Flexural Ductility of High-Strength Concrete Beams

By

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ملخص البحث

يتناول البحث دراسة ممطولية الكمرات الخرسانية المسلحة ذات الخرسانة عالية المقاومة معمليا ونظريا، وتشتمل الدراسة على المتغيرات التالية : مقامة الخرسانة للضغط ، ونسبة الحديد الطولي المشدود، وكذلك المسافة البينية بين الكانات . و تمت دراسة كل متغير على حدى مع ثبات المتغيرات الاخرى. وخلصت الدراسة الى ان الكمرات التى تحتوى على خرسانة عالية المقاومة تعطي ممطولية اكثر من مثيلاتها من الخرسانة عادية المقاومة. كما اثبتت الدراسة ان زيادة نسبة حديد تسليح الشد يسبب نقص كبير فى ممطولية الكمرات. وقد اظهرت الدراسة التأثير الايجابى لزيادة عدد الكانات (تقليل المسافة البينية بينها) على ممطولية الكمرات.

Abstract

High-strength concrete is a far more brittle material than normal-strength concrete. As a result, it is important to investigate the ductility of high-strength concrete members. This paper study experimentally and theoretically the flexural ductility of High-Strength simply supported reinforced concrete beams in pure bending. The principle test variables were the concrete compressive strength, the amount of longitudinal tension reinforcement, and the spacing of stirrups.

The effect of each variable was studied separately, while the other variables were kept at constant or near constant values. The paper concluded that high-strength concrete beams exhibit qualitatively similar trends in ductility when compared with normal-strength concrete, and that, despite high-strength concrete being a more brittle material, flexural beams made with high strength concrete exhibit greater ductility. As expect the paper showed that the increase in percentage of tension longitudinal reinforcement cause a decrease in the ductility. The paper also showed a positive effect of the increase of stirrups on ductility.

1-Introduction

the objective of this paper is to study the ductility of high-strength concrete beams. The behaviour of ultra high strength concrete members were investigated in refs[1,2,3]. In ref[1], the specimens were clearly reinforced as columns and tested as beams under two point loading without axial load. In ref.[2]. the high-strength concrete was light weight. To achieve the objective of this paper eleven beams were tested. The variables of this study were, the concrete compressive strength, the amount of tension reinforcement, and the spacing of stirrups. The beams were tested under the action of two points load up to the yield and beyond it. The experiment measurements included the yield load (P_y), the ultimate load (P_u), the deflection, and the strain.

2- Test Program

The test program consists of eleven reinforced concrete beams as shown in table (1). All beams are 12x25 cm in cross section with clear span 300 cm. The tested beams cover the studied parameters which are :

The concrete compressive strength (C_{cu})

The amount of longitudinal tension reinforcement (A_s).

The spacing of stirrups.

The concrete compressive strength were 410 and 920 kg/cm^2. The later one was made using silica fume in concrete mix. The longitudinal tension reinforcement varied from 2Φ12 tell 2Φ25. The spacing of stirrups were 10 and 5 cm.

3-Test Apparatus and instrumentation

Vertical steel space frame with dimension 3x3x3 m was used with a 20 ton mechanical screw jack with 30 cm stroke. The beams were subjected to two symmetrical concentrated loads. as shown in fig(1). The distance between these two symmetrical loads was 65 cm apart. The load was incrementally applied up to and beyond the ultimate loads. The load was measured using two load cells of maximum capacity 10 ton. Deflection was measured using three dial gauges at the bottom face of the beam (tension side). The three dial gauges were with 3 cm displacement range and 0.01 mm accuracy. two of the dial gauges were placed under the two acting concentrated loads while the third one was located at the middle of the span. The strains were measured using electrical strain gauges, which were stacked on the surface of tension reinforcement to check the yielding of this reinforcement. The cracks initiation and propagation were plotted.

4- Test results

The effect of the studied parameters is discussed in the following paragraphs. These parameters are the concrete compressive strength, the amount of longitudinal tension reinforcement, and the lateral reinforcement (spacing of stirrups).

