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SPLAY DETAILING OF STEEL FIBRE REINFORCED CONCRETE OPENING CORNERS

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ABSTRACT

The influence of detailing on the behavior of steel fibber reinforced concrete (SFRC) opening corners is reported. Mixed rather than one, aspect ratio of crimped-type steel fibers was used in the concrete. The variable investigated, was the amount of splay steel in the corner. The inclusion of splay steel stiffens the joint and substantially increases its effectively used in the currently recommended splay steel content could be effectively used in the corner hence the failure occurs due to formation of a hinge in one of the members framing into corner rather than a diagonal tension failure at the corner itself, as obtained in non-fiber concrete opening corners. On the basis of the results of this and another investigation on SFRC opening corners, it can be concluded that splay steel contents in excess of the hitherto recommended 50% of the main steel percentage, can be efficiently used in SFRC opening corners.

Keywords: crimped-type steel fiber aspect ratio, mixed aspect ratio, and splay steel, Joint efficiency.

INTRODUCTION

The detailing played a primary role in influencing the behavior concrete opening corners. Many theoretical and experimental studies [1,2,6,7] have concluded that the reinforcement detailing of opening corners is more sensitive as compared to that in closing corners. A number of investigations [1-9] have shown that corner joints in reinforced concrete Structures under opening bending moments have significantly reduced efficiency, compared with the moments carrying capacity of the members framing into the joint. The nature of the forces set up in the joint is such that inevitably, failure [1,2] takes place due to the formation of a diagonal tension crack, as schematically illustrated in Fig. 1. Since concrete is weak in tension, it is imperative that the detailing of the joint be such that the diagonal tensile forces in the corner are primarily resisted by the rebars, whose layout should preserve the structural integrity and prevent separation at the corner.

On the basis of his investigations with a number of detailing options, Nillson [1,2] has suggested the use of overlapping U-type bars at corners, such that acceptable behavior in terms of serviceability, strength, ductility, and ease of fabrication and placement of the rebar cage is obtained.

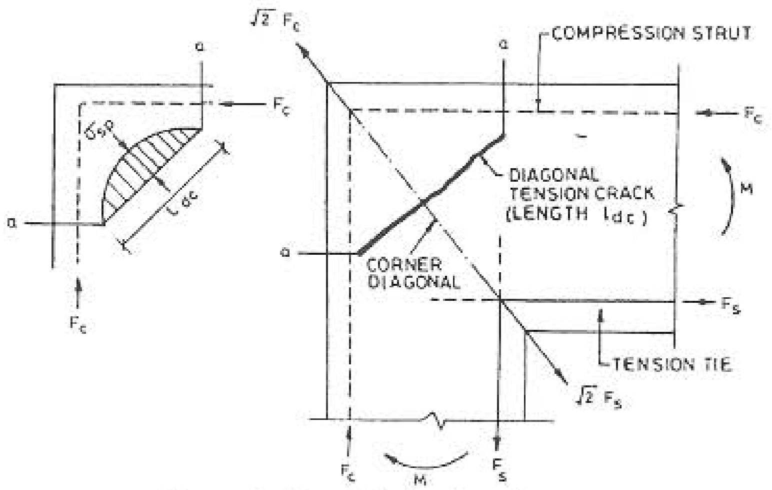

Figure 1. Truss idealisation of corner

The distribution of elastic stresses in an opening corner is show in Fig. 2. According to the theory of elasticity, the magnitude of the stresses normal to and along the corner diagonal is influenced by the structural action at the re-entrant corner. The provision of a haunch at the re-entrant corner has been shown to have a negligible influence [1,2], though the presence of reinforcement at the re-entrant corner in the form of splay bars (inclined bars) substantially modifies its behavior [1,2,3]. The splay steel helps to localize and contain the crack initiated along the diagonal direction at the re-entrant corner. Nilsson [1,2] investigated the influence of splay steel by varying its content. Two options were available. The option of keeping the number of splay rebars constant in the test specimens and varying the bar diameter was adopted, such that continuity among the rebars in the members framing into the corner was maintained. Three splay steel percentages with respect to the main tension reinforcement, viz. 100%, 69.4% and 44.4%, corresponding to 4 numbers of 12-mm, 10mm, and 8-mm bars respectively, were investigated by him.

