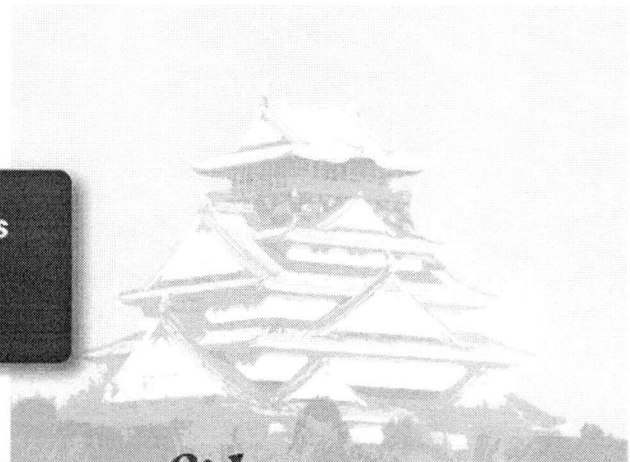
Proceedings of the first *fib* Congress 2002 Disk A

fib 2002
Osaka Congress

fib
CEB•FIP



- Table of Contents
- Author Index

Proceedings of the first *fib* Congress 2002

Organized by
Japan Prestressed Concrete Engineering Association
Japan Concrete Institute

PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED BY EXTERNAL PRESTRESSING TENDONS IN COMPARISON TO OTHER STRENGTHENING METHODS

Joao Bento de Hanai
Professor of Civil Engineering *
e-mail: jbhanai@sc.usp.br

Tatiana Gesteira Martins de Almeida
M.Sc. in Structural Engineering *
e-mail: tatiana@cpunet.com.br

Department of Structural Engineering
University of Sao Paulo at Sao Carlos, Sao Carlos - BRAZIL

Keywords: strengthening, beam, reinforced concrete, prestressed concrete, external tendons.

1 INTRODUCTION

Many techniques had already been developed for strengthening of reinforced concrete beams, such as the addition of longitudinal reinforcement and concrete on the tensioned face, the application of steel plates, the bonding of fiber reinforced composites and the use of external prestressing tendons. Each one of these methods has advantages and disadvantages and the choice of one of them must be based on the best cost-benefit correlation.

The most suggestive differential presented by the prestressing method when compared to the other is its active characteristic. Deformation of the beam under external load is not needed to start the action of the reinforcement. Moreover, the application of prestress forces enhances the shear strength. Such aspect might be decisive for the choice of this technique. Through the external tendon prestressing, it is possible to improve the active behavior of the beams, reducing its deflection and cracking.

There are several profiles for the external tendons to be considered. The choice must be done according to the desirable effect to be achieved and the cost-benefit correlation of each solution. Fig. 1 shows some of the most common arrangements for external tendons.

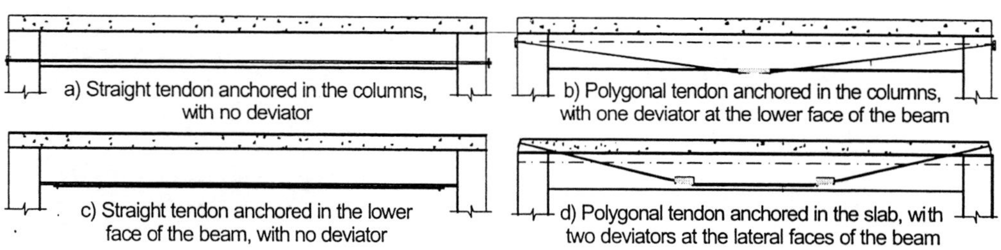


Fig. 1 Examples of tendon profiles

In cost analysis the type and quantity of deviators exert a great influence. When polygonal tendons are utilized, it is important to keep in mind that tendon direction changes in the deviators must be smooth. This is necessary to not cause stress concentration in those points, which can produce a premature rupture of the tendons. The use of metallic curved tubes is very common in deviators. Such solution offers a larger contact area between tendon and deviator support.

This paper mainly focuses the experimental study conducted by ALMEIDA (2001) [1] in the analysis of strengthening methods with external prestressing tendons. A comparison of its results is made with those obtained by REIS (1998) [2] who analyzed strengthened reinforced concrete beams with addition of steel bars or plates and concrete on the tensioned face.

2 EXPERIMENTAL PROGRAM

The experimental program consisted of the strengthening and analysis of three reinforced concrete beams with a T-shape transversal section and 3 m span, as shown in Fig. 2.

