EXPERIMENTAL STUDY ON THE INFLUENCE OF THE REBAR ARRANGEMENT AND OF THE SHAPE OF THE CROSS-SECTION ON THE FRACTURE OF LRC BEAMS

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Abstract. The experimental program reported in this paper investigates the sensitivity of lightly reinforced concrete beams (LRC) to the shape of the cross-section and to the rebar arrangement. Twenty-four micro-concrete reinforced beams were tested; these were rectangular and T beams reinforced with one, two or three rebars aligned horizontally or vertically. The concrete mechanical properties were all obtained from independent tests. Likewise, experimental errors due to material heterogeneity or incorrect set-up of the tests were minimized to ensure a high level of control during the execution of the program. The experimental results exhibit maximum load *shape effect*, i.e. the maximum load does not vary as no-tension hypothesis indicates. Beams in which rebars are aligned horizontally show a secondary load peak after cover cracking, while a vertical arrangement of the rebars provokes more energy dissipation and ductility in the post-peak response.

Resumen. El programa experimental que exponemos en este comunicación investiga la sensibilidad de las vigas de hormigón débilmente armadas (LRC) frente a la forma de la cabeza de compresión y a la disposición de la armadura traccionada. Ensayamos 25 con dos secciones diferentes, unas rectangulares y otras con forma de T. Asimismo se ha variado la distribución del armado colocándolo en varias capas, pero tomando el mismo valor para el recubrimiento mecánico en todas los casos. Las propiedades mecánicas del hormigón se obtuvieron por medio de ensayos independientes. Del mismo modo, los errores debidos a la heterogeneidad del material o a la incorrecta realización de los ensayos se redujeron al mínimo. Los resultados experimentales muestran un *efecto de forma*, es decir, que la carga máxima obtenida no varía como es esperable según las formulaciones clásicas para las vigas en T. Respecto a la distribución de las barras las vigas en las que el armado se encuentra en una sola capa presentan un pequeño pico secundario después de haberse fisurado el recubrimiento. Por otra parte las disposiciones del armado en varias capas provocan una disipación de energía mayor, lo que se traduce en una respuesta más dúctil en la respuesta post-pico.

1. INTRODUCTION

This paper presents very recent results of an experimental program aimed at disclosing advanced aspects of the fracture behavior of lightly reinforced concrete beams. In particular, the program was designed to investigate the dependence of these beams on (1) the arrangement of the reinforcing bars around the steel centroid; and (2) the shape of the cross-section. All the beams were made out of the same materials —micro-concrete and steel bars— whose properties remain constant throughout the program. Nevertheless, the beams are reinforced differently by changing the number of bars, the spacing between them and the arrangement of bars around the steel centroid.

Various experiments on lightly reinforced beams [1-7] were based on the idea that minimally reinforced beams are brittle structures susceptible to theoretical analysis by fracture mechanics. These experimental programs showed that brittle collapse of lightly reinforced beams is size dependent, suggesting that the failure is due to fracture processes in concrete. Specifically, Hededal and Kroon [4] considered the bond-slip properties of the reinforcement and found that they substantially influence the response of the beam. Ruiz et al [6] made a set of tests that disclosed the influence of several parameters —size, steel ratio, steel yield strength and bond-slip properties— on the fracture behavior. In addiction, they made a complete material characterization by direct testing that made objective numerical modeling possible [6,8].

However, there were still some points to study. On the one hand, all the works approaching collapse of brittle beams by fracture mechanics have been done on rectangular beams —Ozcebe et al. [9] used a technological approach to study the failure of T beams—. On the other hand, Ruiz et al. [10] and Ruiz [8] showed theoretically that other parameters with influence on the problem were the concrete cover and the type of arrangement of the bars around the steel centroid. Thus a need was felt for an experimental program covering such topics.

The paper is structured as follows: a brief overview of the experimental program is given in Section 2. The materials and specimens are described in Section 3. Section 4 summarizes the experimental procedures. The experimental results are presented and discussed in Section 5. Finally, in Section 6 some conclusions are extracted. We can anticipate here that the tests are sensitive to both the shape of the cross-section and the arrangement of the rebars around the centroid. Specifically, when bars are aligned vertically the beam behavior is more ductile than with a single layer reinforcement.

