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Prestressed fiber reinforced concrete beams with reduced ratios of shear reinforcement

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Abstract

This paper presents an analysis of the influence of prestress and fibers on the shear behaviour of thin-walled I-section beams with reduced shear reinforcement ratio. Reduction of shear reinforcement in prestressed precast beams can make the reinforcement simpler and may increase the productivity in long line precasting beds. The use of short fibers can improve the shear strength and ductility. Nine concrete beams were built (six with prestressing forces) with three different mixtures: without fibers, with steel fibers, and with polypropylene fibers. Shear reinforcement ratios varied from 0 to 0.225% (geometric ratio). It was noted that prestressing increases cracking strength (both in bending and shear), extends the non-cracked area, and makes the compression struts less inclined. In the case of fiber reinforced concrete beams, control of cracking is more effective and consequently deflections are smaller. Ductility is also increased. Both fibers and prestressing reduce stresses in the stirrups and increase shear strength.

Keywords: Concrete beam; Prestressing; Shear strength; Fiber reinforcement; Precast concrete

1. Introduction

Reduction of shear reinforcement in precast concrete elements may improve the production process and diminish costs. The feasibility of this alternative for beams will depend on its performance under shear forces (strength and ductility), avoiding any brittle failure.

The study of the shear behaviour of concrete beams is a rather complex one [1–4]. For this reason, several models have been proposed to represent the behaviour of concrete beams subjected to shear forces. Most of the calculation methods are of an empirical nature [5–9].

Prestressing reinforcement is usual in long-line bed precasting processes because it improves structural performance of elements and can increase productivity. Although the influence of prestressing in shear strength is usually considered a secondary benefit to flexure design, it is very significant when cracking is limited. Researchers, however, have not yet arrived at a consensus regarding the contribution of prestressing with straight cables on shear resistance [10].

The use of short fibers in concrete offers noticeable advantages, such as limited cracking and increased toughness. It can also increase shear strength, allowing reduction of stirrup reinforcement, and improve ductility and safety [11–13].

The influence of fibers on shear strength has been studied by several authors to quantify the increase of resistance and to associate a model for calculation [14–17].

The calculation methods used for concrete beams without fibers would incorporate the contribution of fibers:

(a) increasing the contribution of the concrete (through the dowel effect, crack friction, and action of the compression zone);

(b) acting directly across diagonal cracks (in a manner similar to the stirrups), where the fibers would resist forces equal to those that cause pull-out or failure, depending on the type and volume of fibers used.

This work analyzes the influence of prestressing and fibers on the structural performance of thin-walled

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I-section beams, with reduced ratios of shear reinforcement [18].

2. Experimental program

2.1. Materials

The materials used in the concrete mixtures were: high initial strength Portland cement, river sand, crushed basalt stone and, in the beams with fiber, superplasticizing admixture. The mixture proportions (by weight) were kept constant at 1 : 2 : 1.3 (cement : sand : coarse aggregate) and 0.45 water/cement ratio. Two types of fibers were used: (a) polypropylene, 42 mm length and 0.05 mm diameter, and (b) crimped steel fiber, 25.4 mm length and 0.2 × 2.3 mm rectangular section.

2.2. Models

Nine I-section beams were produced, varying the types of fiber, the existence of prestressing, and the shear reinforcement ratio. In the beams with fibers, the volume added to the concrete was kept constant, i.e., equal to 0.5% of polypropylene fiber or 1% of steel fiber. Simultaneous to the production of these beams, six 150 × 300 mm cylindrical test samples were molded to determine the mechanical properties of the concrete.

Shear reinforcement (stirrups) consisted of 3.4 mm diameter wires with a 750 MPa yield strength. Longitudinal reinforcement consisted of 9.5 mm strands (seven wire prestressing strands) and 1770 MPa yield strength.

The first six beams had the same shear reinforcement, among them three beams with prestress and three without. In each group of three specimens, only the concrete mixtures varied, that is, two mixes with fibers and one without fibers. In the third group of three beams, also prestressed, shear reinforcement was still more reduced in comparison with the former groups.

