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PRESTRESSING OF PRECAST FERROCEMENT ELEMENTS

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ABSTRACT

This paper presents the effect of prestressing in precast thin-walled concrete elements, that can be seen as ferrocement or reinforced mortar ones. It is a structural alternative for ferrocement that reduces the deflections and delays or eliminates the cracking. The use of prestressing techniques also permits the application of large opening welded meshes, reduction of the steel ratio, easy casting, transporting and erection.

Its differences with traditional ferrocement and reinforced concrete are discussed. The study investigates the interface between ferrocement and prestressed concrete, and a design example of precast elements for a small storage building is described.

The results of experimental tests over two beams are presented. The beams had the same section, but the mesh reinforcements were different: one was reinforced with welded wire mesh and the other with an expanded metal mesh. Loss of prestress, cracking moment, width and spacing cracks, deflections and ultimate strength were measured.

INTRODUCTION

The application of prestressing in ferrocement elements can improve, in addition to the lightness and low permeability characteristics, a better bending performance and a higher deformation and cracking control. Also, the precasting potential becomes stronger with the use of small prestressing bed. The mechanization and quality control level may vary due to the performance and production requirement, characterizing differentiated productive centers regarding the amount and refinement of the equipments.

The lightweight precast elements can be used in the various urban infra-structure constructions, such as pedestrian and small road bridges, culverts, retaining wall, water tanks, etc., in addition to buildings designed for schools, nurseries, or rural storehouses, barns and others.

GENERAL ASPECTS

Along with the design and execution are the main recommendations given by the ferrocement and prestressed concrete specifications. Not always, however, they coincide. Besides that, the prestress in thin-walled elements require further care. This way, some characteristics

of this "material" make it different from the traditional ferrocement and prestressed concrete, and place it on the interface defined by them.

- MORTAR: The high mechanical strength (typical on ferrocement) is essential to absorb the stresses due to the prestress, including the manufacturing stage. The good compactness is also important to assure the reinforcement cover efficiency, which will be lower than the traditionally recommended one for the prestressing tendon. Therefore, regarding the consumption of cement and the w/c factor, the usual recommendations of ferrocement must be seen.

- PRESTRESS REINFORCEMENT: The stranded cable and the indented wire are better as they show a good adherence. However, the high bond stress, the small element thickness and the fine grained mortar make difficult the adherence. In this way, small diameters are preferred, since they distribute the bond stresses better and this turns easy their arrangement into the thin walls. Unfortunately, in Brazil, small diameter stranded cable are only manufactured in the normal relaxation category. Low relaxation steels should be better, because the final prestress effects are achieved with smaller steel area.

- MESHES: Since the prestress introduces a good cracking control, the possibility of using welded meshes with large openings is extended. Besides this, it can be noticed that the cracks that exceptionally occur, often close again when the live load is removed. Nevertheless, a closely spaced and small width cracking must be kept. The expanded metal mesh may be a feasible alternative. Its lower mechanical efficiency would be compensated by the prestress.

- REINFORCEMENT AT THE ANCHORAGE ZONE: in the region of the adherence mobilization, additional meshes should enclose the prestressed tendon, according to recommendations of the soviet code [1]. This arrangement is not efficient to absorb the tensile stresses towards the thickness. It should be replaced by a helicoidal reinforcement when the wall thickness can be enlarged.

- REINFORCEMENT COVER: In prestressed ferrocement, reinforcement cover will be lower than the recommended by the prestressed concrete codes for the prestressing tendons (20 to 55 mm). For the mesh wires it is limited to assure the efficiency of the distributed reinforcement for cracking control. To protect the prestressing tendon against corrosion, it will be higher than the recommended for the meshes (6 to 8 mm). Then it is considered that a 10 mm cover for the prestressing tendon can be indicated, looking to the good quality of the mortar and the hard control of the cracks (with the prestressing and the meshes).

- CALCULATION: In general, it follows the usual calculation of structural concrete, by incorporating the peculiarities which arise from the prestressing forces over thin-walled sections with distributed reinforcement.

The cracking moment is calculated by adding the decompressing moment (which turns null the tension on the pre-compressed flange) to the corresponding one due to further loads, until the first cracks strength is reached.

In the case of partial prestressing, when cracking is permitted for some load combinations, the crack width should be limited according to the same criteria adopted for the ferrocement (0.10 to 0.15mm), since larger values are not compatible with the reduced reinforcement cover. The calculation of the cracking width should take into account the mesh type, reinforcement cover, maximum reinforcement strain and other parameters that are involved in the cracking phenomenon.