2. OVERVIEW OF THE EXPERIMENTAL PROGRAM

The experimental program was intended to study whether the fracture of lightly reinforced concrete beams depends on the rebar arrangement and on the shape of the cross-section.

We used two different rebar distributions around the steel centroid, which was kept in the same relative position for all the beams. To show the influence of the shape of the cross-section on the fracture process we selected rectangular and T beams. In addition, the program had to provide an exhaustive material characterization to allow a complete interpretation of the test results that could be useful for future investigations. Finally, the behavior of the laboratory beams should be representative of the behavior of beams of ordinary size made of ordinary concrete.

Regarding the scale of the specimens, Hillerborg's brittleness number β_H was used as the comparison parameter. As a first approximation, two geometrically similar structures will display a similar fracture behavior if their brittleness numbers are equal [11,12]. β_H is defined as:

$$\beta_H = \frac{D}{l_{ch}}, \text{ where } l_{ch} = \frac{EG_F}{f_t^2} \tag{1}$$

D is the depth of the beam and l_{ch} is Hillerborg's characteristic length; E is the elastic modulus, G_F the fracture energy and f_t the tensile strength. According to this, a relatively brittle micro-concrete was selected with a characteristic size of approximately of l_{ch} = 90 mm (the details of the micro-concrete are given in the next section). Since the characteristic length of ordinary concrete is 300 mm on average, laboratory beams of 150 mm depth are expected to simulate the behavior of ordinary concrete beams 500 mm in depth, which is considered a reasonable size for the study.

Figure 1a sketches the dimensions of the rectangular and T beams chosen for this experimental program. Note that the T beam is built by thickening the head of the rectangular beam by 50%. Figure 1b depicts the five kinds of arrangement of the reinforcement bars around the steel centroid. We use 1, 2 or 3 rebars aligned horizontally or vertically. Figure 1c names the resulting combinations for future reference. For instance, a T2V beam is a T beam reinforced by means of 2 bars aligned vertically.

Standard characterization and control tests were performed to determine the compressive strength, tensile strength, elastic modulus and fracture energy of the con-

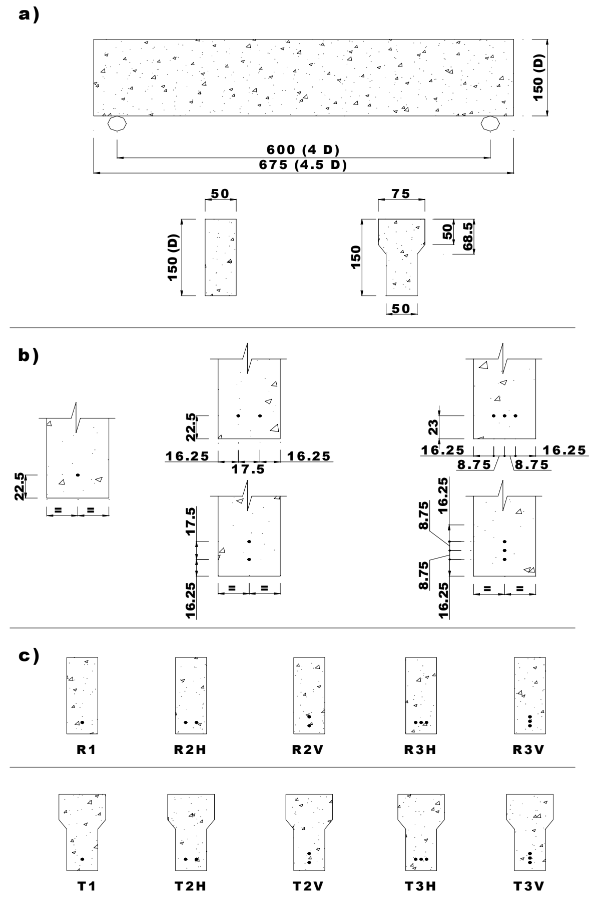

Fig. 1. (a) Rectangular and T cross-section dimensions; (b) rebar arrangements; (c) specimen nomenclature.

concrete. Steel properties were provided by the rebar maker. The properties of the steel-to-concrete interface were not measured directly. Nevertheless, we estimated their value using the Model Code [13] (see next section for details).