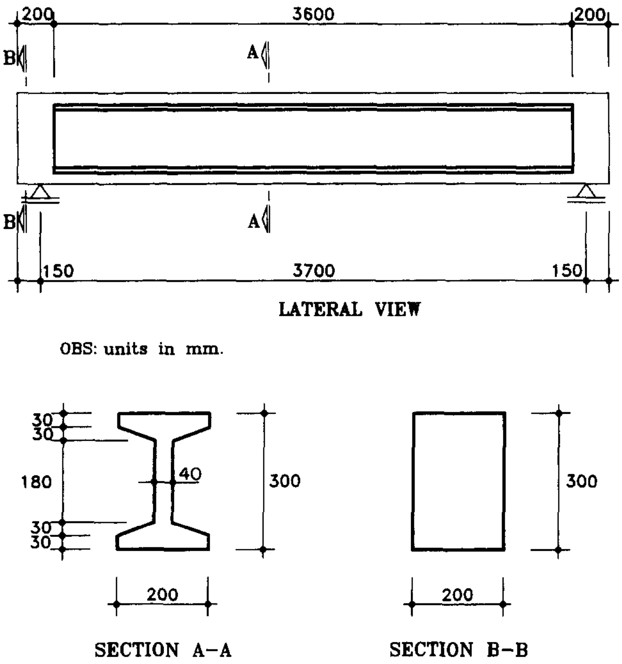

Fig. 1. Geometric characteristics.

The prestressing force was kept approximately equal to 105 kN (on the day of the test) on all the prestressed beams. The beams were tested by application of two point-loads, with the shear span equal to 4 d (d is the effective height of the section). Table 1 summarizes the principal data from the nine beams. Fig. 1 shows the geometry of the beam and Fig. 2 illustrates the reinforcement and the loading scheme.

The beams were instrumented with electrical strain gauges on the concrete compression zone (symbol C), on the longitudinal reinforcement (symbol A) and on the stirrups (symbol E). Also, three direction electric strain gauges (rosettes, R) were placed on the web. In addition LVDT gauges were installed on the supports, the middle of the span, and at the loading sections. Fig. 3 shows the position of the gauges and the symbols.

Table 1
Test beam characteristics

Beam	Fiber: volume and type (P – polyp. S – steel)	Superplasticizer (%)	Prestress	Geometric shear reinforcement ratio	Stirrup spacing (mm)	Shear reinforcement (cm^2/m)
V1	–	–	Without	0.225	200	0.9
V2	0.5% P	1%	Without	0.225	200	0.9
V3	1% S	0.65%	Without	0.225	200	0.9
V4	–	0.3%	With	0.225	200	0.9
V5	0.5% P	1.5%	With	0.225	200	0.9
V6	1% S	1%	With	0.225	200	0.9
V7		0.5%	With	0	–	0
V8	0.5% P	1.5%	With	0	–	0
V9	1% S	1%	With	0.162	280	0.65