In prestressed ferrocement, it is understood that the partial prestressing (in some cases limited prestressing) is the most indicated, even though the environment aggressiveness is taken into account (ferrocement, in general, is not recommended in corrosive environments). When cracks appear, their width are controlled by the prestressing force and by the steel meshes.

In the calculation of the prestressing progressive losses, the possibility of larger parcels due to the concrete creep and shrinkage (due to the high cement consumption and the high surface/volume relationship) is considered without changes with respect to the prestressed concrete design method.

About the beam deflections, the contribution of prestressing is significant on the enlargement of the ferrocement application. The calculation method is the usual, which can or not take into account the cracking and the variation of the stiffness along the span. The prestressing can incorporate an initial negative deflection and provides a predominantly linear behaviour of the concrete elements.

In this work, the occurrence of side instability was simply dropped for flexion and two-support precast elements if:

$$\frac{L \cdot h}{b_f^2} \geq 500$$

L - theoretical span
h - section height
b_f - compressed flange width

DESIGN EXAMPLE

Some components were studied (roof and channel beams, support beams, wall panels and foundation beams) of a precast lightweight storehouse, as illustrated in Figure 1.

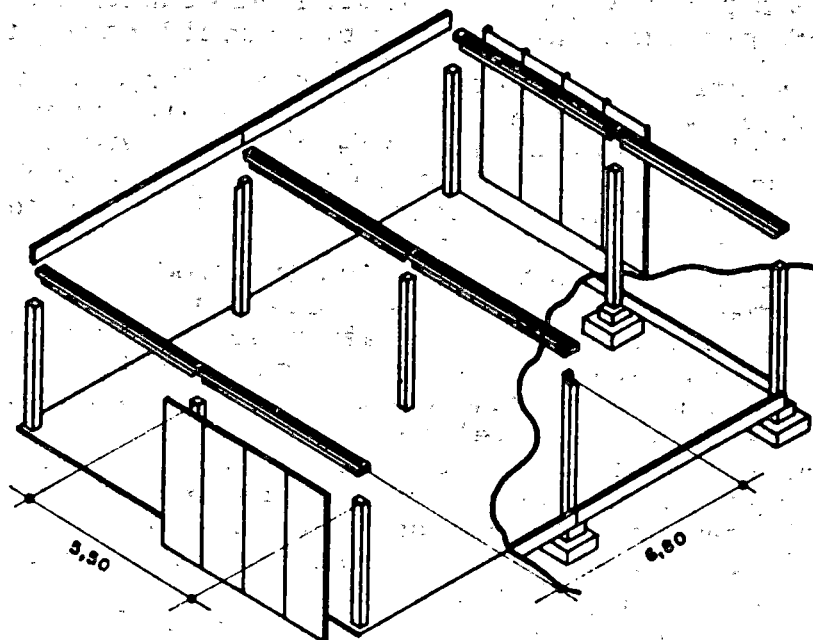
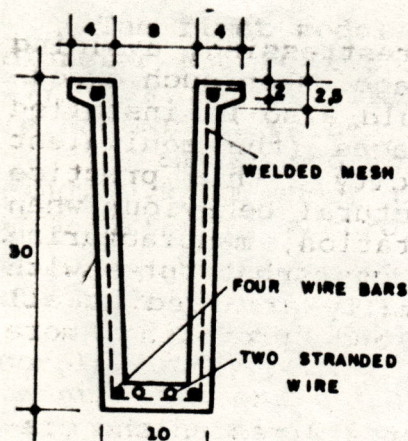


Figure 1 - Perspective of the storehouse

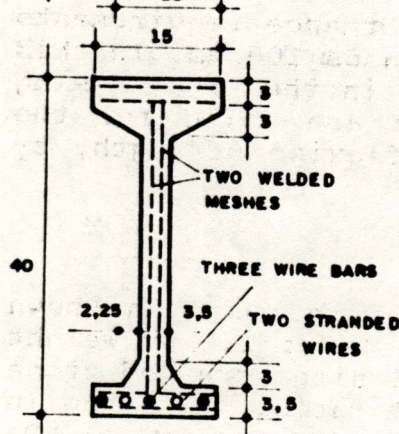
For each component several section shapes were investigated. The storehouse dimensions also varied, and elements of up to 10m long were studied. The elements were calculated with partial and limited prestressing, submitted to bending. The live load (wind + overload) was considered as 0.50 kN/m^2 , both for suction and overpressure.