3. MATERIALS AND SPECIMENS

3.1 Micro Concrete

A single micro-concrete mix was used throughout the experimentation, made with a lime aggregate of 5 mm maximum size that follows the corresponding Fuller curve, and normal Portland cement (ASTM type I). All the cement used was taken from the same cement container and dry-stored until use. The mix proportions by weight were 3.2 : 0.5 : 1 (aggregate: water: cement).

All the specimens were made from 6 batches of 35 litres. Batch 1 was devoted to tuning the experimental set-up and thus the specimens made out of it are not considered for getting material properties or conclusions. There was a strict control of the specimen-making progress, to minimize scatter in test results. We made characterization specimens of all batches. The Abrams cone slump was measured immediately before casting, the average value being 12 mm. All the specimens were cast in steel molds, vibrated by a vibrating table, wrap-cured for 24 hours, demolded, and stored for 4 weeks —until they were tested— in a moist chamber at 20 °C and 98% of relative humidity. Table 1 shows the characteristic mechanical parameters of the micro-concrete determined in the various characterization and control tests.

Table 1. Micro-concrete characteristics.

	$f_c^{(a)}$ MPa	$f_{ts}^{(b)}$ MPa	$E_c^{(a)}$ GPa	G_F N/m	l_{ch} mm
mean	48.7	4.8	25.9	74.9	93.7
std. dev.	1.4	0.5	5.4	10.5	—

(a) Cylindrical specimens, compression.
(b) Cylinder splitting (Brazilian).

3.2 Steel

For the beam dimensions selected, and the desired steel ratios, the diameter of the steel bars had to be smaller than that of standard rebars, so commercial smooth wires with a nominal diameter of 2.5 mm were used to achieve the desired reinforced configuration for different specimens.

The mechanical properties of the wires were measured by standard tensile test. The elastic modulus was 212 GPa, the standard yield strength for a strain of 0.2% was 810 MPa, the yield strength was 870 MPa, and the ultimate strain was 6.0%. The properties of the steel-to-concrete interface were not measured directly. The Model Code [13] suggests that in our conditions the maximum tangent stress in the interface can be 1 MPa.

3.3 Characterization and control specimens

Cylindrical specimens whose dimensions were 150 mm in length and 75 mm in diameter were cast to determine standard mechanical properties. We made 5 specimens from each bath, 3 for compression tests and 2 for splitting tests.

Notched plain concrete beams were used to characterize concrete fracture properties. All the beams were 50 mm thick, 75 mm depth and 337.5 mm long. Out of each batch we made 4 specimens. The notch was sawn at the central cross-section to a depth of half the total beam depth.

3.4 Reinforced micro concrete beams

Figure 1 summarize the geometrical characteristics of the reinforced concrete beams. The specimens were cast in metallic molds, with the reinforcing wires protruding at the ends through holes in the mold walls. The micro concrete was compacted on a vibrating table. During casting and vibration the wires were tensioned by nuts to hold them tight and in place. The tension of the wires was released right before demolding. The wires were left protruding from the end of the beam. No hooks or anchors were used.

4. EXPERIMENTAL PROCEDURES

4.1 Characterization and control tests

Compression tests were carried out on 18 cylindrical specimens —three from each batch— according to ASTM C-39 and C-469 except for a reduction in size. The strain was measured over a 50 mm gage length by means of two inductive extensometers placed symmetrically. The tests were run under displacement control, at a rate of 0.3 mm/min.

Brazilian tests were also carried out on 12 cylindrical specimens —two from each batch— following the procedures recommended by ASTM C496. The specimen was loaded through plywood with a width of 178 of the specimen diameter. The velocity of displacement of the machine actuator was 0.3 mm/min.

Stable three-point bend tests on notched beams were carried out to obtain the fracture properties of concrete following the procedures devised by Elices, Guinea and Planas [14-16]. The span was 340 mm. During the test the beams rested on two rigid-steel semi-cylinders laid on two supports permitting rotation out of the plane of the beam and rolling along the beams longitudinal axis with negligible friction. These supports roll on the upper face of a very stiff steel beam fastened to the machine actuator.