4-1 Effect of Concrete compressive strength

The increase of compressive strength from 410 to 920 kg/cm^2 doesn't cause any variation in yielding loads of tested beams. This result is very clear by comparing the yielding loads for beams B_1, B_2, and B_3 with the similar ones for beams B_4, B_5, and B_6 respectively as shown in table (2). This table shows also that this increase in concrete compressive strength cause an slight increase in ultimate loads for beams B_4, B_5, and B_6 comparing with the similar beams B_1, B_2, and B_3 respectively. General by using concrete with high-strength equal to 2.24 times concrete strength equal to 410 kg/cm^2, the average gain in ultimate loads for the tested beams is only about 13% . the gain in final ductility factor of tested beams due to using ultra high strength concrete (C_{cu}=920 kg/cm^2) is much noticeable than the gain in ultimate loads (table (2) and figure (13)). The final ductility factor for beams B_4, B_5, B_6 which have concrete compressive strength 920 kg/cm^2 are 1.86, 1.83, 1.89 times the final ductility factors for beams B_1, B_2, B_3 (respectively) which have concrete compressive strength 410 kg/cm^2. It is important to explain that the final ductility factor is defined as the ratio between the final deflection (the deflection when the load decreases to 80% of its ultimate value along the descending branch of the load deflection curve) and the deflection at the point of yield of reinforcing steel[1,4]. Figures (2 to 7) show the load deflection curves for beams (B_1 to B_6). From these figures it is noticed that for the same longitudinal and lateral reinforcement, the beam with higher strength has less deflection than a similar beam with lower strength concrete at the same load level up to the yielding. This is understandable because the modulus of elasticity of concrete increases with strength. For most of beams with higher strength concrete (C_{cu}=920 kg/cm^2), there's a sudden dorp in load followed by an increase in the load secondly. This drop is due to crushing in high strength concrete, which is accompanied by a voice of explosion. The beams with higher concrete showed a slightly increase of initial cracking load compared with the similar beams with lower strength concrete fig.(14). The change of concrete compressive strength doesn't cause a change in failure mode which is general yielding of steel prior the failure by crushing of concrete in the compressive zone.

4-2 Effect of amount of longitudinal tension reinforcement

As known the increase in the amount of longitudinal tension reinforcement in beams caused a proportional increase in yielding and ultimate loads of these beams, which is accomained by a dramatically decrease in ductility factor. Table (2) and fig. (13) shows the decrease in final ductility factors for tested beams due to the use of big amount of longitudinal tension reinforcement for both normal and high strength concrete whatever the spacing of stirrups. For beams B_1, B_2, and B_3 with concrete compressive strength 410 kg/cm^2 and with stirrups spacing 10 cm, the percentages of longitudinal tension reinforcement of these beams are 0.86%, 1.5%, and 1.9% and the corresponding ductility factors are 15.2, 4.86, and 4.45 respectively. For beams B_4, B_5, B_6, B_7, and B_8 with concrete compressive strength 920 kg/cm^2 and with stirrup spacing 10 cm, the percentage of longitudinal tension reinforcement of these beams are 0.86%, 1.5%, 1.9%, 2.9%, and 3.7% and the corresponding ductility factors are 28.2, 8.9, 8.43, 3.1 and 2.23 respectively. For beams B_9, B_{10}, and B_{11} with concrete compressive strength 920 kg/cm^2 and with stirrup spacing 5 cm, the percentage of longitudinal tension reinforcement of these beams are 0.86%, 1.5%, and 1.9% and the corresponding ductility factors are 31.1, 10.48, and 9.46 respectively. By comparing the load deflection curves for beams with the same concrete strength and spacing of stirrups but different amount of longitudinal tension reinforcement, it is found that beams with low percentage of longitudinal tension reinforcement show large deformation at relatively constant high loads and the drop-off in the load carrying capacity is gradual [see figure 2, 5, 10 for beams B_1, B_4, B_9 which have percentage of longitudinal tension reinforcement equal to 0.86%]. On the other hand the beams with high percentage of longitudinal tension reinforcement show significant dropoffs in load carrying capacity immediately upon crushing of the compression concrete. which usually accomained the attainment of the maximum load [see figures 8, 9] for beams B_7, B_8 which have percentage of longitudinal tension reinforcement equal to 2.9%, and 3.7 % respectively. The cracks for beams with low-percentage of longitudinal tension reinforcement are relatively wider at the end of the test compared with the similar ones with high percentage of longitudinal tension reinforcement and that is due to the excessive deflection of the first ones. All beams failed in the flexure except beam B_8 which failed in shear. Beam B_8 has percentage of longitudinal reinforcement equal to 3.7 % which is the highest value of longitudinal reinforcement for the tested beams.