The designed elements were lightweight and complied with the serviceability and safety requirements with small reinforcement rates, keeping the height/span relationship between $1/18$ and $1/40$. Three examples were selected to illustrate some results (Figure 2).



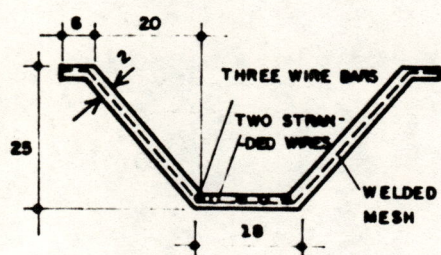
CHANNEL BEAM

span: 5.5m
 dead load: 190 kN/m
 live load: 340 kN/m
 mortar ultimate compressive strength: 40 MPa
 wire mesh yield strength: 600 MPa
 (diameter 2.77mm and 50mmx100mm opening)
 steel bar yield strength: 600 MPa
 (diameter 6.3mm)
 stranded wires yield strength: 1530 MPa
 stranded wires ultimate strength: 1800 MPa
 (3 wires of 3.0mm diameter)



FOUNDATION BEAM

span: 7.5 m
 dead load: 610 kN/m
 live load: 250 kN/m
 mortar ultimate compressive strength: 40 MPa
 wire mesh yield strength: 600 MPa
 (diameter 2.77mm and 50mmx50mm opening)
 steel bars yield strength: 600 MPa
 (diameter 6.3mm)
 stranded wires yield strength: 1487.5 MPa
 stranded wires ultimate strength: 1750 MPa
 (7 stranded wires - 3/8")



ROOFING BEAM

span: 10.0 m
 dead load: 45 kN/m
 live load: 50 kN/m
 mortar ultimate compressive strength: 40 MPa
 wire mesh yield strength: 600 MPa
 (diameter 2.0mm and 50mmx100mm opening)
 steel bars yield strength: 600 MPa
 (diameter 6.3mm)
 stranded wires yield strength: 1800 MPa
 stranded wires ultimate strength: 1530 MPa
 (2 wires of 2.0mm diameter)

Figure 2 - Some results of the example

From this study it is possible to make some comments:

- due to the small thickness of the walls, depending on the geometry of the section, the amount of mortar at the compressed zone may not be sufficient to the section strength, thus requiring a complementary reinforcement. The sections with flanges solve this problem very well.
- the sections with geometric center approximately equidistant from

the edges allow a uniform distribution of the prestressing, avoiding excessive tension stress at the manufacturing stage. When such excessive tension stress occurs, stranded cables should also be installed in this region. Despite some design disadvantages (the equivalent prestress force remains with a lower eccentricity), this practice should be made, as it improves the element structural behaviour when it is submitted to exceptional loads (transportation, manufacturing and erection). The use of tendons at opposite edges substitutes with advantage the complementary bars which are normally arranged at all the mesh folds, assuring a cover control and providing more stiffness.

- the effect of spacing between the mesh transverse wires on the cracking control and shear strength, meets the performance requirements if it is adopted as equal to 50 mm and in some cases 100 mm. In this last case, a thickening of the web or a increase in the prestressing force may be necessary. The same wire spacings are valid for the longitudinal direction, in the analysis of the flexion strength, by adopting wire diameter close to 2,5 mm.

EXPERIMENTAL TESTS

Two models with the same geometric section were made, as shown in Figure 3. The used mortar composition was 1 : 1.7 : 1.1 by weight (high initial strength cement, medium sand, small sized crushed stone with a 6 mm maximum size) and a 0,48 water/cement ratio, resulting in a cement consumption of 500 kg/m³ and an average strength of 40 MPa in compression.