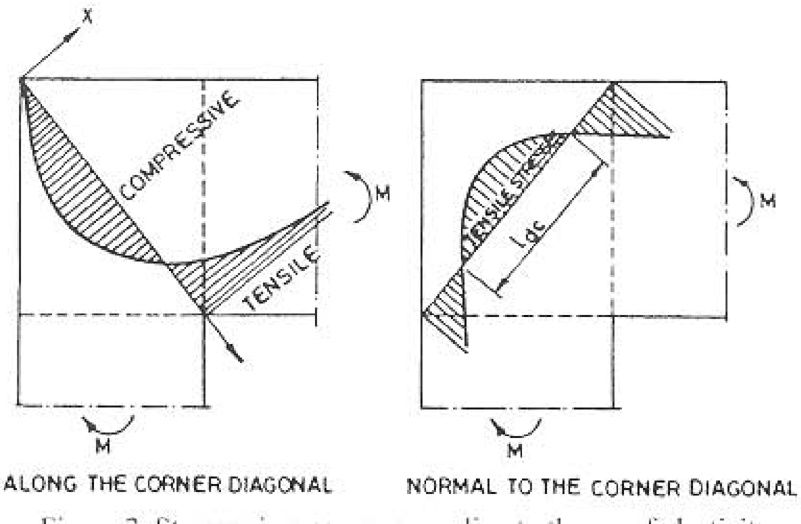

Figure 2. Stresses in a corner according to theory of elasticity

The other available option was of changing the number of rebars linearly, keeping the bar diameter constant, in the process eliminating any influence of the bond characteristics of the different sized rebars on the strural performance of the splay steel. As compared to an deficiency of 87% for the control specimen without splay steel, Nilsson [1,2] obtained efficiencies of 114, 115 and 123% for 100, 69.4 and 44.4% splay steel contents, indicating an average efficiency gain of around 30% due to inclusion of splay steel.

Besides this efficiency gain, of particular interest is the lower corner efficiency reported for higher splay steel contents, in contrast to the predictions of the theory of elasticity. It may also be noted that efficiency gain is more or less the same for 100 and 69.4% splay steel content (around 27%), though a larger gain in the corner efficiency (35%) was obtained at 44.4% splay steel content, corresponding to 4 rebars of 8-mm diameter. In addition to better efficiency, Nilsson [1,2] recommended the nominal splay steel content of 50% on the basis of his observation of yielding of the splay rebars at 44.4% content in contrast to 69.4 and 100% content.

Although the splay rebars in Nilsson's [1,2] specimens were anchored in the compression zone, the influence of the inferior bond characteristics of the 12-mm and to some extent the 10-mm rebar vis-à-vis the 8-mm rebars on the performance of the splay steel cannot be ignored. This argument is further strengthened by the fact that corner efficiencies for 100% and 69.4% splay contents are more or less the same and significant rise in efficiency is obtained at 44.4% splay content. Since the rebar diameter had, in addition to the splay steel content, become an additional variable, it is rather difficult to draw clear-cut conclusions about the influence of splay steel content on the behavior of the corner.

Available experimental evidence [3,10,11] shows that a substantial improvement in the tensile response of concrete can be obtained by including steel fibers in the matrix, with the fibersacting as crack arrestors and enhancing the strength, ductility and energy absorption capacity of the member in question.

Ezeldin and Balaguru [12] have reported significant improvements in bond strength upon inclusion of fibers in concrete. The mode of failure was also changed from the brittle bond failure observed in plain concrete to a ductile one. They have also observed that the addition of steel fibers contributes little to the bond strengths of smaller diameter rebars (9-mm diameter, #3), because in the case of these rebars, the bond failure is due to collapse of compression struts, not greatly strengthened by steel fibers. But the presence of steel fibers, giving an effect comparable to confining concrete, has a more effective contribution to the bond strength of larger diameter bars. Swamy and Al-Noori13 have also reported improved bond strength due to fiber addition. They have shown that the anchorage bond strength of deformed bars is 40% higher in steel fiber concrete than in plain concrete. Soroushian, Mirza and Alhozaimy14, obtained increases in local bond strength of deformed bars in confined concrete as in beam-column connections, to the tune of 33% on application of 0.5% volume fraction of deformed fibers Harrajli and Salloukh15 have also reported a substantial increase in the development/splice strength of rebars in steel fiber-reinforced concrete.