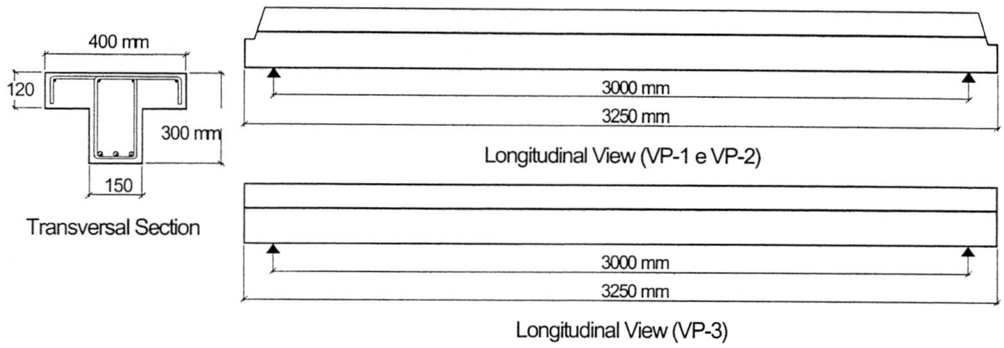


Fig. 2 Longitudinal view and transversal section of the r.c. beams to be strengthened

Fig. 3 illustrates the test set up. Two reaction frames were installed at the ends of the beam which was tested in upside down position. Initially the beam was submitted to pre-loading forces to simulate a permanent loading in a real situation. The loading consisted of two concentrated forces applied by hydraulic jacks at the thirds of the span. Under the action of such load, the r.c. beam was strengthened by the prestressing of two external tendons. The prestressing tendons had a polygonal configuration and they were also deviated at the thirds of the span. Each tendon consisted of a 12.7 mm diameter seven-wire greased strand.

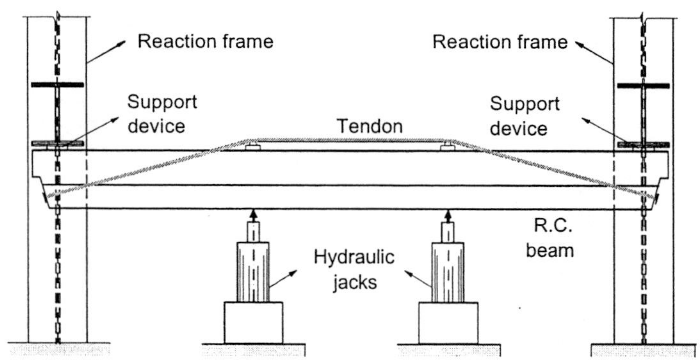


Fig. 3 Test set up

The parameters that changed during the tests were the shear reinforcement ratio and the profile of the external tendons.

The VP-1 beam had shear reinforcement similar to the beams of REIS (1998) [2] (8 mm stirrups each 90 mm). For the other two tested beams (VP-2 and VP-3), the shear reinforcement was reduced to equalize the shear ultimate load capacity to the flexural ultimate load capacity in the r.c. beams to be strengthened (6,3 mm stirrups each 130 mm). Three bars of 16 mm diameter were used in the tension zone of the beam and four 8 mm bars were used in the compression zone. Special reinforcement was disposed in the anchorage zones of prestressing tendons.

For VP-1 and VP-2 beams, the external tendon was anchored in the beam flange and for VP-3 beam it was anchored in the web. Such procedure intended to analyze the effects of the tendon profile in the shear strength.

The external prestress contributes to shear resistance in two different ways. The first one corresponds to the axial compressive stresses, that decreases the slope of the concrete internal struts and consequently the tension stresses in the stirrups. The second corresponds to the vertical force introduced in the deviator, which reduces the shear action in the beam. The intensity of both effects for a given prestress force varies according to the tendon profile. The diagram for bending moments due to external prestress also varies according to the shape of the external tendon.

Fig. 4 characterizes the profile of the external tendons and the transversal reinforcement ratios for the three tested beams. It is also noticeable that for the VP-2 and VP-3 beams a different type of deviator was used in relation to VP-1. That happened due to the premature rupture noticed in the test of VP-1 (squeeze of the strand wires at the deviator zone). For the VP-2 and VP-3 beams a new deviator was designed to offer a smooth change of direction for the external tendon. Fig. 05 illustrates the two different deviators used.