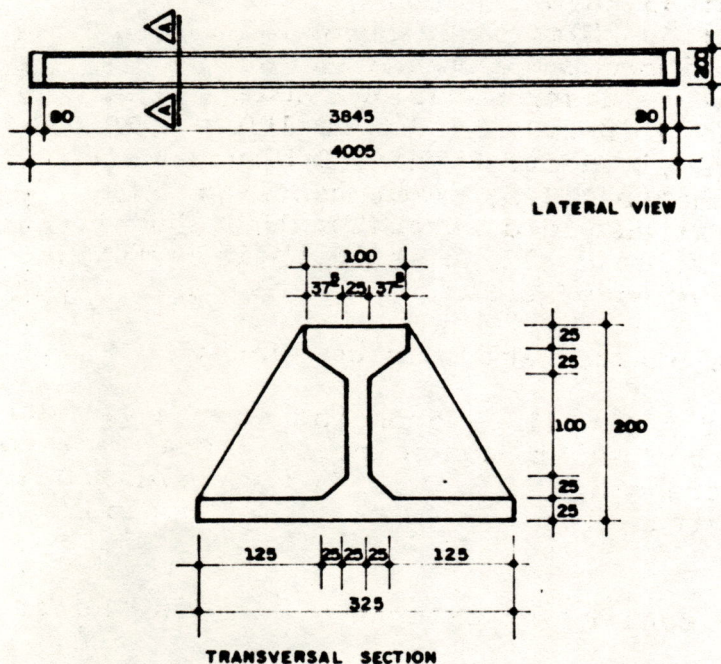


Figure 3 - Side view and transversal section of part of the models

The first model was reinforced with welded meshes (2.5 mm wire diameter and 50 x 50 mm openings), with 840 MPa ultimate strength, 777 MPa yield limit, and 197000 MPa modulus of elasticity (experimental values).

In the second model the expanded mesh was used (18 x 50 mm opening, 0.9 mm sheet thickness, and 1.5 mm strip width). The meshes were arranged according to the minor mechanic strength direction; however, this was advantageous under constructive aspects. The mesh strength in this direction is 298 MPa.

In both models only one mesh was disposed along the section. The complementary reinforcement bars had 4.5 mm diameter, 737 MPa ultimate strength and 651 MPa yield strength. The prestressing reinforcement consisted of four tendons (3 ϕ 2.5mm each one), of normal relaxation steel, 1800 MPa ultimate strength and 1530 MPa yield strength. The initial force was 85.48 kN. Figure 4 shows the model reinforcements.

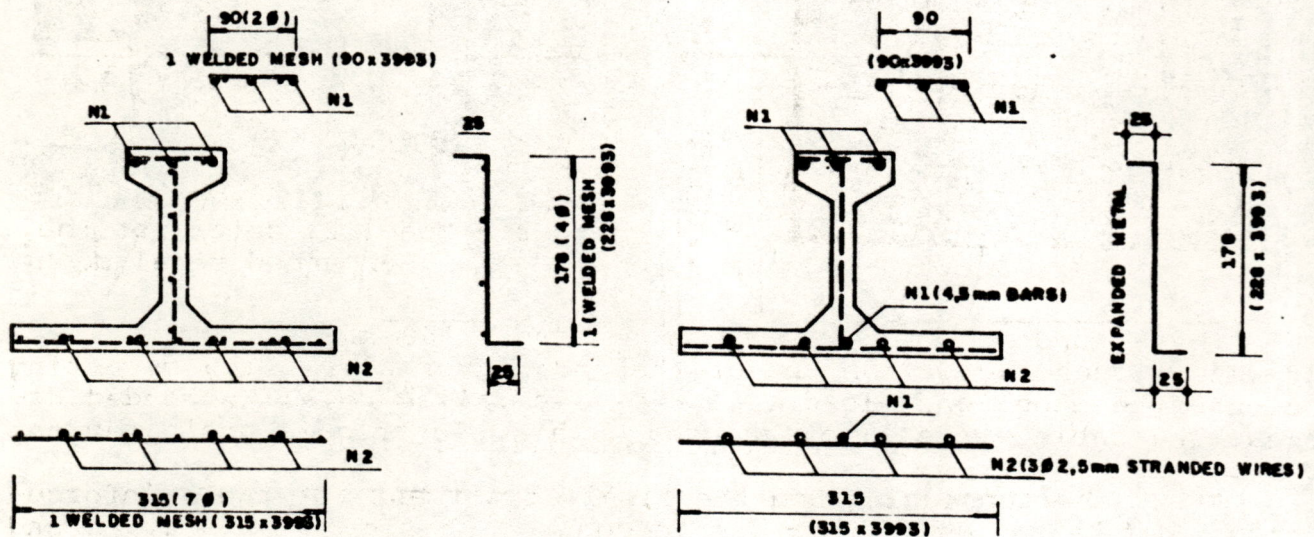


Figure 4 - Model reinforcements

At the ends, in a 25 cm length, an additional mesh was installed involving the stranded cables. The cover had 10.5 mm for the stranded cables and 8 mm for the mesh external wires.

Photo 1 illustrates the model 1 in the mould without the stranded cables, and photo 2 a detail of the mesh of the model 2.