Abdul-wahab3 carried out pioneering investigations on steel fiber reinforced concrete opening corners. The results illustrate, the influence of steel fibers in modifying the behavior the corner reinforced with splay steel. The influence of steel fibers in modifying the behavior of the corner reinforced with splay steel. The control specimen with U-type detailing (with no splay steel) showed an efficiency of 47% and on addition of splay bars at 100% of the main constant moment acting on it and hence such a member may fail at any section, independent of the distance from the corner. This, however, is not likely to significantly influence the behavior of the corner as such.

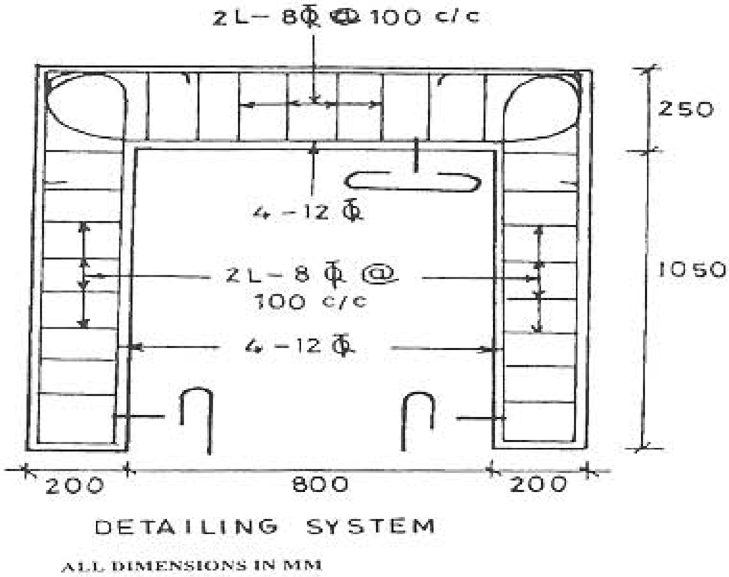

Figure 3. U-type detailing

The influence of splay steel was investigated by keeping the rebar diameter constant and varying the number of rebars such that effect of the splay rebar content could be isolated.

Four steel fiber concrete specimens, concrete specimens, containing 1, 2, 3 and 4 nos. of 12-mm diameter rebars as splay, corresponding to 25%, 50%, 75% and 100% of the main steel percentage respectively were cast The main steel percentage in all these specimens was kept constant at 0.76% (4 nos.-12mm diameter). The details of all the specimens are listed in Table 1.

Table 1. Details of test specimen

Specimen	Fibre volume fraction	Crimped-type fibre mix proportion (by mass)		Cube compressive strength (Mpa)	Detailing	
		Aspect ratio 40	Aspect ratio 20		Tension steel (A_{ST})	Splay steel (% A_{ST})
SP4	-	-	-	43.03	0.76%(4-12MM)	-
A1	1.25%	100%	-	50.05	0.76%(4-12MM)	-
B2	1.25%	-	100%	52.97	0.76%(4-12MM)	-
C2	1.25%	65%	35%	44.03	0.76%(4-12MM)	-
G1	1.25%	65%	35%	54.67	0.76%(4-12MM)	25
G2	1.25%	65%	35%	53.57	0.76%(4-12MM)	50
G3	1.25%	65%	35%	51.40	0.76%(4-12MM)	75
G4	1.25%	65%	35%	54.55	0.76%(4-12MM)	100

NOTES

- 25mm long flat crimped fibres. aspect ratio=20
- 50mm long flat crimped fibres. aspect ratio=40
- percentage of tension Steel=100 (Area of Steel)/bd

MATERIALS

The 12-mm-diameter Tor steel bars, used as main steel in all the specimens, had nominal yield strength Of 415 Mpa. The stirrups were fabricated using 8-mm-diameter tor steel and the hanger bars consisted of 6-mm-diameter plain mild steel bars. Minimum shear reinforcement as per specifications of IS 456-200019 governs in the specimens and the shear steel was designed accordingly and detailed as per SP-34 (1987) 20. All rebars used in the experimental program conformed to requirements of IS 1786-1985 [21].

