301**	-	-	**903**
B0-South (TTFRC4)	Shear	**375**	-	-	**1243**

(a) Formation of air pockets at the north end of beam B3 and south end of beam B5 might have reduced the effective prestress as well as the shear strength.

(b) In the load tests, south ends of the beams were tested to failure followed by the north ends. Hence, the south ends of all the beams failed first with a sudden release of energy during the shear failure. This disruptive failure caused the prestressing strands to slip, thereby reducing the effective prestress force at the north ends of the beams. This may have caused the reduction in shear strengths at the north ends of the beams.

Thus, in the case of north end of beam B3 and south end of beam B5 the considerably low shear strengths might have been due to the reason (a) and (b) together, as mentioned above. Whereas, only reason (b), described above might have been responsible in reducing the ultimate shear capacity at the north ends of beams B0, B2 and B4.

Previous research has reported a reduction in shear strength due to the end zone cracking and thereby increasing the transfer length (Slapkus *et al.* 2002). But the results of beam B0 contradict this finding. Beam B0 had no end zone cracks and air-pockets, but its north end had considerable lower shear strength than the south end. Hence, end zone cracks might not be the cause of reduction in shear strength.

3.2 Ductility Observed in Shear Force-Deflection Curves: Fig. 3 shows the plot of shear force acting on the south end of the beams against the beam deflections. The shear force plotted in this figure was obtained from the reading of the load cells placed under the end supports of the beams and was also verified by load equilibrium computations. The deflection was obtained from the readings of the LVDT placed under the individual beams at the location of the end actuator.

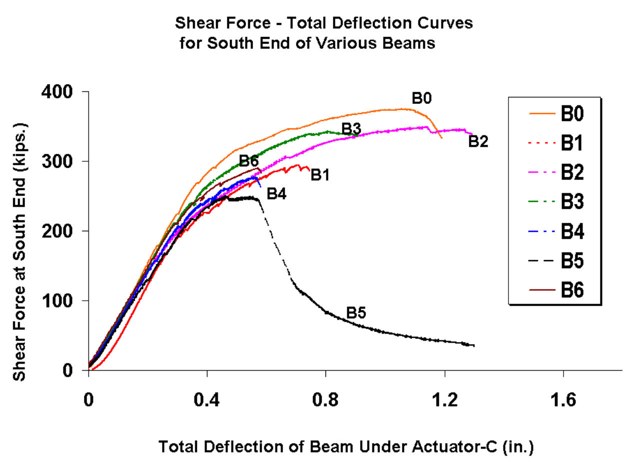

Fig. 3 Shear Force - Deflection Curves for South End of the Beams B0 to B6

In general, SCFRC beams have demonstrated higher ductility than the other beams with steel fibers. The failure of beams B1 and B6 were quite sudden and brittle; without any warnings even in a very low displacement control rate. On the other hand, almost all the fiber reinforced beams failed in a ductile fashion with prior warnings. It should be noted that the fiber factors for beams with short fiber were 55 and 82.5 whereas the fiber factor for the beams with long fiber was comparatively smaller, i.e. 40. From the ultimate shear capacities of all the fiber reinforced beams, it could be seen that the beams with greater fiber factor performed better than the beams with smaller fiber factor.

3.3 Shear Crack Patterns and Shear Crack Widths: Shear cracks were continuously tracked and measured during the load tests of the beams. A grid was marked on the beam-web of all the beam-ends to facilitate easy identification and location of the shear cracks. Since LVDTs were installed on the west side of the beam-ends, shear crack measurements were taken only on the east side of the beam-ends. Hand-held microscopes were utilized to precisely measure the shear crack width.

Table 3 Shear Crack Spacing of Beams B0 to B6 at North and South Ends

Beam (Mix)	**Steel Fibers (% vol)** (Type)	**Transverse Steel** (%vol)	**Concrete Strength** (ksi)	**Shear Crack Spacing** (in.)	**Shear Force at Onset of Shear Crack (Crack Width = 0.001 in.)** (kips.)
B1-North (TTC1)	0	4.2	12.2	3	140
B1-South (TTC1)	0	1.0	12.2	5	100
B2-North (TTFRC1)	1 (SF)	1.0	10.3	3	160
B2-South (TTFRC1)	1 (SF)	0.42	10.3	5	150
B3-North (TTFRC3)	0.5 (LF)	1.0	11.2	2	115
B3-South (TTFRC3)	0.5 (LF)	0.42	11.2	4	130
B4-North (SCFRC1)	0.5 (LF)	1.0	10.9	2	145
B4-South (SCFRC1)	0.5 (LF)	0.42	10.9	4	145
B5-North (SCFRC3)	1 (SF)	1.0	8.9	2	125
B5-South (SCFRC3)	1 (SF)	0.42	8.9	3	125
B6-North (SCC2-3)	0	4.2	10.6	4	115
B6-South (SCC2-3)	0	1.0	10.6	5	120
B0-North (TTFRC4)	1.5 (SF)	0	14.5	2	160
B0-South (TTFRC4)	1.5 (SF)	0	14.5	2	175