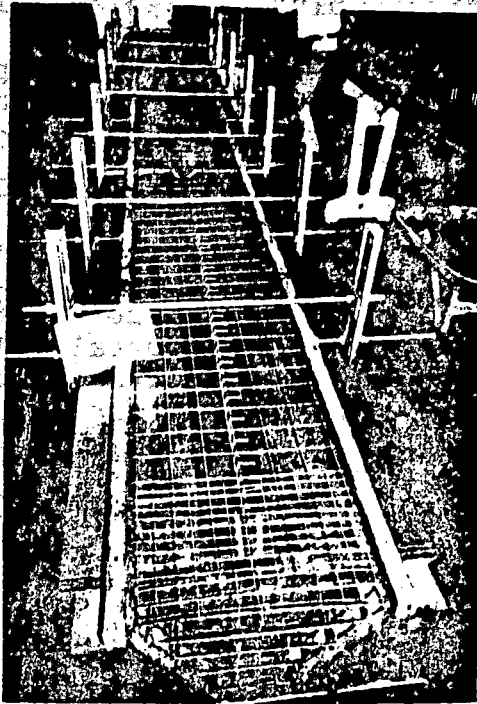


Photo 1 - Model 1 without the stranded wires in the mould

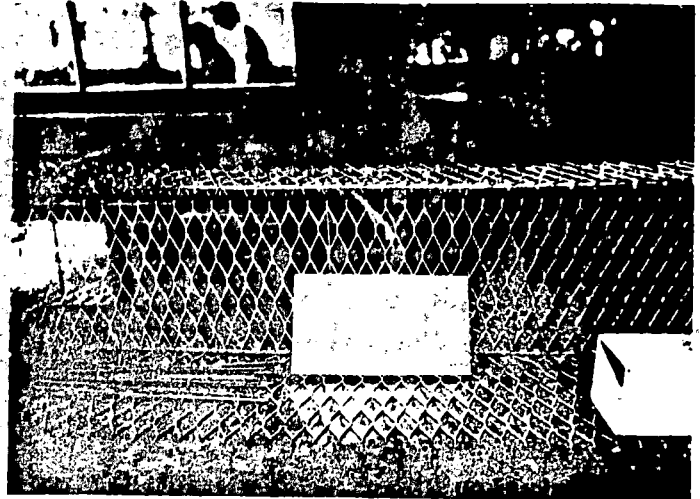


Photo 2 - Model 2: detail of the expanded metal mesh

The stranded wires were tensioned by a 160 kN monosystem jack, of manual anchorage, from one of the ends, over a 12 x 1.5 m casting bed. At the other end, load cells were installed on all stranded cables. The cables were also equipped with 3 electrical strain gauges, one on each wire.

After the tensioning and the final adjustment of the reinforcements, the beams were cast. Mortar control samples were moulded and tested at 1, 4 and 7 days. The evaluation of the mortar strength permitted the release of the cables from the anchorages at 4 days. The models were cast in the inverted position, through the tensioned flange, as to harness an existent formwork.

The beams were cured for 3 days under a permanently wet foam. The prestressing release was gradually made, with the aid of two hydraulic jacks and by removing special steel shims that supported the anchor frames on the end bed. Photo 3 shows the anchor detail and photo 4 shows the aspect of the tensioned stranded cables.

- BENDING TESTS: The models were tested with the tensioned flange upwards, for a better view of the cracks. The loads were applied (from bottom to top) by two hydraulic jacks, supported on concrete blocks over a reaction slab, at 1.50 m distant points from the supports. For the test accomplishment, besides the 12 strain gauges bonded in the stranded cables, 2 load cells with the jacks, 5 mechanical strain gauges on the mortar (3 on the tensioned flange and 2 on the compressed flange, at the middle of the span), 2 electrical strain gauges on the mortar (on the compressed flange) and 5 displacement dial gauges along the span were installed.

-RESULTS: it follows some of the obtained results:

-Mortar average strength at 7 days, tension, compression, and modulus of elasticity, respectively:

MODEL 1: 4.2, 43 and 32500 MPa

MODEL 2: 3.9, 44 and 36000 MPa

-Figure 5 shows the diagrams of the prestressing force variation during the manufacturing stage until the test accomplishment.

-Figure 6 shows the load-deflection diagrams (theoretical and experimental), corresponding to the deflection in the middle of the span.

-Figure 7 shows the load-strain diagrams (mortar strains that were measured in the tensioned and compressed flanges, at the middle span section).