4-3 Effect of spacing of stirrups

The use of stirrups with spacing equal to 5 cm instead of spacing equal to 10 cm doesn't cause any variation in yielding loads of tested beams. This result is shown in table (2) by comparing the yielding loads for beams B_4, B_5, and B_6 with the similar ones for beams B_9, B_{10}, and B_{11} respectively. The use of stirrups with spacing equal to 5 cm instead of spacing equal to 10 cm cause an increase in ultimate loads for beams B_9, B_{10}, and B_{11} comparing with the similar ones for beams B_4, B_5, and B_6 respectively. The average gain in ultimate loads due to the decrease of spacing of stirrups from 10 cm to 5 cm is about 1.14. The final ductility factors for beams B_9, B_{10}, and B_{11} which have 5 cm stirrups spacing are 1.1, 1.18, 1.12 times the final ductility factors for beams B_4, B_5, and B_6 (respectively) which have 10 cm stirrups spacing. The change of stirrups spacing doesn't cause any variation in load deflection curves for the tested beams up to the yielding load. This result in noticeable by comparing the load deflection curves in figures 5, 6, and 7 with the load deflection curves in figures 10, 11, and 12 respectively. The change of spacing of stirrups from 10 cm to 5 cm seems to have no considerable effect on neither the cracks nor the mode of failure.

5- Theoretical study for the ductility

As shown in fig. (13) the data of the tested beams is not enough to plot the curves that represent the relation between the ductility factor and the percentage of tension reinforcement with different values of concrete compressive strength (C_{cu}), so we will plot this relation using a theoretical study for the ductility. Ductility may be defined as the ratio of the curvature at the ultimate to the curvature at the point of the first yield of steel (Φ_u/Φ_y) [5,6]. Theoretical calculation of the ductility factor (Φ_u/Φ_y) is investigated in ref.(6) considering the non linearity of concrete and using the following equations. The equation for calculating the curvature at the first yield (Φ_y), assuming the compression reinforcement is yielded is:

$$\varphi_y^5 + A\varphi_y^4 + B\varphi_y^3 + C\varphi_y^2 + D\varphi_y + E = 0 \qquad (1)$$

Where:

ϕ_y : is the curvature at first yield of steel

$\in_s$: is the steel strain

$\in_c$: is the concrete strain

A, B, C, D, and E are functions of steel and concrete strains and their dimensions are in (bounds and inches). These functions can be expressed as follows:

$$A = -(5\times \in_s + 0.001)/d$$

$$B = (10\times \in_s^2 + 0.4\times \in_s + 2.4\times 10^{-5})/d^2$$

$$C = -(10\times \in_s^3 + 0.6\times \in_s^2 + 7.2\times 10^{-5} \in_s)/d^3$$

$$D = (5\times \in_s^4 + 0.04\times \in_s^3 + 7.2\times 10^{-5} \in_s^2 - 4.8\times 10^{-11} f_y(A_s - A_s`)/(f_c`*b))/d^4$$

$$E = -(\in_s^5 + 0.01\times \in_s^4 + 2.4\times 10^{-5} \in_s^3)/d^5$$

After calculating φy from equation (1), compression reinforcement stress must be recalculated. If the compression reinforcement stress is found to be less than the yield strength, equation (1) must be modified as follows :

$$\varphi y^5 + A\varphi y^4 + B\varphi y^3 + F\varphi y^2 + G\varphi y + E = 0 \qquad (2)$$

A, B, and E are as describe before. The functions F and G can be expressed as follows:

$$F = (10\times \in_s^3 + 0.06 \in_s^2 + 7.2\times 10^{-5} \in_s + 4.8\times 10^{-11} A_s \times E_s(d - d`)/(f_c`*b*d))/d^3$$

$$G = (5\times \in_s^4 + 0.04 \in_s^3 + 7.2\times 10^{-5} \in_s^2 + 4.8\times 10^{-11} f_y(A_s - A_s`)/(f_c`*b*d))/d^4$$