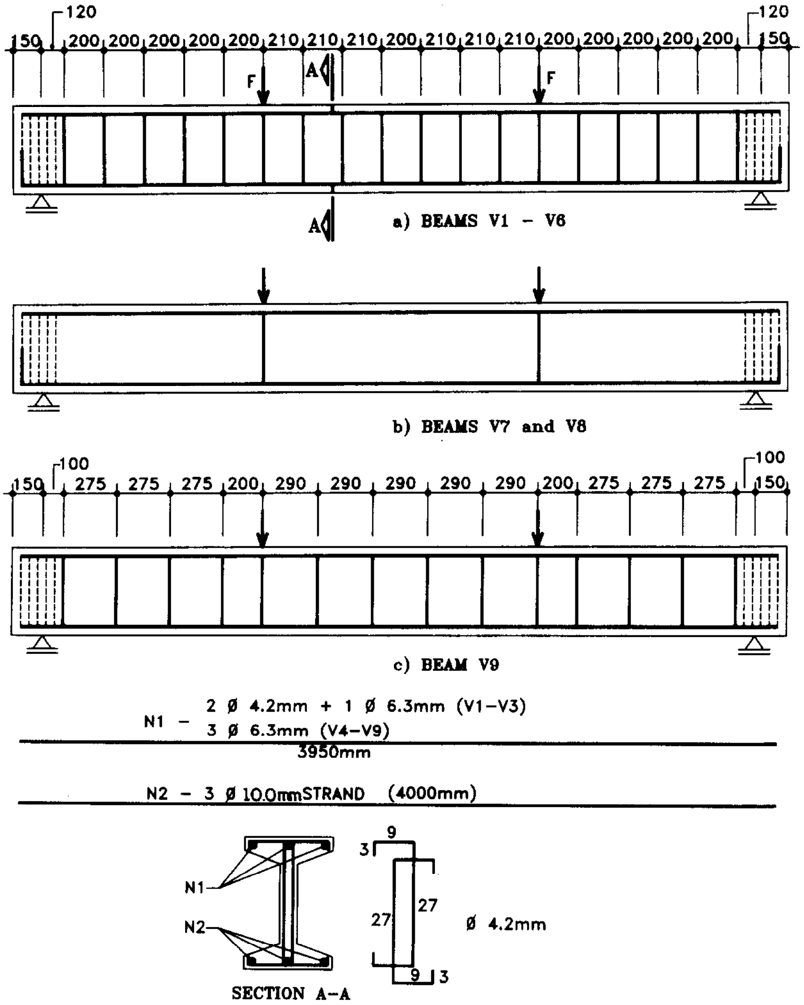

Fig. 2. Detail of beam reinforcements.

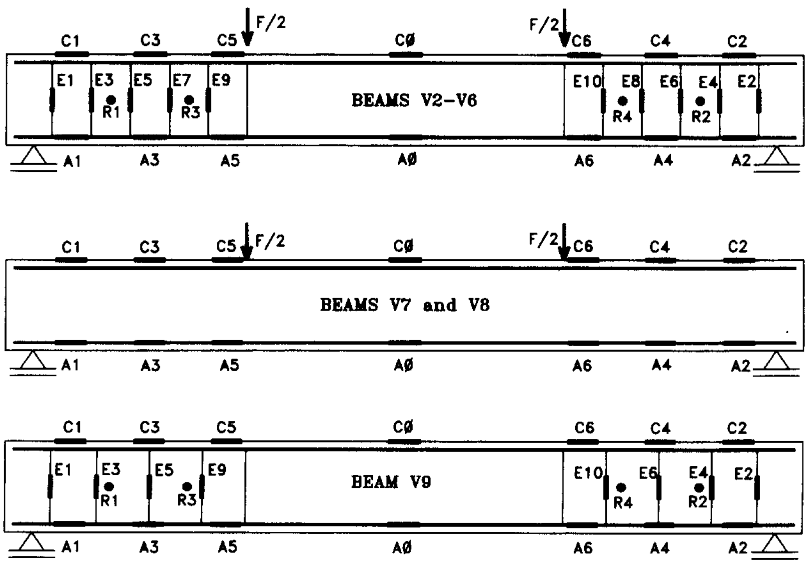

Fig. 3. Position of instruments and symbology.

3. Analysis of results

3.1. Properties of concrete

The addition of fibers decreased the workability of the fresh concrete, particularly in the case of polypropylene fiber, which had a very high aspect ratio (length/diameter ratio). Table 2 shows the values of compressive strength, tensile strength and initial modulus of elasticity, at the age of the concrete of each tested beam. The last column of Table 2 shows the values of the modulus of elasticity divided by the square root of compressive strength, as an attempt to minimize the influence of concrete strength on this parameter.

It was noted that the introduction of fibers did not increase compressive strength. However, there was a variation of strength associated with the conditions of matrix consistency. The values were lower in the case of the polypropylene fiber concrete beams, where alteration of the consistency is more significant. Variation in the remaining beams was more discrete, the highest variation occurring in the beam without fibers (beam V1) in which no superplasticizer was used. Tensile strength of steel fiber concrete measured in split tests was higher, regardless of the value of compressive strength.

Table 3 summarizes the results, grouped into the three types of mixtures utilized. The modulus of elasticity of steel fiber concrete was higher, while the value for polypropylene fiber was lower. The differences practically disappear in the case of the last column of the Table 3, suggesting that concrete strength may be the determinant factor for the value of modulus of elasticity.

3.2. Ultimate strength

A view of the beams after testing is shown in Fig. 4. Table 4 summarizes the main data on failure: minimum strut slope realized and maximum shear force.

The theoretical values of ultimate shear force (V_u) and longitudinal reinforcement yielding force (V_f) are also shown. The ultimate shear forces for the prestressed beams were calculated following two methods based on the truss analogy (taking into account the term of the concrete contribution – V_c). The first method is based on increased V_c (according to the relation between decompression bending moment and maximum design moment). The second one takes into consideration the increased resistance equivalent to shear force decompression.

In Table 4, the $V_{u,rel}$ values were obtained by dividing the ultimate experimental forces (V_{max}) by the square root of the concrete compression strength. This was done to highlight the influence of the fibers and prestress on the results.