The plain and fiber concrete used in the experimental program were designed using the ACI Mix Design Method. Since the same mix was to be employed for plain and fiber concrete, the recommendations of ACI Committee 544 [22] were taken into account while deciding the mix proportions. Grade 43 ordinary Portland cement was used in the concrete mix by weight of proportions 1:2.33:2.66 (cement: fine aggregate: coarse aggregate). The fine aggregate consisted of locally available dredged river sand and the coarse aggregate consisted of 19mm down crushed rock. A water-cement ratio of 0.4 was complemented by 1% by mass of cement of "Roff" Super Plast 820 super-plasticizer to obtain adequate workability for the plain and fiber reinforced concretes. The fibers used in the specimens, procured from Chennai, India, were 50-and 25-mm-long crimped-type steel fibers with an ultimate tensile strength of greater than 600 Mpa and a nominal cross section of 2x0.6mm giving aspect ratio of 40 and 20, respectively.

The specimens were cast horizontally on level ground in the casting yard using mild steel formwork. Prior to casting, the forms were coated with shutter release oil on the inside surfaces and 25-mm-thick cover blocks were used with shutter release oil on the inside surfaces and 25-mm-thick cover blocks were used to give the desired cover to the rebars.

The concrete was prepared using a tilting-type concrete mixer, and due care was taken during preparation of the mix to avoid fiber balling. Since the influence of the fiber concrete on the structural performance of the corner was being investigated, it was exclusively used in the corner zone and beyond, in the two members framing into the corner, for a distance equal to the respective member depth. Plywood separation pieces were used in the formwork to segregate the fiber concrete zones during concreting and after completion of the same, these were removed and the concrete re-vibrated to ensure continuity between plain and fiber concrete. The use of an internal vibrator ensured good compaction of the concrete. The specimens were stripped after 24 h of casting, and covered with Jute bags, which were kept moist by periodically sprinkling them with water. Curing in this manner was carried out for 15 days after which the specimens were left in the laboratory till the time of testing, which was 28 days after the day of casting. Control specimens consisting of cubes (150x150x150mm) cylinders (150x300mm) and prisms (100x100x450mm) were also cast with each specimen to determine the compressive and splitting tensile strengths, modulus of elasticity, and modulus of rupture. All the specimens were tested under pure positive (opening) moment using the basic loading arrangement shown in Figure. 4. The monotonically increasing load was applied in increments of 3.5KN using a hydraulic ram. A time interval of around 10 minutes was given between two increments of load so as to record the observations and allow the crack growth to stabilize. The load applied was measured using a sensitive proving ring, and the deflections and consequent changes in the corner angles were measured using dial gauges having a least count of 0.01mm. Steel strains were measured using electrical resistance-type strain gauges with a gauge length of

5mm, the strain gauges being mounted on the rebar prior to casting. Concrete surface strains at selected locations along the corner diagonal were measured using 65-mm-gauge-length electrical resistance-type strain gauges.