The equation for calculating the curvature at ultimate (φu), assuming the compression reinforcement is yielded is :

$$\phi u = H\left[I \in_{cu}^2 + J \in_{cu} + K\right] \qquad (3)$$

where

$$H = f_c`b/f_y(A_s - A_s`)$$

$$I = 0.5\ Z$$

$$J = (1 + 0.002\ Z)$$

$$K = (0.004/3 - 0.002 - 2 \times 10^{-6} Z)$$

after calculating the curvature using equation (3) the compression reinforcement stress must be recalculated. If the stress is found to be less than (f_y), equation (3) must be modified as followed:

$$L\phi_u^2 + M\phi_u + N = 0 \tag{4}$$

where

$$L = \left(A_s`d`E_s/(f_c`b)\right)$$

$$M = \left(\frac{A_s \cdot f_y}{f_c`\cdot b} - \frac{A_s`\cdot \in_{cu}}{f_c`\cdot b}\cdot E_s\right)$$

$$N = -\left(I \in_{cu}^2 + J \in_{cu} + K\right)$$

using the above equations figure (15) could be plotted for the theoretical curvature ductility factor (Φ_u/Φ_y) versus the percentage of tensile steel for concrete compressive strength (C_{cu}) equal to 410, 920 kg/cm^2. Although the theoretical ductility factor is calculated using the curvature and the experimental ductility factor is investigated using the deflection, the theoretical ductility factor showed a good compatibility with the test results. For example the gain in the theoretical curvature ductility factor due to increase the compressive strength from 410 kg/cm^2 to 920 kg/cm^2 is 85%. While the gain in the final ductility factor experimentally is varied between 83% and 89%. So the above equations can be used in calculating the theoretical curvature ductility factor for high strength concrete.

6- Conclusions

Based on the experimental results of the tested beams and the theoretical analysis the following conclusions can be suggested:

1- The increase in concrete compressive strength from 410 kg/cm^2 to 920 kg/cm^2 cause an average increase in ultimate load equal to 13% and average increase in final ductility factor equal to 86%, but it has no effect on the yielding load of the tested beams.

2- The beams with higher concrete strength (C_{cu}=920 kg/cm^2) suffered less deflection than a similar beams with lower concrete strength (C_{cu}=410 kg/cm^2) at the same load level up to the yielding load. They also had a slightly increase of initial cracking load compared with the similar ones with lower strength concrete.

3- The ductility factor decreases dramatically due to the increase of percentage of tension reinforcement.

4- The beams with low percentage of tension reinforcement show large deformation at relatively constant high loads and the dropoff in the load carrying capacity is gradual, on the other hand the beams with high percentage of tension reinforcement show significant dropoff in load carrying capacity immediately upon crushing of the compression concrete, which usually attainment of the maximum load.

5- The decease of stirrups spacing from 10 cm to 5 cm cause an average increase in ultimate load equal to 14% and average increase in final ductility factor equal to 13%, but it has no effect on yielding load of the tested beams.

7- Reference

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2- Shuaib H. Ahmed and Roy Borker, "flexural behaviour of reinforced high-strength light weight concrete beams", ACI. Structural Journal, Vol. 88, January-February 1991, PP. 69-77.

3- Roghu Pendyala, Priyan Mendis, and Indubhushan Patnaikuni, "full-range behaviour of high strength concrete flexural members: comparison of ductility parameters of high and normal strength concrete members", ACI. Structural Journal, Vol. 86, No. 4, January-February 1996, PP. 30-35.

4. Shaker A. El-Behariy, H. Shaneen, Gamal . Khaleel, and Ahmed I. Abdel-Mouti "Flexural Ductility of Reinforced Concrete Beams" Second Alexandria Conference of Structural and Geotechnical Engineering; 18-20 April, 1994

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Table (1) Properties of tested Reinforced Concrete Beams

Beam No.	C_{cu} kg/cm^2	Tension Rft.		Compression Rft.		Stirrups	
		A_s	f_y t/cm^2	A_s	f_y t/cm^2	No/m	f_y t/cm^2
B1	410	2 ϕ 12	4.1	2 ϕ 10	4.2	10 ϕ 6	3.65
B2		2 ϕ 16					
B3		2 ϕ 18					
B4	920	2 ϕ 12	4.1	2 ϕ 10	4.2	10 ϕ 6	3.65
B5		2 ϕ 16					
B6		2 ϕ 18					
B7		2 ϕ 22					
B8		2 ϕ 25					
B9	920	2 ϕ 12	4.1	2 ϕ 10	4.2	20 ϕ 6	3.65
B10		2 ϕ 16					
B11		2 ϕ 18					