The last column shows the relation between experimental and theoretical ultimate shear forces. For the prestressed beams, two ratios are shown according to the two calculation methods mentioned earlier.

The addition of fibers improved the shear strength, except in the beams without stirrups. Prestressing provided the same result, but with higher intensity, and regardless of the shear reinforcement.

Strut slope close to failure was lower in the cases of prestressed beams. The effect of fibers and of the reduction of shear reinforcement in this phenomenon was slight.

Table 2
Properties of the concrete

Beam	Age (days)	Compressive strength f_c (MPa)	Tensile strength f_t (MPa)	Modulus of elasticity E_c (MPa)	Relative modulus of elasticity $E_c/f_c^{\ 0.5}$
V1	8	48.5	3.1	37 490	5383
V2	7	37.4	2.1	30 800	5036
V3	7	52.8	3.6	37 050	5099
V4	8	57.2	3.0	35 870	4742
V5	7	52.1	3.2	32 860	4552
V6	11	59.1	3.5	38 030	4947
V7	7	52.1	2.2	33 580	4652
V8	7	44.9	3.1	34 670	5174
V9	8	52.3	3.4	35 280	4878

Table 3
Average values of the corresponding mixtures

Concrete mix	Compressive strength f_c (MPa)	Modulus of elasticity E_c (GPa)	Relative modulus of elasticity $E_c/f_c^{\ 0.5}$
Plain concrete	52.6	35.6	4926
Polypropylene	44.8	32.8	4921
Steel	54.7	36.8	4975