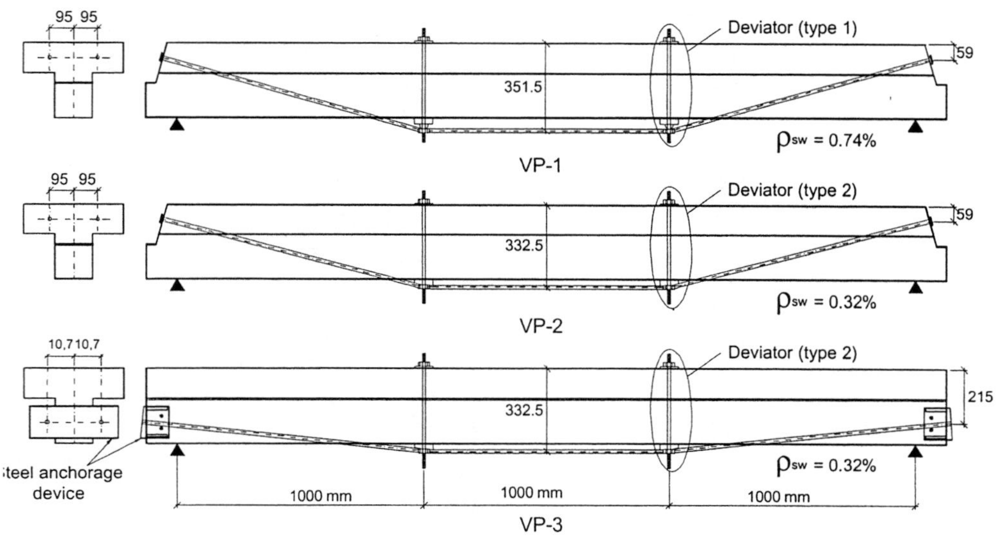
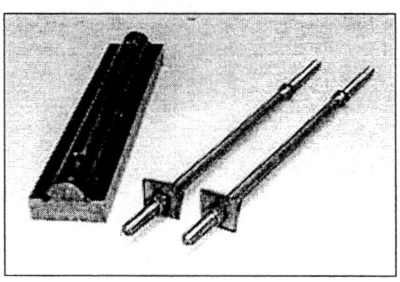
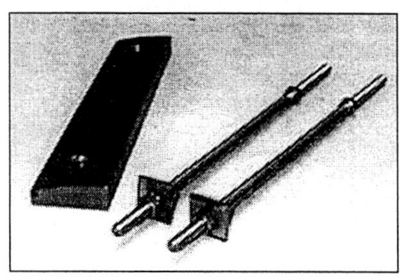


Fig. 4 Tendon profiles and shear reinforcement ratios



a) deviator type 1



b) deviator type 2

Fig. 5 Deviators

For the anchorage of tendons an ordinary system of steel wedges was used. For VP-3 a steel device was designed to compose the anchorage on the beam web.

The concrete mechanical properties on the age of the tests were experimentally obtained and they are shown in Table 1. Steel bars were also tested to find their mechanical properties. The results are shown in Table 2. For the prestressing reinforcement (greased plastic coated strands), the mechanical characteristics provided by the manufacturers were used (Table 3).

The instruments used in the models were electrical strain gages, displacement transducers and load cells, as shown in Figure 6.

Table 1 Concrete mechanical properties on the age of test

Beam	f_{cj} (MPa)	f_{tj} (MPa)	E_c (MPa)	E_{cs} (MPa)	Slump (cm)
VP-1	27.5	2.20	32,381	29,036	5.05
VP-2	31.6	2.48	29,906	28,190	4.85
VP-3	31.3	2.94	31,758	28,030	5.30

Table 2 Mechanical properties of the passive reinforcement

Beam	ϕ (mm)	E_s (MPa)	f_y (MPa)	ε_y (%o)
VP-1	8.0	208,051	577	2.8
	16	210,000	535	2.5
VP-2	6.3	213,416	618	2.9
and	8.0	221,104	569	2.6
VP-3	16	209,148	535	2.6

Table 3 Mechanical properties of the active reinforcement

ϕ (mm)	E_{ps} (MPa)	f_{py} (MPa)	ε_{py} (%o)	f_{pu} (MPa)
12.7	208,000	1.820	8.8	2,000