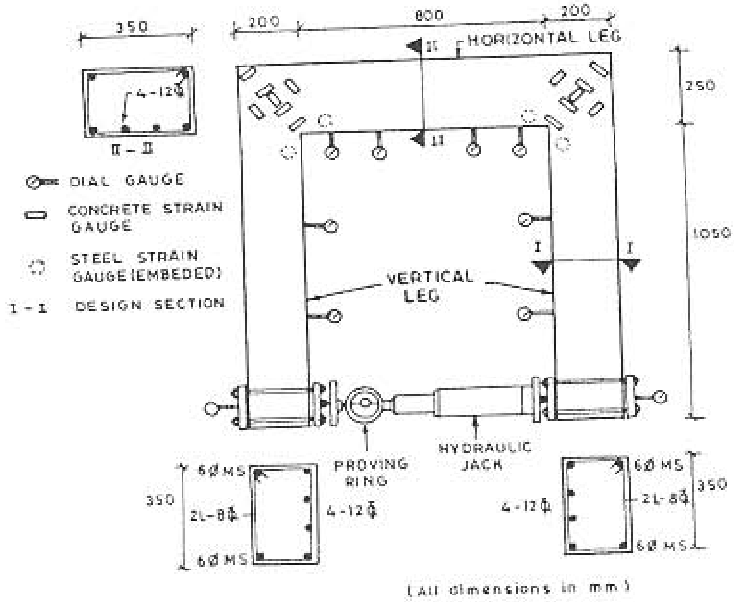

Figure 4. Loading arrangement

Concrete surface cracks were measured with an illuminated optical microscope having a least count of 0.01mm. During the course of the test, crack patterns were marked with paint on the whitewashed top face of the specimen. The loading arrangement, location of the dial gauges and the nominal position of strain gauges on the concrete and rebars are shown in Figure. 3.

As the test progressed, horizontal displacements of the specimen farming members and strain gauge readings at each stage of loading, the development and propagation of cracks, crack widths, load at first visible surface crack and the mode of failure of the specimens were noted. The control specimens were tested on the same day as the corner specimens, and their test results are summarized in Table 1.

EXPERIMENTAL RESULTS AND DISCUSSION

The dimensions of the specimens were selected that calculated ultimate moment of resistance (Nominal Strength Muc) for section II (in the horizontal framing member of the specimen, Fig. 4) is about 30% higher than that for section I (in the vertical framing member of the specimen, Fig. 4.). Section I-I is accordingly the design section. The Nominal Strength Muc was calculated using the concrete stress block given in IS 456-2000 [19]. The corner joint is expected to at least transfer the moment from the weaker member framing into it onto the stronger member. The theoretical ultimate moment of resistance of section I-I is taken as the reference value for computing joint efficiency. The failure moment (M_{ul}) determined experimentally is compared with the nominal theoretical ultimate moment of resistance (M_{uc}) of the design section. The value M_{ut}/M_{uc} x100 is a measure of the efficiency of the joint. This value must be greater than or at least equal to 100% in order that the joint may be as strong as the weaker cross section framing into it.

The observed concrete surface crack widths and corner efficiencies are reported in Table 2. In all the specimens the corner crack widths at 0.50 M^{uc}, corresponding to service loads, were within the Code prescribed limit of 0.30mm. In the absence of rational detailing, the corner would have failed prematurely at loads much lesser than the moment capacity of the adjoining members. The U-type detailing adopted in this study, confines a large part of the corner concrete within itself and serves to preserve its integrity in spite of the large strains and deformations that corner undergoes.

Table 2. Test rest results

Specimen	Corner surface crack width AT 0.50 M_{UC} (MM)	Corner surface crack width before failure (MM)	Theoretical ultimate moment M_{UC} (kNM)	Test failure moment M_{UT} (kNM)	Corner efficiency M_{UT}/M_{UC}x100	Mode of failure
SP4	0.36	0.83	25.54	23.52	92.09%	DTC
A1	0.13	0.90	25.83	30.99	1119.99%	DTC
B2	NIL	0.35	25.92	25.60	98.73%	DTC
C2	0.06	0.74	25.59	32.86	128.70%	DTC
G1	0.25	0.92	25.98	41.15	158.40%	DTC
G2	0.22	1.60	25.94	39.02	150.42%	DTC
G3	0.20	1.20*	25.87	43.22	167.04%	DUCTILE
G4	0.13	1.14**	25.97	42.85	165.00%	DUCTILE

DTC: Diagonal Tensile Crack
*Crack Width at Hinge 3.2MM
**Crack Width at Hinge 3.0MM

For the plain concrete control specimen SP4, an efficiency of 92.09% was obtained. Specimen C2 was the same as SP4, except for the addition of 1.25% volume fraction of crimped-type steel fibers in the mix ratio by mass of 35%:65% of 25-mm and 50-mm long fibers On comparing the performance of C2 with SP4, the effectiveness of the fibers in complementing the role of the rebars is evident, and a significant improvement in the corner efficiency to 128.40% was obtained for specimen C2. SP4, it is interesting to compare the performance of C2 with A1 (containing 1.25% volume fraction of 50-mm-long crimped type fibers only) and B2 (containing 1.25% volume fraction of 25-mm-long crimped type fibers only). Specimen C2 retained the superior strength characteristics of A1 along with the better serviceability behavior of B2. A comparison of the load-deflection curves of SP4, C2 A1 and B2 is presented in Fig. 5.