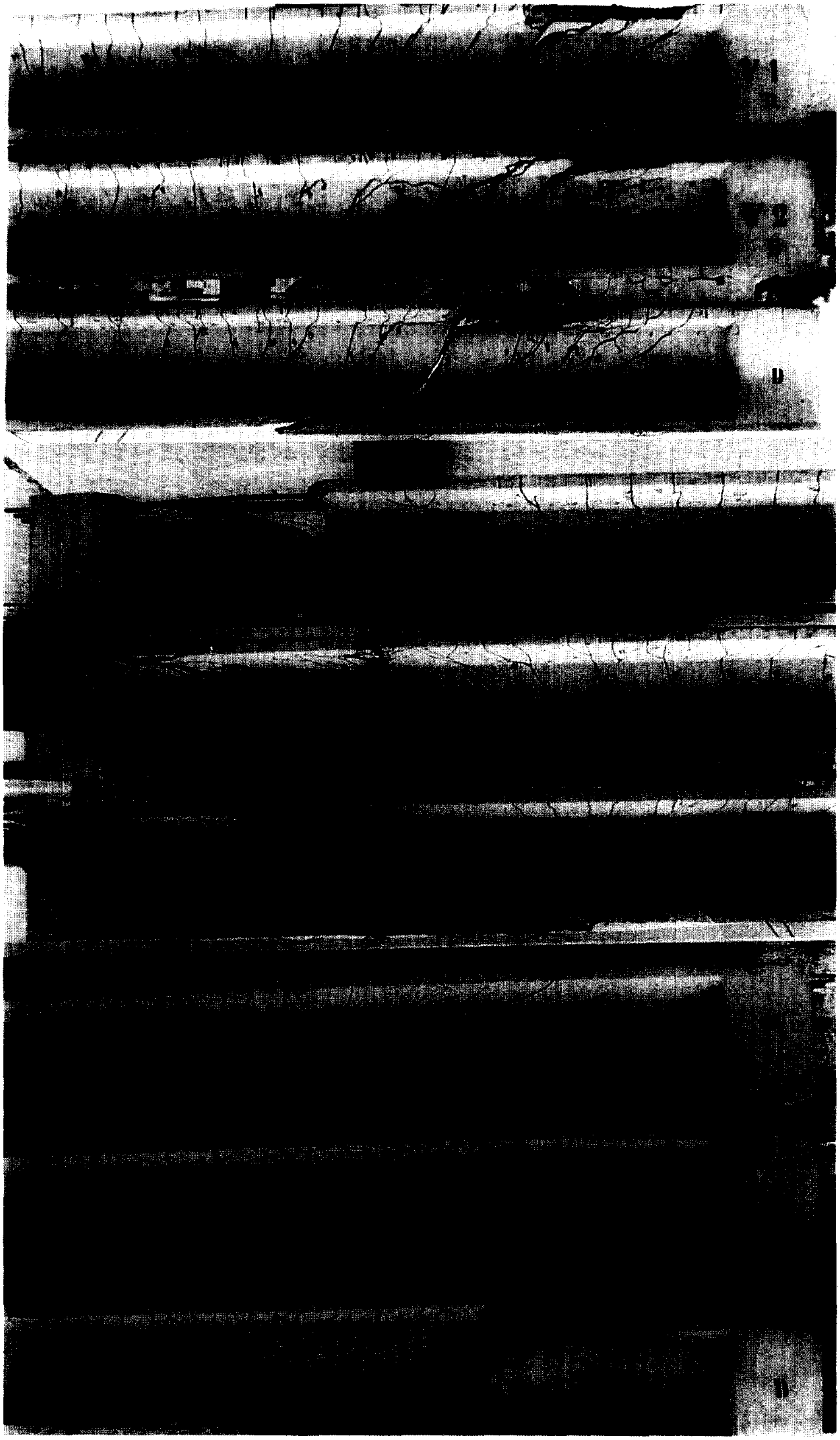

Fig. 4. View of the beams after failure.

Table 4
Parameters on failure

Beam	Compressive strength f_c (MPa)	Minimum slope of the compression struts (grads)	Ultimate shear force V_{max} (kN)	V_u (kN)	V_f (kN)	$V_{u,rel}$ (kN)	Experimental/ theoretical ratio
V1	48.5	24	42	28.9	69.6	6.03	1.45
V2	37.4	27	50	27.7	68.6	8.18	1.81
V3	52.8	26	50	29.4	69.8	6.88	1.7
V4	57.2	20	63.5	36.4/49.5	70.1	8.40	1.74/1.28
V5	52.1	20	73.5	35.6/48.6	69.8	10.18	2.06/1.51
V6	59.1	21	71.5	36.7/49.9	70.2	9.3	1.95/1.43
V7	52.1	17	47	21/42.2	69.8	6.5	2.24/1.11
V8	44.9	20	45	19.6/40.4	69.3	6.72	2.30/1.11
V9	52.3	20	72.5	30.4/51.1	69.8	10.03	2.39/1.42

The ultimate shear force was much higher than the one obtained theoretically, confirming the conservative approach of the formula, which underestimates the contribution of concrete in shear resistance.

When the effect of prestressing is disregarded in the beams without stirrups, the relation between the experimental and theoretical values is close to 2.35. The difference in the beams with stirrups was slightly lower. This occurred because, besides the significant and predictable contribution of the stirrups, the concrete contribution (dowel effect, crack friction and the action of the compression zone) in the transfer of transversal forces diminished, since cracking was more intense. The increase of resistance due to prestressing was proportional to the decompression of the section analyzed.

Increased strength in the fiber reinforced beams varied from 8 to 10 kN (13% to 19%). When one considers the variation of the relation between theoretical and experimental maximum loads, that takes into account the influence of the quality of the concrete on the behaviour of the beam, this increase varied between 12% and 24%. There was a variation of 14% and 36% in the experimental maximum loads divided by the square root of the concrete compressive strength ($V_{u,rel}$), which probably overestimates the influence of concrete on strength behaviour. In the beams without stirrups, despite the nominal 4% reduction in strength, there is also an increase in the $V_{u,rel}$ value (3.4%).

Since there was a practically constant strength increase in all the beams except in those without stirrups, i.e. between 8 and 10 kN, the contribution of fibers can be considered equivalent to a fraction of the shear reinforcement. The performance of beam V9 confirms the possibility of an advantageous partial substitution of stirrups for fibers.

3.3. Cracking and deflection

In the first six beams, the closer spaced flexure cracks occurred in the fiber reinforced beams. The influence of fibers on first crack strength was not observed.

Contrary to what occurred with the influence of fibers, the difference between shear force corresponding to first inclined crack and shear force failure did not increase with prestressing. In the prestressed beams, the increase of the shear force corresponding to first inclined crack was proportional to the decompression of the section subjected to the maximum bending moment. The uncracked zones at the ends of the prestressed beams was larger, although cracking near the middle span was similar to that observed in the non-prestressed beams. This happens because decompression at the extremities of the beams occurs later.