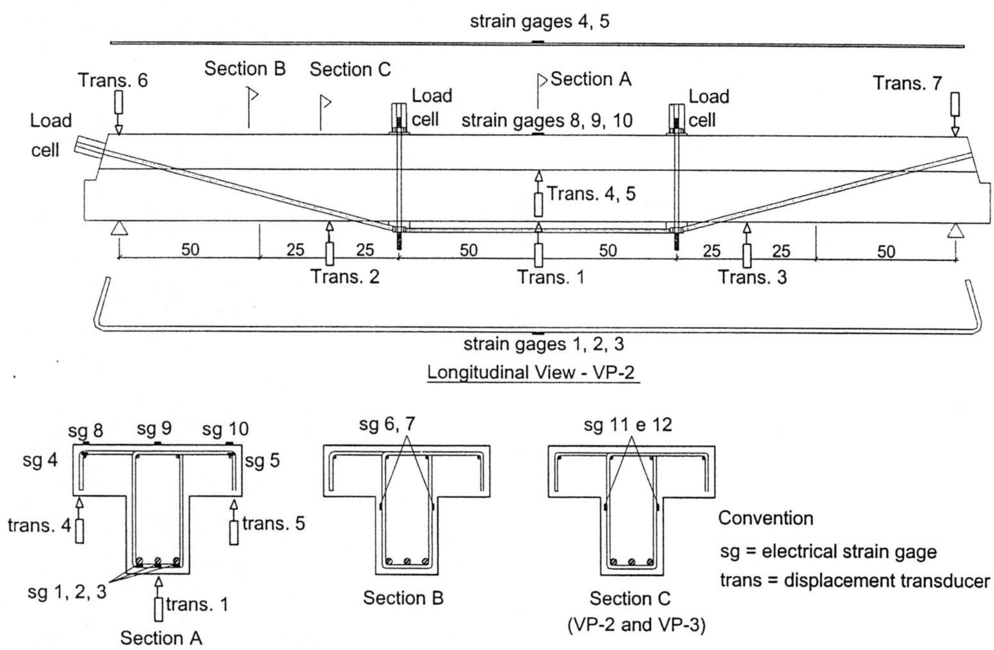


Fig. 6 Instrumentation of beam VP-2

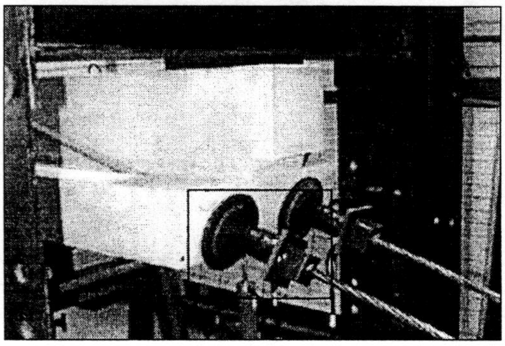
3 TEST PROCEDURE

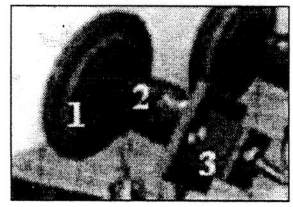
The tests consisted of three stages: pre-loading, prestressing of tendons and final loading up to collapse.

In the first stage, an increasing loading was applied to the beam with 2.5 kN of increment in each hydraulic jack until the cracking phase of the beam, and then 5.0 kN until a 40 kN force was achieved.

Such loading intended to simulate a part of the permanent load of the beam in a real situation. By the end of the first stage, all beams were cracked and had deflections of approximately 6 mm.

In the second stage, the external force applied remained constant while the prestressing tendons were positioned and tensioned. VP-1 and VP-2 had their tendons prestressed at once, with readings of the measurement instruments at each 20 kN increase. For VP-3, the prestress was conducted in smaller steps to minimize the effects of unbalanced forces in the steel anchorage device. Also in this case the readings of the measurement instruments were done each 20 kN increment. In Fig. 7 it can be noticed the details of the tendon anchorage the dead edge of VP-1 and the position of the load cells.





1 – Load distribution steel plate
2 – Load cell
3 – Wedge and case

Fig. 7 Details of the dead anchorage of the strands

The third stage began after the anchorage of the tendons, with increase of the applied force in increments of 15 kN until the collapse of the beam. The flexural cracks appeared when the force was approximately 70 kN. Shear cracks appeared when the force was 130 kN for VP-1 and VP-2 and 115 kN for VP-3. The longitudinal reinforcement started yielding when the force reached 160 kN for the three tested beams.

The beams were expected to collapse after yielding of the internal reinforcement and further concrete crushing. However, right after the yielding of the passive reinforcement there was a rupture of at least one of the strand wires, with a consequent interruption of the test. That happened when the force reached 180 kN for VP-1, 190 kN for VP-2 and 185 kN for VP-3. Before rupture, forces in the strands were around 140 kN for VP-3 and 151 kN for VP-2, quite inferior to the predicted yielding force (around 180 kN). By the end of each test, the plastic sheaths of the strands were removed, to certificate that the rupture always happed over the deviator.