Table (2) Results of tested Beams

Beam No.	P_y ton	P_u ton	Deflection at P_y (mm)	Deflection at 0.8 P_u (mm)	Final Ductility factor
B1	3.0	4.25	10.7	163	15.2
B2	5.5	6.10	14.0	82	4.86
B3	6.0	6.50	14.3	78	4.45
B4	3.0	4.75	7.10	200.5	28.2
B5	5.5	7.00	13.5	120	8.9
B6	6.0	7.30	14.0	118	8.43
B7	12.1	12.8	20.8	64.5	3.1
B8	11.5	11.7	21.5	48	2.23
B9	3.0	5.10	7.00	217.5	31.1
B10	5.6	8.20	13.5	141.5	10.48
B11	6.0	8.60	13.9	131.5	9.46

Note : Beam B8 failed in shear

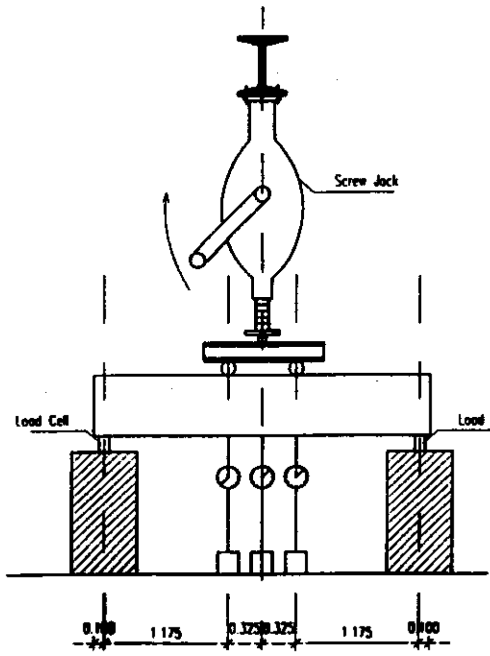