Although the beam had a relatively thin web, the first shear cracks always resulted from the prolongation of bending cracks. There was no influence of fibers in relation to the instant when shear cracks appeared. However, after inclined cracking, additional strength was greater in all the fiber reinforced beams except in those without stirrups. Shear cracks at the extremities of the beam were more numerous in the case of fiber reinforced beams, which allowed strength increase. In addition to the direct action of fibers as shear reinforcement, this is also due to the indirect effects of the alternative shear transfer mechanisms (dowel effect and crack friction) and to the greater efficiency of stirrups in such a situation. This advantage, however, was not extended to the beams without stirrups, where failure occurred soon after formation of the diagonal crack.

The observations on cracking were confirmed by the analysis of deflections (shown in Fig. 5). Deflection was smaller in all the fiber reinforced beams except those without stirrups. Steel fiber showed the best performance. All the load-deflection curves show three distinct phases, with the linear stage longer in the prestressed beams in every case.

3.4. Strain in the strands

None of the beams showed longitudinal reinforcement yielding. Deformations on the shear span predicted by considering only bending moments were

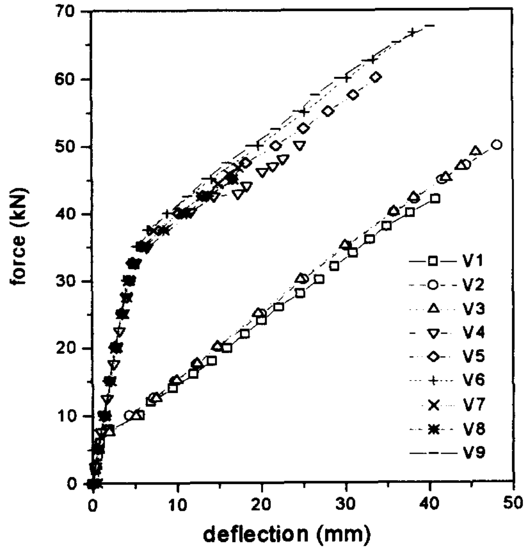

Fig. 5. Load-deflection curves.

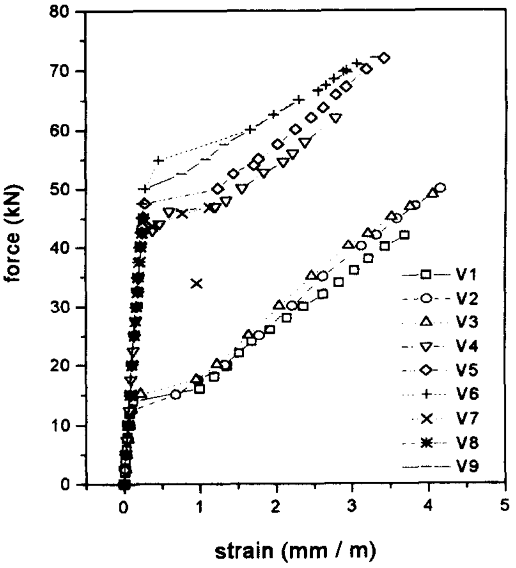

Fig. 6. Strain in the strands (points A3–A4).

generally larger than expected, which confirms the validity of the modified truss analogy. No significant differences were observed in the evolution of strains in the strands due to the introduction of fibers. The most significant alteration with regard to prestressing was the extended non-cracked stage.

Measurements taken at points A3–A4 illustrate the support effect to the struts provided by longitudinal reinforcement, since they are located in sections where the principal struts converge.

Dowel effect possibly was increased by the addition of fibers and it can be estimated by relating the value of maximum strain of the strands at these points at the instant of collapse. Evolution of deformations at these points is shown in Fig. 6.

The deformations in V2, V3, V6 and V9 were relatively high compared to that observed in the middle of the span. Therefore, the fiber reinforced concrete beams, where the dowel effect has acted for a longer period and delayed concrete splitting, showed a better performance.

3.5. Strain in the concrete

Neither of the two beams without stirrups showed any reduction of compression strain at the end of testing because the failure was very brittle and the phenomenon could therefore not be recorded. Significant tensile strains were recorded close to the supports in both beams. Decompression mostly begins with the effective mobilization of the longitudinal reinforcement in the corresponding section. Thus, it always occurred earlier in the models without prestress.

Decompression always occurred at points C3–C4, but in no case were tensile strains recorded. Close to the loading points (C5 and C6), a discrete reduction of strain was observed on only two beams. The strain evolution in the middle span was more uniform, according to the characteristics of the composite and the bending moment action.

The strains in the stage prior to decompression were greater in polypropylene fiber reinforced beams at every point, due to the lower value of the concrete modulus of elasticity.