The tests were performed in control position. We used three linear ramps at different displacement rates: 10 μm/min during the first 15 min, 50 μm/min during the following 15 min and 250 μm/min until the end of the test. Reinforced beam tests

4.2 Reinforced beam tests

The reinforced beams were tested in three-point bending. In principle the experimental set-up was similar to that described for the plain notched beams. Nevertheless, the first set of experiments showed that the beams were not stable after the peak load. Thus, in order to control the fracture process, we added a resistive extensometer centered on the tensioned face of the beam with a gage length of 100 mm. This device measured a combination between the stretching of the concrete in the lower surface of the beam and the crack mouth opening displacement (CMOD). This kind of test control leads to stable tests in which the entire post-peak behavior is recorded.

The tests started in load control until reaching 5 KN, which was done in 5 min. This loading ramp was fully within the linear response of the beams and provoked the opening of the aforementioned extensometer at an average rate of 2 μm/min. Then we passed the control of the test to CMOD and kept the opening rate constant during the following 30 min. this ramp allowed us to obtain the post peak behavior of the beams. Finally we changed to displacement control at a rate of 0.2 mm/min until the end of the test.

5. RESULTS AND DISCUSSION

5.1 Characterization tests

The main results for the characterization tests were given in Table 1. Standard deviation between specimens made from different batches was of the same order as between specimens from the same batch, which shows that the process of making the specimens was properly standardized. We also reach the same conclusion if we notice the low values of the standard deviation of the compressive and tensile strengths. In contrast, the elastic modulus and the fracture energy have deviations of 20 and 15% of their respective mean values. In the case of E there may be some spurious scatter attributable to a deficient resolution of the LVDTs used to measure the strain (only 4×10^{-4}). However, the deviation in the fracture energy can be considered as normal if we take into account that the procedures to obtain G_F also include analytical data manipulation when getting the not-measured energy [17].

5.2 Steel slip bond properties

The value of the shear strength τ_c at the steel-to-concrete interface according to the Model Code is of the order of 1 MPa. The Model Code also suggests a definite bond-slip law for the interface that can be of interest to model the global behavior of the beams.

Experimental data on this topic is available in scientific literature. For example, Ruiz et al. [6] measured τ_c for smooth wires of the same kind of steel and got a mean value of 0.5 MPa, the standard deviation being 0.2 MPa, which represents 40% of the mean. They used pull-out tests and assumed that the interface behaved in a rigid-perfectly plastic manner. When modeling bending tests it seemed that the interface was actually stronger than suggested by the pull-out tests. Indeed, it was necessary to consider a τ_c several times bigger than the measured one to model the global beam resistance. This may be due to the normal forces acting over the reinforcing wire during the bending process. Such forces can slow the progress of the debonding process and increase the friction when the bars start to slip.

5.3 Reinforced beam tests

All the experimental load-displacement (P-δ) curves for the reinforced beams are drawn in Figure 2. The plots are arranged so that the amount of reinforcement is kept constant for columns and the type of alignment for rows. The two uppermost rows contain the results of the beams with rectangular cross-section, while the two lowermost rows depict the curves for the T-beams. Each single plot depicts the curves for two identical specimens. As it is well known, the boundary conditions at the point where the actuator applies the load may generate small variations in the global flexibility of the beam. Consequently, in order to facilitate the comparison between similar beams, the initial slope of the curves is corrected to the theoretical value stemming from strength of materials.

Regrettably, a few tests were not stable due to the extreme sensitivity of the machine to the parameters defining the control loop. Specifically the two R2H and one of the T2H were unstable and the snap-back stretch of the P-δ curve was not caught. Nevertheless they are drawn in Figure 3 to keep the symmetry of the experimental program.

A typical P-δ curve (for instance, any of the R3H) starts with a linear ramp-up. There is a loss of linearity before reaching the load peak, which indicates the initiation of the fracture process. Right after the peak the displacement snaps back while the beam loses resistance. The load transfer between the concrete and the reinforcement enables the beam to recover and generates a U-shaped stretch in the P-δ curve. A sudden drop in the load signals the slipping of the reinforcing wires, for the interface was not strong enough to cause the yielding of the steel.

Next we discuss the results focusing on their sensitivity to the shape of the cross-section and to the number and alignment of wires.