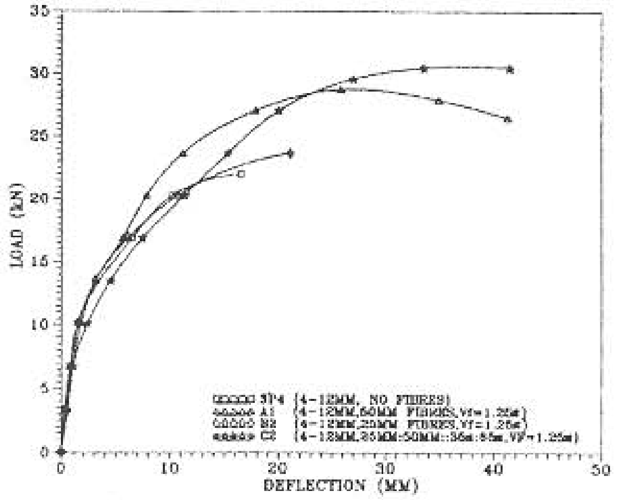

Figure 5. Load-Deflection Curves (Plain and Fiber Concrete Specimens)

EFFECT OF PERCENTAGE SPLAY STEEL

The load-deflection curves of fiber concrete specimens with variable splay steel contents are shown in Fig. 6.

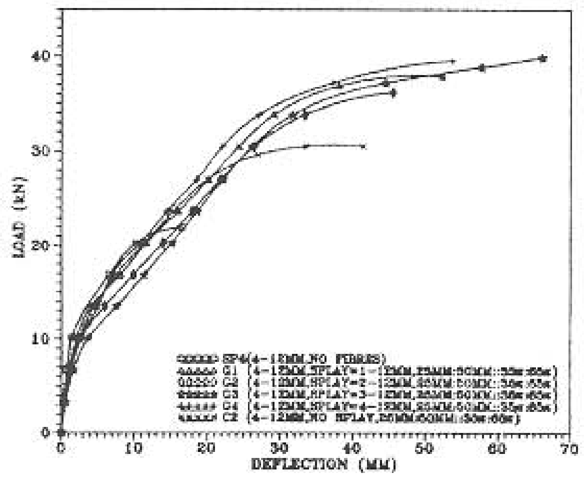

Figure 6. Load-Deflection Curves (Variable Splay Steel)

The addition of even a small amount of splay steel significantly alters the behavior of the corner and the load-deflection curves for different splay steel contents show a remarkable similarity to each other. For all the specimens with splay steel, in general, the cracking at the corner was accompanied by the formation and growth of flexural cracks in the adjoining members, with cracks in the horizontal framing member of the specimens being spaced more or less evenly. As the loads increased, the growth of the cracks in the adjoining members increased rapidly as compared to that in the corner. In the case of specimens G3 and G4, a widening of one of the cracks in the horizontal framing member of the specimen was observed, with this crack gradually progressing towards the compression zone of the member.

At impending failure, the rebars in the tension zone of the horizontal framing member were bridging the partially separated corner faces at rapidly widening crack, and failure was marked by the progress of the crack towards the extreme compression fiber. This was accompanied by crushing and sapling of the extreme fiber concrete, until the test had to be terminated due to an explosive fracture of the rebars. This localization of the crack growth in the horizontal framing member of the specimen at almost constant moment capacity indicates the formation of a plastic hinge and was observed in G3 and G4. Hence for the first time in the study, the zone of failure in G3, containing 75% of main steel as splay steel and in G4 containing 100% of main steel as splay steel, was effectively shifted away from the corner. Efficiencies of 167.04% and 165% were recorded for specimens G3 and G4, in contrast to 158.40% and 150.42% for specimens G1 and G2. Overall, these efficiencies indicate no liability on the use of higher splay steel percentages in steel fiber reinforced concrete opening corners and unlike plain concrete corner with splay steel, a rather favorable structural response was obtained at 75% and 100% splay steel contents.