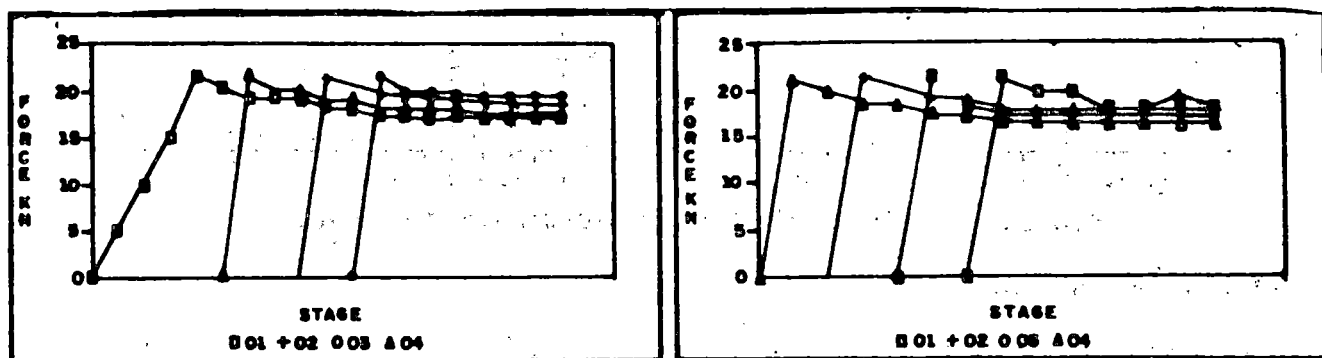


Figure 5 - Prestressing force variation

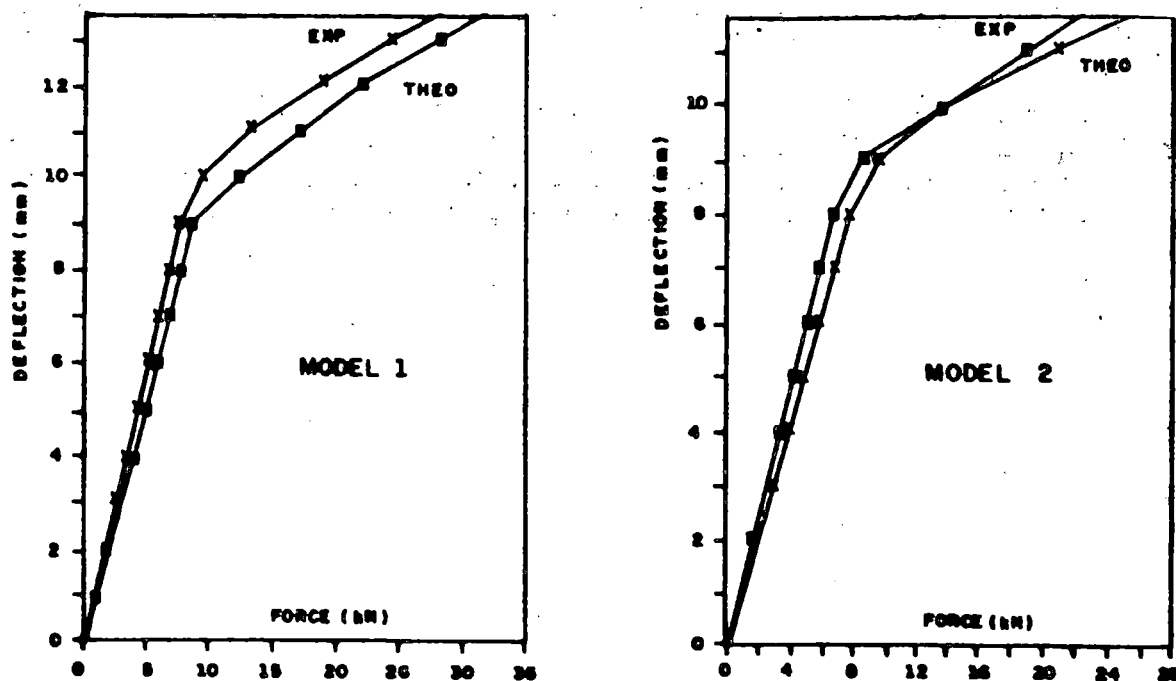


Figure 6 - Load-deflection diagrams

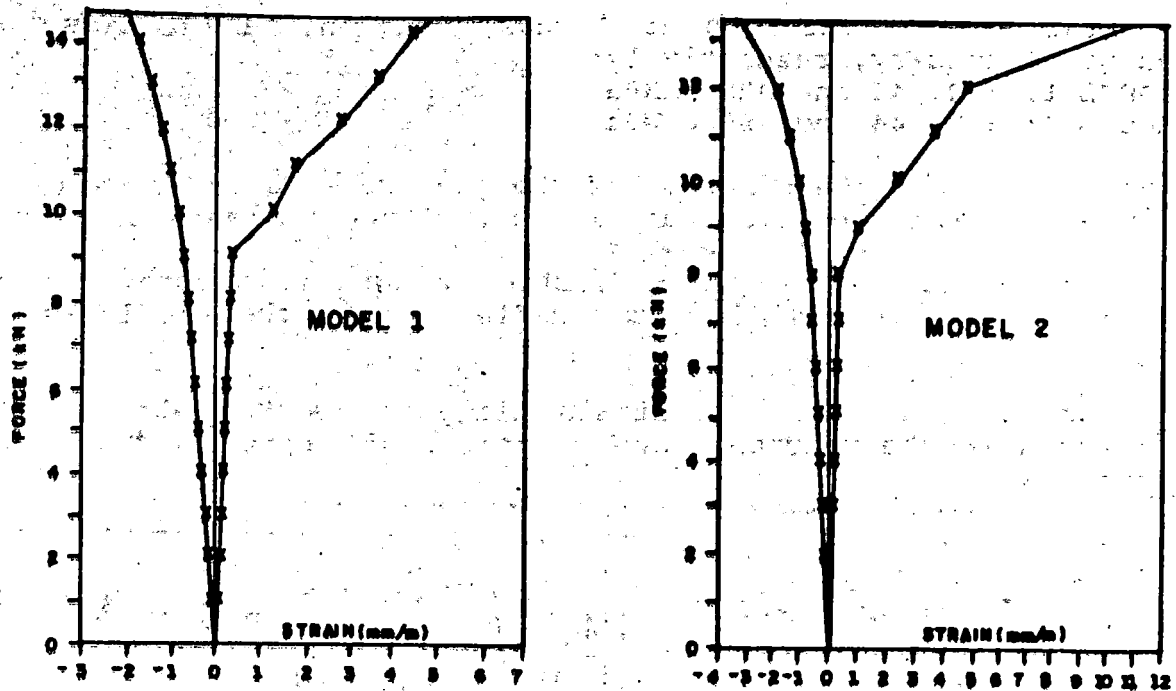


Figure 7 - Load-strain diagrams on the mortar

ANALYSIS OF THE RESULTS

- Prestressing losses (Table 1): except during the cables tensioning, when the load cells provide an accurate measure of the prestressing force, the values were estimated from the variations of the strains that were indicated by the strain gauges installed on the stranded cables.

- Cracking moment: a theoretical value of the cracking moment was obtained by taking the experimental values of the test-day mortar tension strength and prestressing force. Besides the excellent approximation between the theoretical and experimental values (Table 2),

it was evidenced the great contribution of the prestressing to the cracking strength (about 2.5 times higher), even for a reduced prestressing degree (0.5 approximately).

- Deflections: as shown by the load-deflection diagrams, the behaviour was very close to the predicted. The Model 2 presented a higher mortar modulus of elasticity than Model 1; even this, the deflections were higher in Model 2, before and after the cracking. This reveals a lesser stiffness provided by the expanded mesh in this case. For the calculation of the theoretical deflection, after the first crack appearance, a 0.85 reduction factor was applied to the mortar modulus of elasticity (that was measured in the tested samples) in conjunction with the consideration of the inertia progressive decreasing.

- Cracking: in Model 1, the cracks appeared with a 0.07 mm width, that increase progressively. Close to the rupture, the values were near 0.25 mm, with crack spacing approximately equal to the mesh transversal wires one (50 mm). The results reveal a good behaviour, taking into account the small reinforcement rate.

In Model 2, the first cracks were 0.10mm width and some of them increased quickly. Near the rupture some had 0.70 mm. The positioning of only one mesh, towards the smallest strength of the meshes, was not satisfactory.

Since in the rupture of Model 2 an excessive deformation was characterized (mortar rupture did not take place), it was possible to note that practically all the cracks closed again when the loading was removed.

In neither of the models shear cracks were noted, even for shear conventional stresses up to 3.4 MPa.