The rosettes used in the web are subjected to the influence of cracks that appear close to them, even when they are positioned between two stirrups, since the existence of complementary struts causes the appearance of shear cracks in this area. Thus, the validity of these results is limited to the stage prior to cracking.

The main alteration in the web strains due to prestressing is related to the direction of the principal strains, as opposed to the strain values, which showed less significant variations.

3.6. Strain in the stirrups

Fig. 7 shows the evolution of the stirrup stresses. In the steel fiber concrete beams, the stirrups were tensioned later and strain remained low. In the case of polypropylene fiber, strain in the stirrups developed at a slower ratio than in the beams without fibers (except in E7–E8), even when they were put into action earlier. Prestressing retarded the action of the stirrups in the same proportion to decompression in the section where they were located.

The contribution of concrete in shear strength can be represented by the value of shear force corresponding to the instant when the stirrups are tensioned. It was almost always higher than the strength of beams without

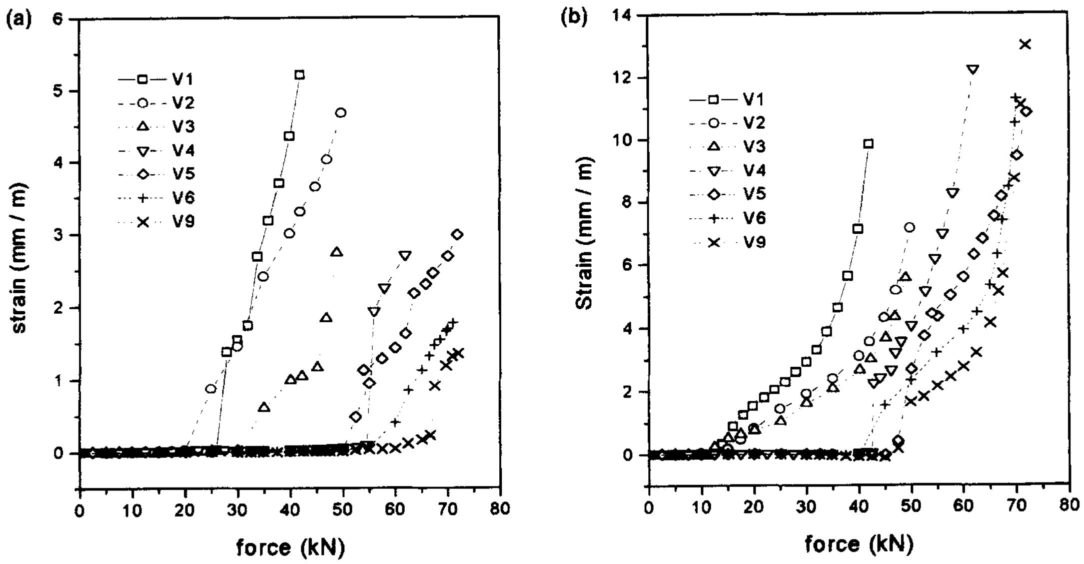

Fig. 7. (a) Strains in the stirrups at the points E3–E4. (b) Strain in the stirrups at the points E9–E10.

stirrups, but eventually diminished with loading. Prestress and fibers were responsible for the larger contribution of the concrete, which is normally considered smaller than the strength of a similar beam without stirrups.

Strain in the stirrups on the polypropylene fiber reinforced beams was higher than in the steel fiber beams. The contribution of polypropylene fiber was significant while the alternative mechanisms still exerted effective action, due to improved crack control. However, in the area of diagonal cracks, the action of this fiber as shear reinforcement was limited, due to the very low modulus of elasticity, which justifies the higher strains in the stirrups closest to the supports. Even so, the strength of these beams was always greater than in the beams without fibers, because of the energy required for pull-out of the fibers. In the case of steel fiber, reduction of strain in the stirrups is due to the higher stiffness of the steel fibers that limit deformation at the cracks. Less energy is required for pull-out, since the quantity of fibers that cross the cracks is smaller.

Regardless of the type of fiber, limitation of cracking improves the performance of the beams because it increases the contribution of alternative shear strength mechanisms.