4 ANALYSIS OF THE RESULTS

During the tests, the average value of the forces applied by the two hydraulic jacks was registered, and all the present results refer to this value. To allow the analysis and comparison of the behavior of the three tested beams, graphics were elaborated with the average values of the measurements: beam deflection at the mid span, longitudinal reinforcement strain, compression concrete strain, and stirrup strain. For VP-2 and VP-3 where stirrups were instrumented in two sections, the average values were considered.

From the force *versus* deflection diagram (Fig. 8) it is noticeable that the behavior of all beams was quite similar. The deflection progress, the deflection recovering during prestress application, the stiffness and stiffness variation during the test, all these parameters were very similar. The first crack force for VP-1 and VP-3 was 17.5 kN and for VP-2, 20kN. The theoretical values were 8.8 kN for VP-1, 10.2 kN for VP-2 and 11.9 kN for VP-3, reasonably inferior to the experimental values. However, when analyzing the diagram of Fig. 8 it is noticeable that the beams start to lose stiffness under a force near to 10 kN. That may be explained by micro-cracking of the concrete, not noticeable without special instruments.

The profile of the external tendon had no importance while affecting the stiffness or deflection recovering of the beams. The higher slope of the tendons in VP-1 and VP-2 causes a higher vertical component of the prestress force, so a favorable effect. In VP-3, the tendon slope is smaller, but this is balanced by the negative moment that appears due to the positive eccentricity (under the neutral line) of the anchorage of the tendon.

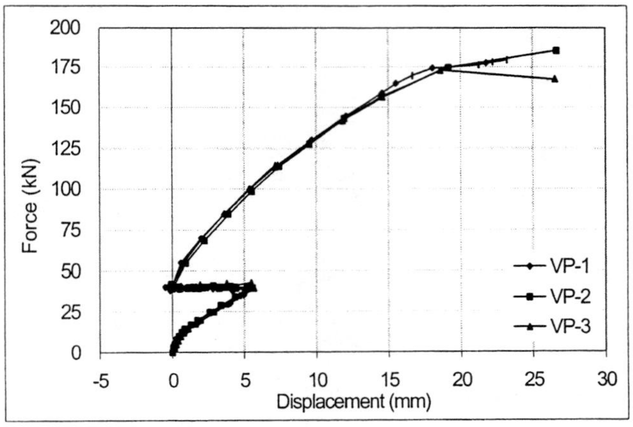


Fig. 8 Force *versus* displacement at the mid span

The strains in the tension reinforcement and concrete in the compressed flange (Figures 9 and 10, respectively) seem to be compatible with the internal forces.

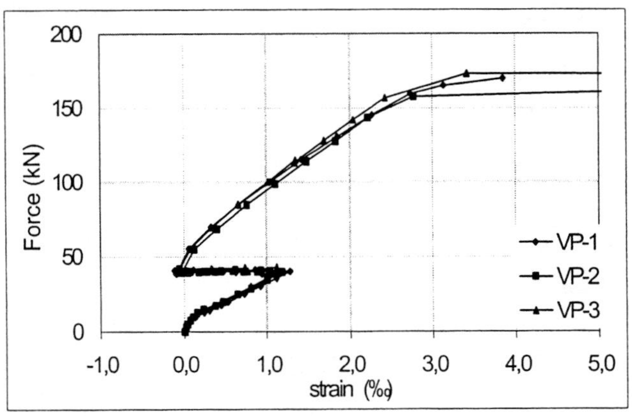


Fig. 9 Force versus strain at the longitudinal passive reinforcement

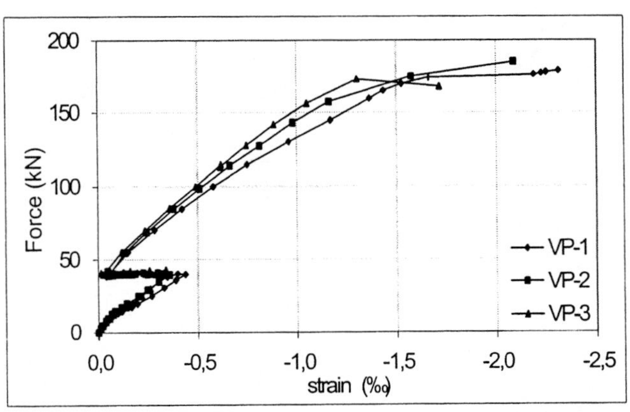


Fig. 10 Force *versus* strain in the concrete in the compression zone

Fig. 11 shows a force *versus* stirrup strain diagram. VP-3 started to present major strains in the stirrups with a lower force, approximately 115 kN. That may be explained by the shape of the tendons and the shear reinforcement ratio in the beam. For VP-1 and VP-2 the deviation angle was higher, resulting in an uplift force also higher, consequently reducing the shear stresses. In spite of the horizontal component of the prestress force being higher for the VP-3 beam, the effect of the vertical component was more important for the delaying of shear cracks. The stirrups of VP-1 and VP-2 started to have an important strain under a force approximately similar to the one for VP-3 (130 kN), despite the stirrups from the VP-1 beam had already shown a previous strain. However, once the reinforcement rate for the VP-1 beam is higher, the stirrups from such beam had a slower strain behavior when compared to the ones from the VP-2 beam, as shown by the slope leaning.