NOTE: **TTC**-TxDOT Traditional Concrete Mix **TTFRC**-TTC + Fibers Mix
SCC-Self-Consolidating Concrete Mix **SCFRC**- SCC + Fibers Mix
SF-Short Fiber ZP305 **LF**-Long Fiber RC80/60BN **TS** - Transverse Steel

From Table 3, it could be observed that except beam B0, the north ends of all the beams had smaller shear crack spacing than the south ends. This was due to the provision of relatively higher amount of transverse rebars at the north ends than the south ends of all the beams. Exception to this observation was beam B0, which had 1.5 % of short fibers and zero transverse rebars at both ends. Hence, beam B0 demonstrated equal shear crack spacing of two inches at either ends.

Steel fibers were clearly observed to restrict the spacing of the shear cracks. All the fibrous beams exhibited comparable and in some cases even smaller crack spacing when compared to the traditional beams B1 and B6. Comparing shear crack spacing in beam B2 and beam B5, it can be seen that short fibers have performed better in SCC than in the traditional concrete mix. Beam B2 with TTFRC1 mix had relatively larger crack spacing than beam B5 with SCFRC3 mix. On the other hand, long steel fibers in beam B3 and beam B4 have restricted the crack spacing much more effectively than the short steel fibers in beams B2 and B5.

Interestingly, beam B0 with only 1.5 % short steel fibers as shear reinforcement had the least shear crack spacing among all the beams. Hence, steel fibers have the potential to restrict shear crack spacing as effectively as the traditional rebars or even better. Table 3 compares the shear forces at both ends of each of all the different beams at the onset of cracking. Cracking has been considered to initiate when the crack width reaches 0.001 inch (i.e. the minimum reading possible with the microscope used for measuring crack width). It can be seen that in this case cracking for beam B0 initiates at the maximum shear force. The cracking at the south ends of all the fiber reinforced beams were found to be at higher shear forces than that in beam B1, which did not contain fibers. This indicates that the addition of steel fibers in beams is notably helpful in preventing the development of initial cracks. Also, the results of beam B0 indicate that the replacement of rebars with steel fibers greatly increases the resistance of the beams to initial cracks. Fibers have effectively delayed the onset of cracks in fiber reinforced beams.

Fig. 4 shows the development of shear cracks with applied shear force for each of the two ends of the various beams. The crack width for beam B0 has been found to be lowest throughout the loading stage. Most of the fiber reinforced beams have performed better in controlling shear crack widths than the south end of beam B1. Again, beams with greater fiber factor (55) seemed to have resisted the growth of shear crack more effectively than the beams with smaller fiber factor (40). Additionally, there were theoretically 50 % more steel fibers per cubic feet of concrete in case of 1 % short fibers (380 fibers/cu.ft. of concrete) than in 0.5 % of long fibers (255 fibers/cu.ft. of concrete). Beam B2 with 1 % short fibers performed comparably well to the traditional beam B1 and beam B6 in resisting the growth of shear crack. Use of 1.5 % short fibers (beam B0) resulted in the reduction of shear crack width by about 50 %, when compared to 4.2 % steel reinforcement in the traditional beam B1 and B6.