Somewhat similar results were observed by Abdul-Wahab3 in his investigations on steel fibre reinforced concrete opening corners. He obtained an unusually low efficiency of 47% for non-fiber concrete specimen with overlapping U-bars only. On the introduction of splay steel equal to the main steel content, in the above specimen, a dramatic improvement in efficiency to 9.30% was obtained. Further addition of 1.50% volume fraction of hooked-end "Dramix" fiber, increased the efficiency to 135.60% Although Abdul-Wahab3 did not investigate the effect of variable splay steel contents, it is evident that considerable improvements in the efficiencies of steel fibre reinforced opening corners were obtained at high splay steel contents.

The findings of the presents study are in contrast to Nilsson's [1,2] observations with varying splay steel contents, where a 9.00% efficiency drop was obtained as the splay steel content increased from 44.40% (4-8-mm rebars) to 100% (4-12-mm rebars) of the main steel content. The variation of corner efficiency with different splay steel contents for the specimens from Nilsson's1,2 study and this study is shown in Fig. 7.

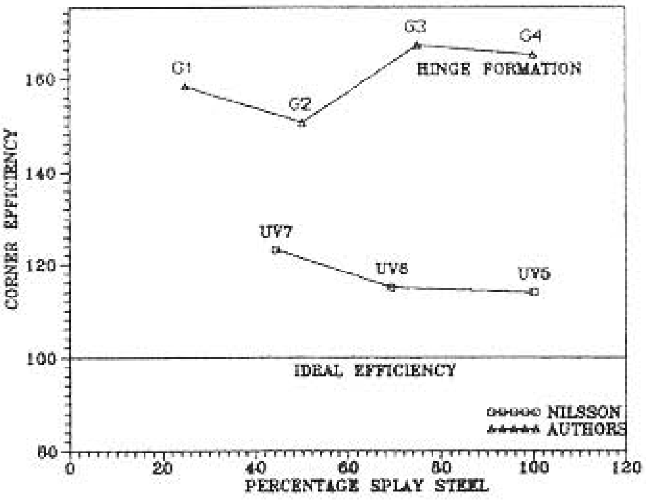

Figure 7. Variation in Efficiency with Percentage Splay Steel

The splay steel in the form of inclined bars serves to bridge the tensile cracks at the re-entrant corner, where the local peak bond stresses can be high. The use of large diameter rebars particularly renders the corner to splitting and/or local slip. The anchorage and development length available for the splay steel in the compression zones of the adjoining members, where they terminate, is rather poor and the situation is further compounded when larger diameter rebars are used. These, have inherently inferior bond characteristics compared to the smaller diameter rebars.

The addition of fiber modifies the bond behavior of the rebars in two ways. First, since the splay rebars are anchored in the compression zone, the increase in compressive strength of concrete to the tune of 10-25%, due to addition of fibers improves the interfacial bond between the rebar and the matrix. Secondly, TM the incorporation of fibers known to significantly enhance the bond strength [12,13,14,15] of the matrix, this role is especially effective for bar sizes in excess of 9-mm diameter.

Consequently, the effective utilization of the 12-mm diameter rebars was possible in the author's specimens in steel fiber concrete. That a ductile failure was obtained in specimens G3 and G4, unlike Nilsson's plain concrete specimens with similar detailing.

CONCLUSIONS

No liability is observed at higher splay steel contents in steel fiber concrete opening corners. Also splay steel equal to the main steel content can be efficiently utilized in corner joints having 1.25% volume fraction of crimped-type flat steel fiber in the mix ratio. Weight of 50 and 25-mm long fibers is 65%,35%, respectively

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NOTATION

b	=specimen width
d	=specimen effective depth
L_{DC}	=length of diagonal tension crack at impending failure
σ_{sp}	=splitting tensile strength of concrete
F_c	=resultant compressive force acting on the corner
F_s	=resultant tensile force acting on the corner
M	=moment acting on the corner
M_{UC}	=nominal theoretical ultimate moment of resistance of design section
M_{UT}	=test failure moment

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