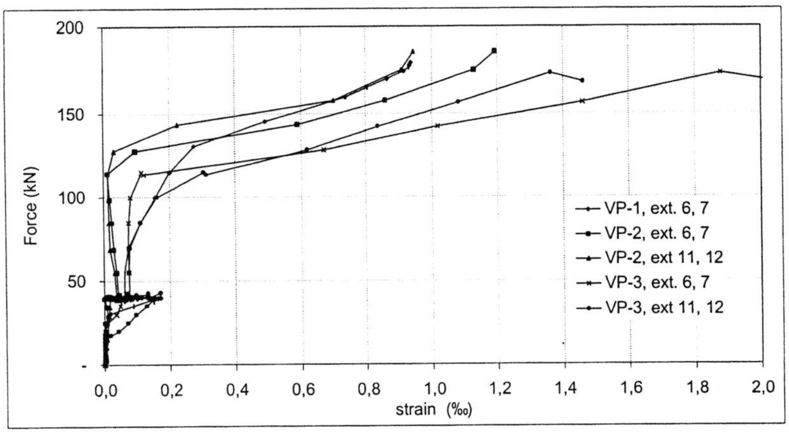


Fig. 11 Force *versus* strain in the stirrups

It is possible to conclude that the external tendon profile and the applied prestress force have a significant influence on the shear cracking force. However, it is the shear reinforcement ratio that controls the growth speed of such strains.

5 COMPARISON TO BEAMS TESTED BY REIS (1998)

REIS (1998) [2] tested seven reinforced concrete beams with original section (before strengthening) and longitudinal and transversal reinforcements similar to the VP-1 beam. The behavior of six from those beams (VA and VC series) is compared to the behavior of VP-1.

The VA series beams were strengthened by addition of regular steel bars to the tension zone. The additional bars were enveloped by a high-performance mortar that bonds the new reinforcement to the original beam (Fig. 12). The cement mortar contained silica fume and superplasticizer. For the VA-2 and VA-3 beams 1% of short steel fibers were added to the mortar. The VC series beams were strengthened by the attachment of a steel plate to their inferior face. The attachment of the plates was done by steel connectors and high-performance grout. In VC-1 the connector consisted of 120 mm length and 12.5 mm diameter steel rods welded to the plate each 200 mm. In VC-2 and VC-3 there were also 8 mm steel hooks welded to the plates each 200 mm. Those hooks were grouted within cavities in the original beam.

The beams were molded in two steps: the first one corresponded to the original beam, and the second one to the strengthening process. All beams were designed to reach the collapse by yielding of the longitudinal reinforcement. Table 4 presents the main mechanical characteristics of concrete and mortar on the age of the tests.

From VA and VC series only VC-2, VC-3 and VC-4 collapsed due to flexural reinforcement yielding. The other three had a premature collapse. VA-1 and VC-1 presented connection fault among old and new parts. VA-2 presented anchorage deficiency for the main reinforcement.

Diagrams in Fig. 13 show that the beams tested by REIS (1998) [2] had a higher stiffness when compared to the VP-1, both before and after the application of the prestress. Such fact was already expected due to the higher height of the transversal section of the VA and VC series beams after strengthening.