Shape of the cross-section

Figure 3a compares P-δ curves corresponding to R and T beams reinforced with 3 horizontal wires (R3H versus T3H). It may seem trivial to point out that T-beams are stiffer and stand more load than their R counterparts. Nevertheless the extent of increase in the peak load is only of 2.5% —as an average of all the tests—, while strength of materials together with the usual no-tension hypothesis would foretell an 8.3% increase, i.e. the load peak increases less than expected. T beams shift upwards the compressive resultant and thus make the variation of tension in the lower part of the beam smoother. We can speak of a kind of *shape effect* that has the same cause as the *size effect*: the initiation and development of the fracture process as well as the crossing of the reinforcement layers by the crack or cracks are related to the gradient of stresses generated in the tensioned fibres.

Amount of reinforcement

The effect of steel ratio and more generally of the strength of the reinforcement on the fracture process is well known [7]. Particularly Ruiz et al [10] observed that the amount of reinforcement does not influence the value of the peak load when the concrete cover is longer then a certain critical cover. Such critical cover depends on the size of the beam and on the parameters that characterize the first stages of the fracture progress. For the beams in this program the critical cover is 15.9 mm, while the minimum cover is 16.25 mm in length (Fig. 1b). Indeed, Figure 3b confirms that observation by plotting the P-δ curves for R2V and R3V beams together: both of them reach approximately the same peak load. The post peak behavior is quite different for beams