The comparison of the crack width and the corresponding reinforcement tension stress values with those from other works developed without the use of prestressing [2], larger cracks were noticed. This can be explained by the smaller amount of meshes and the larger mesh opening used here. Another explanation for the larger width of the cracks is the proximity of the cracking moment to the ultimate moment (0.68 ratio). That is, when the first crack appeared, the beam was near the collapse. In this case, the complementary reinforcement should be increased.

- Rupture: in the analysis of the ultimate moment, the experimental values were very close to the theoretical ones (Table 3).

Table 1 - Losses of prestress force (%)	model 1	model 2	theoretical
wedging	5.9	8.3	6.4
shrinkage + stress relaxation + displacement of frame (until transfer)	14.8	18.0	12.2
elastic shortening of the concrete	2.2	4.7	3.5
gradual losses (until the tests)	5.2	6.5	3.4
total	20.9	27.1	24.3

Table 2 - Cracking Moment			
Model		neutral axis(cm)	Mr(kNm)
1	theo	8.9	14.2
	expe	7.9	14.3
2	theo	8.9	13.1
	expe	8.8	13.0

Table 3 - Ultimate Moment			
Model		neutral axis(cm)	Mu(kNm)
1	theo	3.4	21.2
	expe	5.1	22.5
2	theo	2.9	20.2
	expe	4.2	19.5

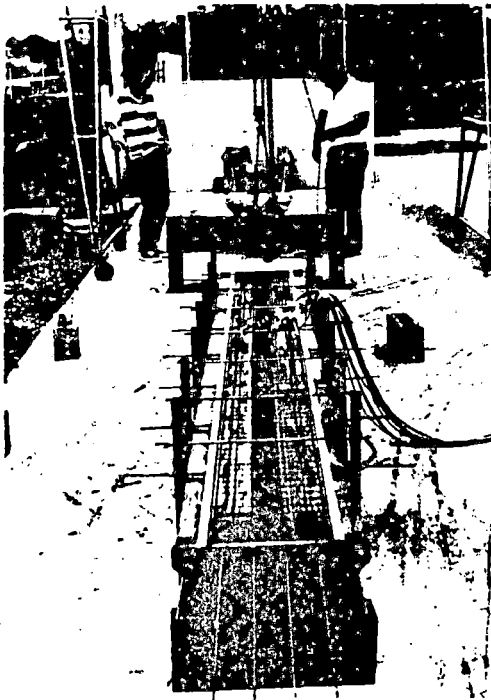


Photo 4 - Tensioned tendons on bed

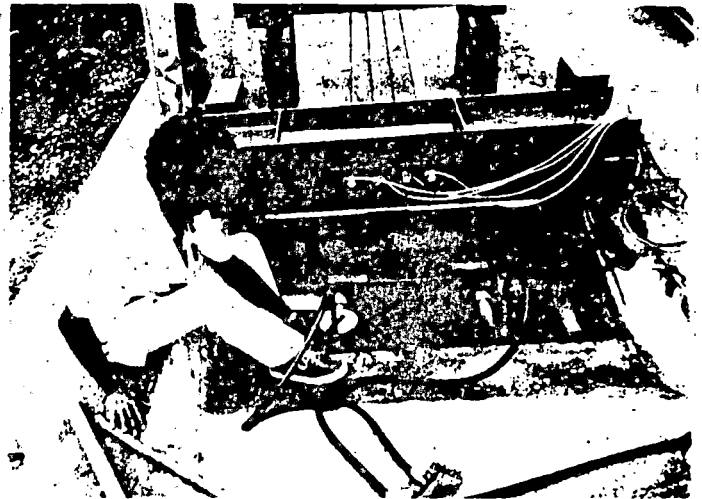


Photo 3 - Anchor end bed detail

CONCLUSIONS

Besides the comments arisen from the storehouse study, the most important conclusions from this work are:

- prestressed ferrocement is a very interesting alternative to structural concrete, in the precast lightweight construction.

- the use of small mesh reinforcement, composed by larger opening welded or expanded meshes, may be compensated by the introduction of prestressing forces. The cracks would be kept with a small width, which close after a transitory load.

- the prestressing is very effective in the deflection control and in the increasing of the cracking moment.

- it is possible to obtain lightweight and resistant elements (5 to 10 kN weight, for 5.5 to 10 m span members, for example), with great transportation and building advantages.

- the regularity and consistency of the experimental results assure its reliability and coherence with the assumed hypothesis, thus encouraging future researches.

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