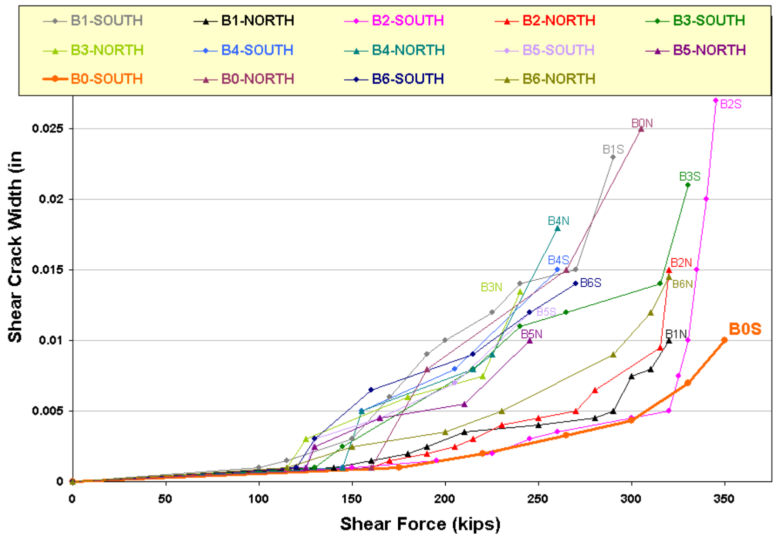

Fig. 4 Variation of Shear Crack Width with Shear Force Measured Using Microscope for Beams B0 to B6

All the above studies clearly indicate that the replacement of shear reinforcement with steel fibers plays an important role in the crack control of the beams.

3.4 End Zone Cracks: End zone cracks appeared at the beam-ends in most of the beams at about 90 days after casting. This indicated that the causes of end zone cracks were time-dependant and produced due to long term effects. These cracks occurred far later than expected. Hence, prestress and thermal loading may not be the only causes of the end zone cracking; secondary time dependent effects such as drying shrinkage, creep and temperature variation might have contributed to the development of these cracks. Beam B0 did not show any end zone crack development at the end region. The cracks in beams B3, B4 and B5 were of very small widths. The cracks developed in beams B1, B2 and B6 during this period were found to be comparatively more prominent. Long fibers in beam B3 and fibers in self-consolidating concrete (i.e. beams B4 and B5) seemed to have performed more effectively than short fibers in beam B2 and traditional beams B1 and B6. North end of beam B3 with 0.5 % long fibers and 1 % traditional transverse rebars had no signs of end zone cracking.

Considering the north and south ends of beam B1, it can be found that the width of crack was not influenced by the amount of end region reinforcement. Thus, a large amount of traditional transverse rebars is not effective in averting the end zone cracks. The transverse steel has only helped in reducing the number and length of cracks. Unlike the traditional end zone reinforcement, steel fibers effectively arrest the end zone crack right at the end face, thereby averting the propagation of the crack into the interior portion of the beam. Previous study of end zone cracking in a prestressed concrete beam by Nanni *et al.* (1992) reported similar findings. The researchers concluded that the transverse rebars did not prevent the end zone cracking, but managed to limit the crack propagation. On the other hand, it seems that steel fibers are more efficient in controlling the end zone cracks and furthermore have shown promising potential in eliminating completely the end zone cracks in the prestressed concrete beams.

4 CONCLUSIONS

(1) Experimental observations revealed that the steel fibers were more effective in controlling/eliminating the end zone cracks than the traditional transverse steel in the prestressed concrete I-beams. Fibrous concrete beams had end zone crack widths much smaller than the control non-fibrous traditional beam. Normal-slump concrete using 1.5 % by volume of short steel fibers (1.2 inches long) without the use of traditional transverse steel reinforcement was successful in complete elimination of the end zone cracks. Additionally, normal-slump fibrous concrete mix with 0.5 % by volume of long steel fibers (2.4 inches long) along with 1 % traditional transverse steel reinforcement was successful in averting the end zone cracking.

(2) Load tests of full-scale prestressed concrete I-beams have shown the effectiveness of steel fibers in increasing the shear strength, crack resistance, and ductility of these beams. Steel fibers were capable of changing the shear failure mode from brittle in case of the traditional non-fibrous prestressed concrete I-beam, to ductile in case of fibrous prestressed concrete I-beams. The tests proved the ability of steel fibers to partially or completely replace the traditional transverse steel reinforcement in the prestressed concrete I-beams. Steel fibers were also helpful in increasing the flexural capacity of the beams. Most of the beams with steel fiber reinforced concrete were stiffer than the control beams with non-fibrous mix. Furthermore, steel fiber reinforced beams demonstrated higher ductility and energy absorption than the non-fibrous beams. In other words, they are very appropriate to resist earthquake loading.

In summary, the research findings in this study clearly show that the use of steel fibers in normal-slump and self-consolidating concrete are effectual to replace the traditional transverse rebars, to control end zone cracking, to augment the shear strength and to enhance the ductility of concrete for earthquake-resistant structures .

5 ACKNOWLEDGEMENT

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