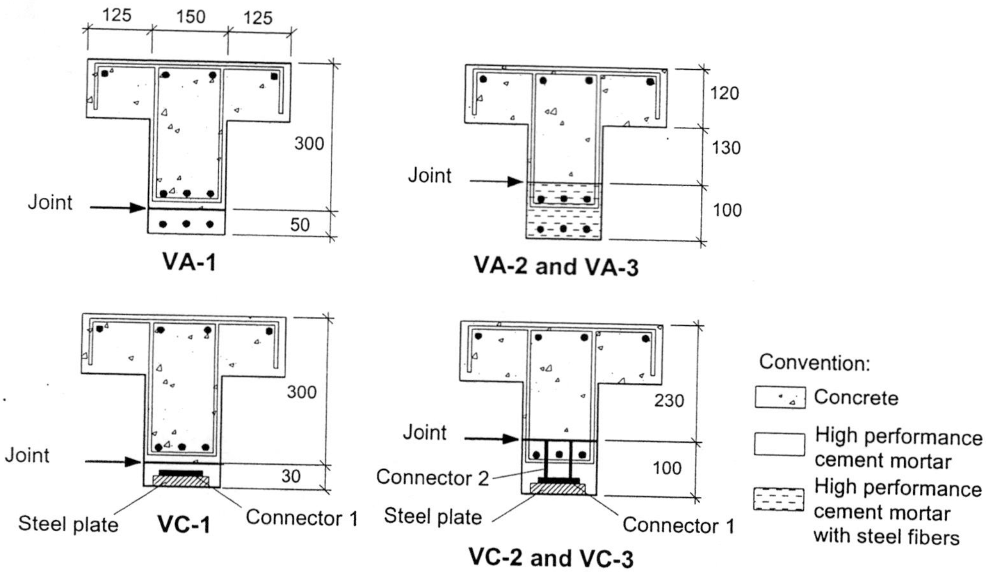


Fig. 12 Transversal sections of the beams tested by REIS (1998) [2]

Table 4 Mechanical characteristics of concrete and mortar at the age of tests

Beam	Original beam concrete					Strengthening mortar				
	Age (days)	E_c (MPa)	E_{cs} (MPa)	f_{cj} (MPa)	f_{tj} (MPa)	Age (days)	E_c (MPa)	E_{cs} (MPa)	f_{cj} (MPa)	f_{tj} (MPa)
VA-1	12	26,834	20,457	34,03	2.75	8	27,837	19,473	46.02	3.87
VA-2	13	35,468	30,218	26.32	2.76	8	28,808	26,483	58.70	4.95
VA-3	175	36,454	32,719	46.04	3.46	7	30,215	28,335	60.23	4.87
VC-1	10	27,187	24,239	22.70	1.91	7	34,498	29,924	66.57	3.10
VC-2	10	27,273	24,440	28.94	2.86	7	28,239	25,934	52.85	3.47
VC-3	75	39,780	33,486	30.00	2.50	8	32,961	28,620	54.69	3.66

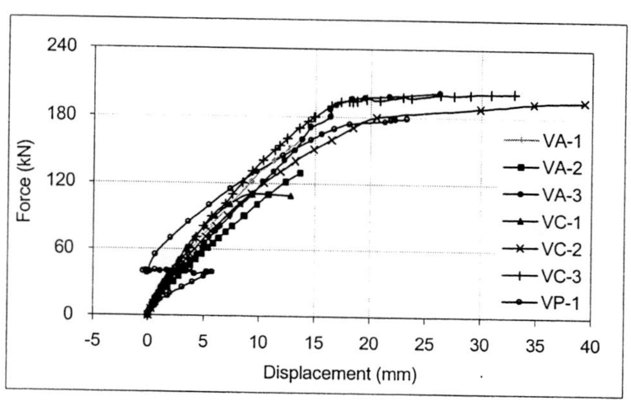


Fig. 13 Force *versus* deflection at mid span – comparison to REIS (1998) [2]

The favorable effect of prestress is evident for the deflection recover of the beam. In service conditions after strengthening, under forces up to 120 kN, VP-1 presents deflections that are quite smaller than the other beams. However, due to its smaller stiffness, such deflections start getting greater than those of VC-3, VA-1, VA-3 and even VC-2 (closer to collapse) when the force increases.

When comparing the strains in the longitudinal reinforcement and in the concrete at the compressed zone (Figures 14 and 15, respectively), it is also possible to notice the positive effect of prestress. After the application of the external prestress up to a force of approximately 90 kN, such strains were smaller than those presented by the beams tested by REIS [2].

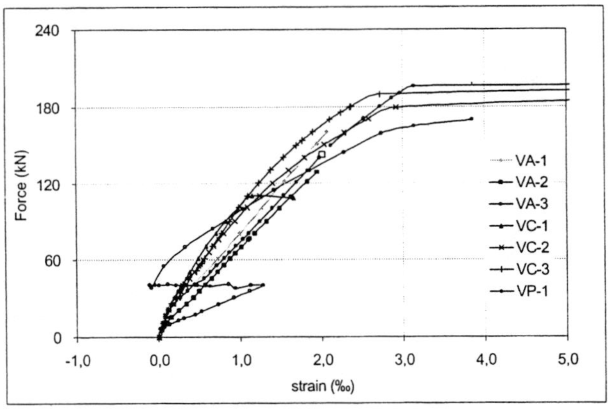


Fig. 14 Force *versus* longitudinal reinforcement strain – comparison to REIS (1998) [2]