4. Conclusions

- The addition of fibers does not increase the compressive strength of concrete, but it can increase tensile strength in some cases. The modulus of elasticity of concrete can be altered with the introduction of fibers.
- The crack spacing in fiber reinforced concrete beams is smaller and its development is slower, particularly in the case of steel fibers. Deflections are consequently smaller. Fibers are also responsible for the larger number of inclined cracks prior to the beam collapse.
- Prestressing increases the elastic–linear stage, but contrary to what the fibers can do, it does not extend the stage between diagonal cracking and shear failure. The appearance of inclined cracks is retarded and consequently the stirrups are tensioned later. Prestressing decreases the slope of the compression struts and increases the extent of the non-cracked area.
- Fiber effectiveness is higher in beams with stirrups. In all the fiber reinforced beams failure was more ductile and there was increased strength, always between 8 and 10 kN. The fibers can be considered as an equivalent shear reinforcement. In this aspect, the advantages provided by steel and polypropylene fibers were similar, but the strain in the stirrups in steel fiber beams was smaller.
- Prestressing also increases shear strength (regardless of the ratio of shear reinforcement, provided there is no longitudinal reinforcement yielding), but in a more significant manner than the fiber addition. The influence of prestressing on beams with reduced ratios of shear reinforcement is equivalent to the decompression of the analyzed section.
- The contribution of the concrete to shear strength can decrease with the load increase. The value of this contribution increases with fibers and prestressing. Contribution values close to the ones observed in similar beams without stirrups have been recorded.
- Calculation of the strain in longitudinal reinforcements resulting from flexure stresses underestimates

its real value, due to the mobilization of the truss mechanism in the transfer of transversal forces and the tied-arch effect.

- The reduction of compressive strain on the concrete reaches sections situated up to 2.2 d away from the supports (and it can reach distances of even more than 3.5 d, when shear failure is not premature). In this area, the load can be transmitted directly to the supports.

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References

[1] American Concrete Institute, Committee 318. Building code requirements for reinforced concrete, ACI Manual of Concrete Practice, vol. ACI318M-83. Detroit, 1985.
[2] CEB-FIP Model Code 1978, Shear and torsion, CEB Bulletin d'Information no. 126.
[3] CEB-FIP Model Code 1990, final draft, CEB Bulletin d'Information no. 204.
[4] Regan PE. Research on shear: a benefity to humanity or a waste of time? The Structural Engineer Oct 1993:337–346.
[5] Al-Nahlawi KA, Wight JK. Beam analysis using concrete tensile strength in truss model. ACI Structural Journal 1992;89(3):282–289.
[6] Bazant ZP, Sun HH. Size effect in diagonal shear failure: influence of aggregate size and stirrups. ACI Materials Journal 1987:259–272.
[7] Chana PS. Analytical and experimental studies of shear failures in reinforced concrete beams. Proceedings of Institution of Civil Engineers, Part 2 1988;85:609–628.
[8] Kotsovos MD, Bobrowsky J. Design model for structural concrete based on the concept of compressive force path. ACI Structural Journal 1993;90(1):12–20.
[9] Reineck KH. Ultimate shear force of structural concrete members without transverse reinforcement derived from a mechanical model. ACI Structural Journal September–October 1991:592–602.
[10] CEB-FIP (1987). Shear in prestressed concrete members (State of the art). Bulletin no. 180.
[11] American Concrete Institute, Committee 544. State of the art report on fiber reinforced concrete. In: ACI Manual of Concrete Practice, vol. 5 (ACI 544.1R-86). Detroit, 1987.
[12] Bentur A, Mindess S. Fibre reinforced cimentitious composites. London: Elsevier Applied Science, 1990.
[13] Shah SP, Ouyang C. Mechanical behavior of fiber-reinforced cement-based composites. Journal of the American Ceramic Society 1991;74(11):2227–2238; 2947–2953.
[14] Swamy RN, Bahia HM. The effectiveness of steel fibers as shear reinforcement. Concrete International March 1985:35–40.
[15] Al-Ta'an SA, Al-Feel JR. Evaluation of shear strength of fibre reinforced concrete beams. Cement and Concrete Composites 1990;12:87–94.
[16] Li VC, Ward R, Hamza AM. Steel and synthetic fiber as shear reinforcement. ACI Materials Journal September–October 1992:499–508.
[17] Lim TY, Paramasivam P, Lee SL. Shear and moment capacity of reinforced steel fiber concrete beams. Magazine of Concrete Research September 1987;39(140):148–160.
[18] Furlan Jr. S Concrete beams with low ratio shear reinforcement: influence of fibers and prestressing. Doctoral Thesis. São Carlos Engineering School, São Carlos, 1995 (in Portuguese).