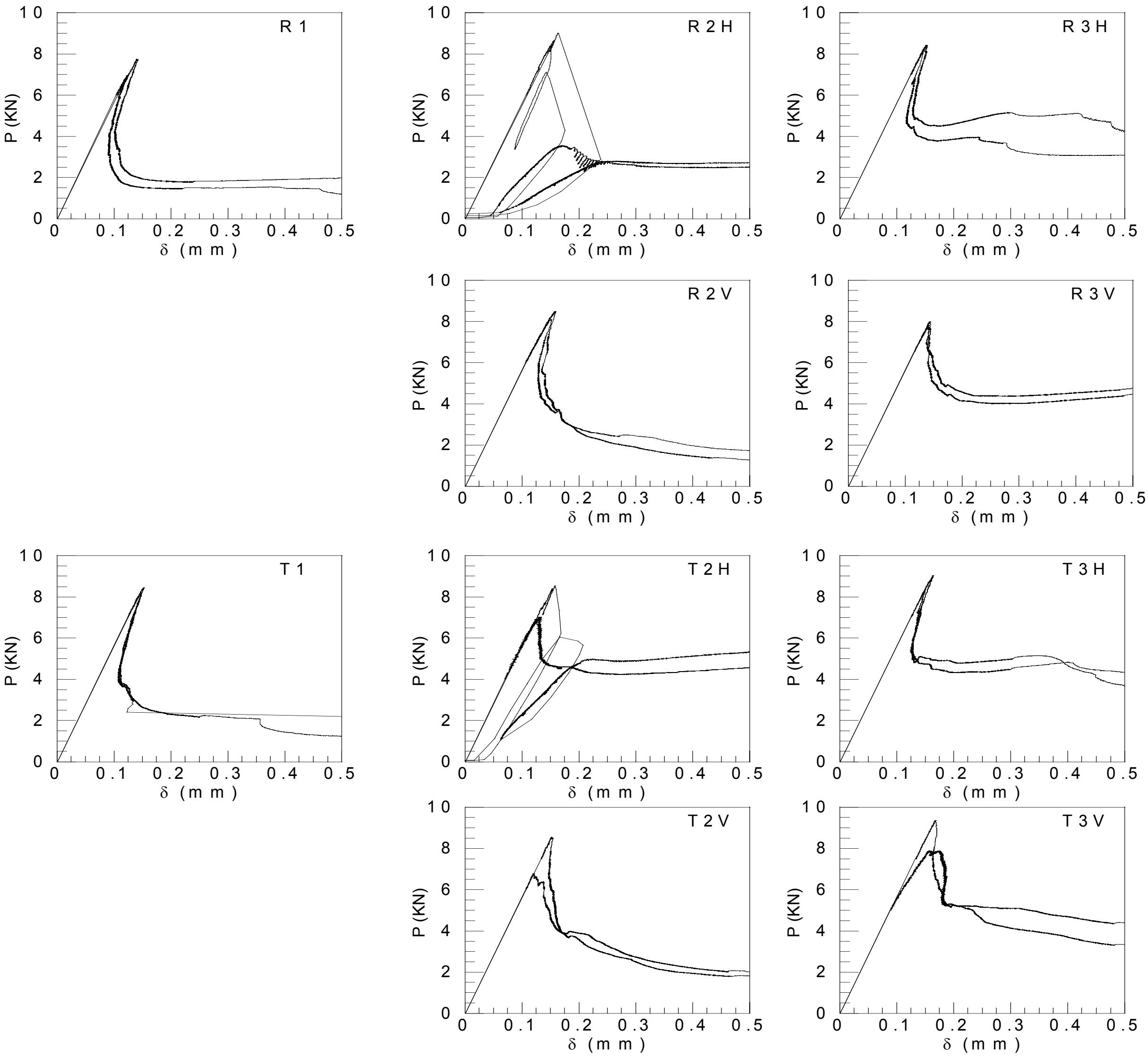

Fig. 2. Load-displacement curves.

reinforced differently: the more reinforcement the beam has the higher values the U-shaped portion reaches.

<u>Alignment of the wires</u>

Figure 3c, d compares P-δ curves for beams that are identical except for the reinforcement alignment around the steel centroid. The H beams, i.e. beams that have the wires aligned horizontally, have just one single layer of wires that produce a secondary peak when the crack zone crosses it. Besides, the behavior of H beams is quite fragile, for the stresses at the steel-to-concrete only develop after a certain crack opening is achieved. In contrast, V beams are more ductile in the post peak response. The crack zone does not develop that easily because it finds several reinforcement layers in its way. The secondary peaks that would correspond to each layer are smeared. In addition, the vertical arrangement of the wires produces a more continuous stress transfer that eventually leads more energy to be consumed at the beginning of the fracture

6. CONCLUSIONS

This paper presents recent experimental results on lightly reinforced concrete beams. A single micro-concrete was used to make all the experiments. We wanted to study the influence of the shape of the cross-section and of the arrangement of the rebars around the steel centroid on the fracture of the beams. Particularly, we made rectangular and T beams with the same depth and the same shape in the lower part of the beam. These beams were reinforced with 1, 2 or 3 rebars that were aligned horizontally or vertically while keeping the relative position of the centroid in all the specimens. Concrete-making and testing procedures were closely controlled to ensure the same material characteristics and to reduce experimental scatter. The following conclusions can be drawn from the study:

- Lightly reinforced beams show a *shape effect* in the maximum load; this effect is comparable to the size

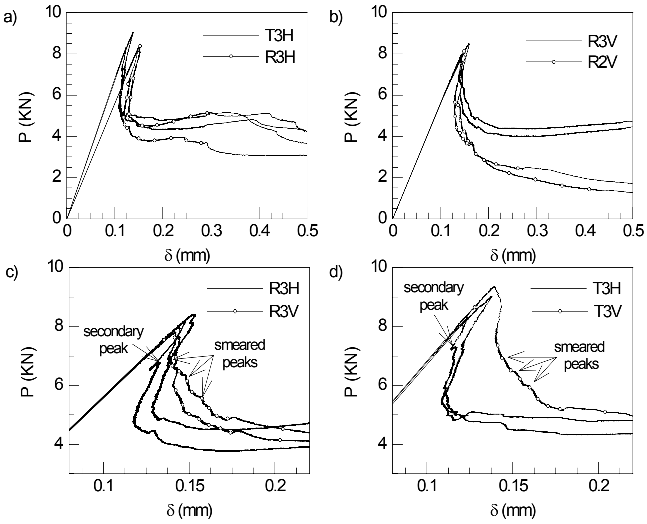

Fig. 3. P-δ curves corresponding to: (a) rectangular and T beams; (b) beams reinforced with 2 and 3 bars; (c) rectangular beams with bars aligned horizontally and vertically; (d) T beams with bars aligned horizontally and vertically.

effect, i.e. the maximum load does not actually vary as no-tension hypothesis indicates.

- In our beams the concrete cover is larger than a certain critical cover length; thus the maximum load is not influenced by the reinforcement.
- Distributing the reinforcement in several layers induces a ductile post peak behavior accompanied by a large amount of energy dissipation. However, a single layer provokes a small secondary peak within the snap back zone of the P-δ curve.
- These experimental results can be used profitably for modeling the behavior of lightly reinforced concrete beams.

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