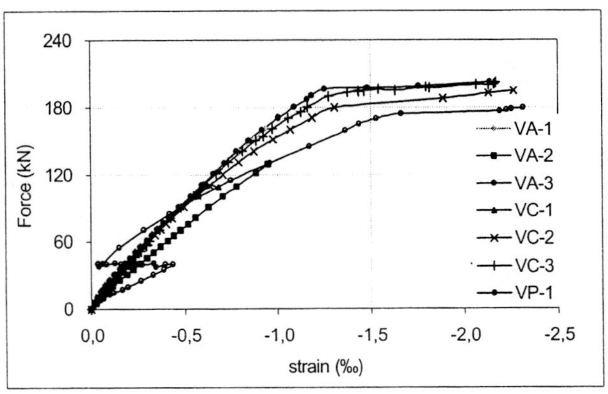


Fig. 15 Force *versus* concrete strain – comparison to REIS (1998) [2]

Other advantage of the external prestress may be noticed by the observation of Fig. 16 (force *versus* stirrup strain). After the application of prestress, the strain increase in the stirrups starts in a loading stage approximately two times higher than in the other beams. The conclusion is that a well-designed prestressing system may represent a good solution for both flexural and shear strengthening.

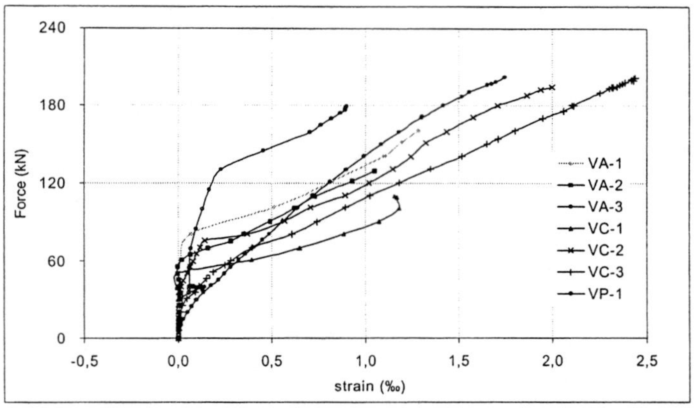


Fig. 16 Force *versus* stirrup strain – comparison to REIS (1998) [2]

6 CONCLUSIONS

From the analysis of the results it is possible to conclude that external prestress highly contributes for the increase of the flexural and shear resistances, improving the service behavior through significant reduction of deflection and cracking.

The tests showed that prestressing of external tendons when applied to beams under loading may lead to a total deflection recovering. Existent flexural cracks may be closed with prestressing of tendons.

About design details it is fundamental to mention that smooth direction changes of the external tendons is important to avoid stress concentration. Deviators must be formed by appropriate beds to ensure a smooth basis for the passage of the tendons.

It was observed that the tendon profile had no significant effect over the stiffness of the beams. The depth of the tendon in the mid span is the most effective characteristic for deflection control. Otherwise the shape of the external tendon has a great influence in the shear resistance. The shear cracking is significantly affected by the changes in the tendon geometry. For the tested beams, a larger deviation angle of the tendon leaded to a higher shear cracking resistance.

From the comparison between the strengthening methods it was possible to notice that despite its smaller stiffness, the beam strengthened with external tendons (VP-1) presented smaller deflections in service conditions. The observed strains in the longitudinal reinforcement and concrete in VP-1 were also smaller when compared to the other beams tested by REIS [2]. The favorable effect of prestress over the shear resistance was clearly observed. The strains in the stirrups in VP-1 were quite inferior than those found in the other beams until the collapse.

ACKNOWLEDGEMENTS

The authors express their gratitude to FAPESP (São Paulo State Research Foundation) for the financial support, to CNPq (National Research Council) for the scholarship and to Belgo-Mineira/Bekaert for the strands used in the tests.

REFERENCES

[1] ALMEIDA, T.G.M. (2001) *Reforço de vigas de concreto armado por meio de cabos externos protendidos* (Strengthening of reinforced concrete beams by means of prestressing external tendons). São Carlos. 142p. MSc. Degree Thesis – Escola de Engenharia de São Carlos, Universidade de São Paulo. In Portuguese.

[2] REIS, A.P.A. (1998). *Reforço de vigas de concreto armado por meio de barras de aço adicionais ou chapas de aço e argamassa de alto desempenho* (Strengthening of reinforced concrete beams by addition of steel bars or steel plates and high performance cement mortar). São Carlos. 179p. MSc. Degree Thesis – Escola de Engenharia de São Carlos, Universidade de São Paulo. In Portuguese.