Fig. (1) Loading Arrangement and Location of Deflectometers

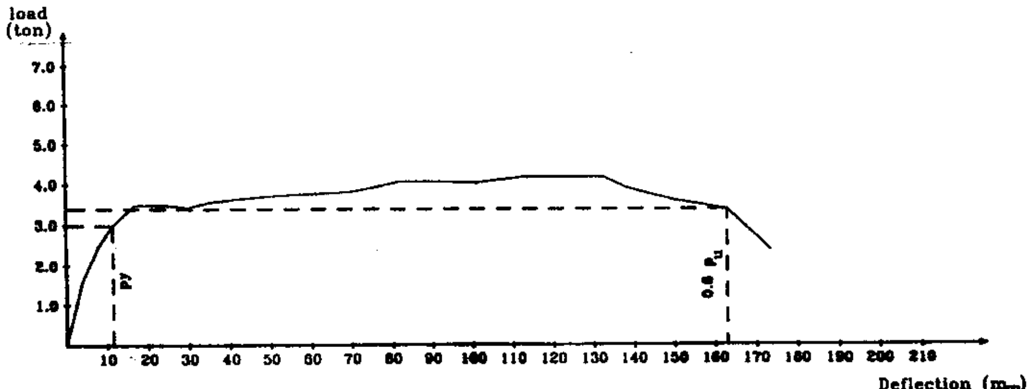

Fig.(2) Load- Deflection Curve For Beam B 1

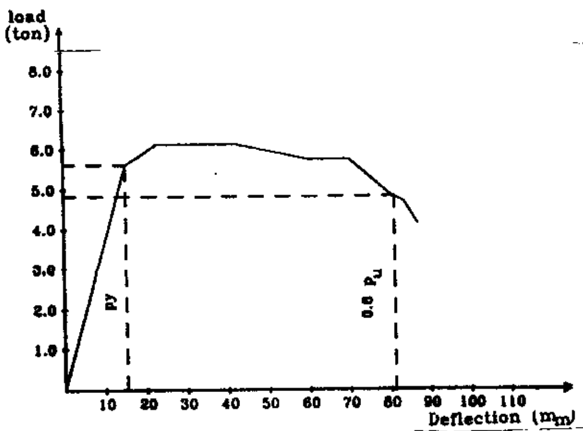

Fig.(3) Load- Deflection Curve For Beam B 2

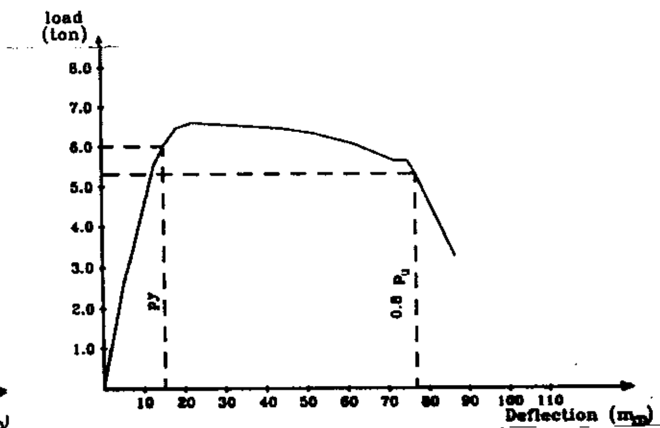

Fig.(4) Load- Deflection Curve For Beam B 3

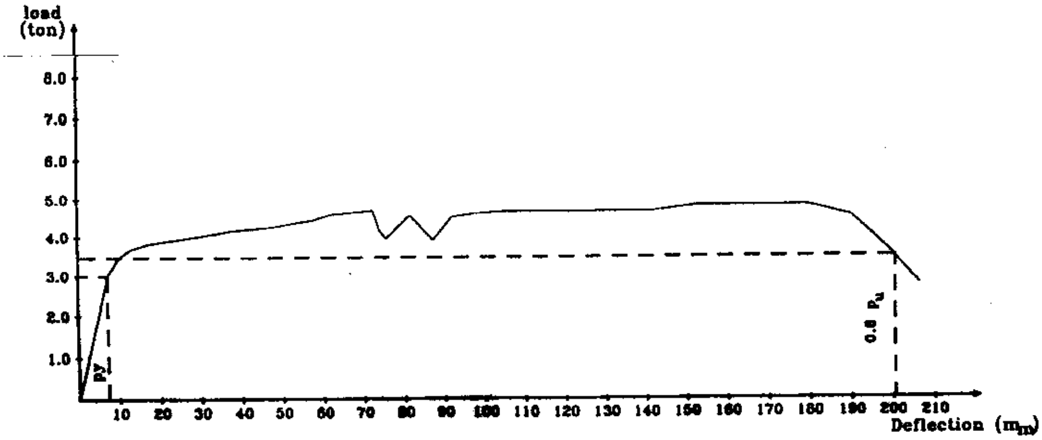

Fig.(5) Load- Deflection Curve For Beam B 4

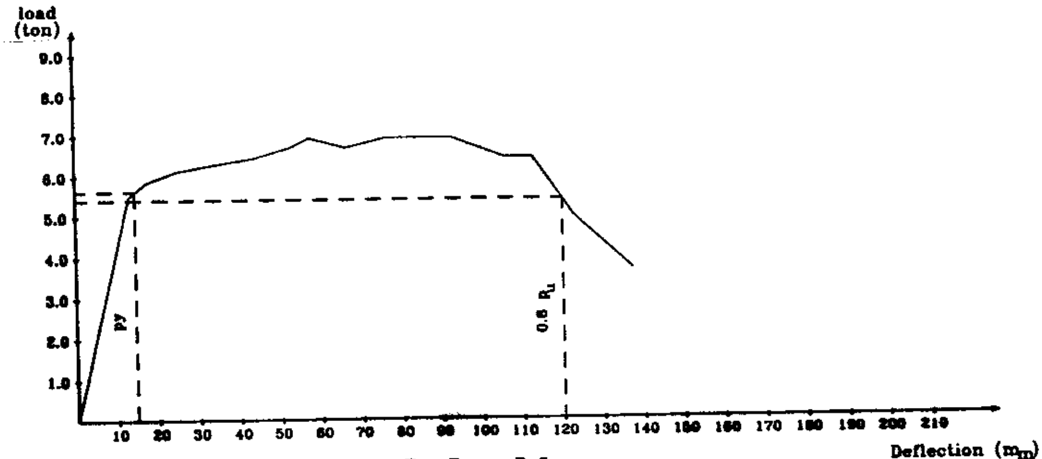

Fig.(6) Load- Deflection Curve For Beam B 5

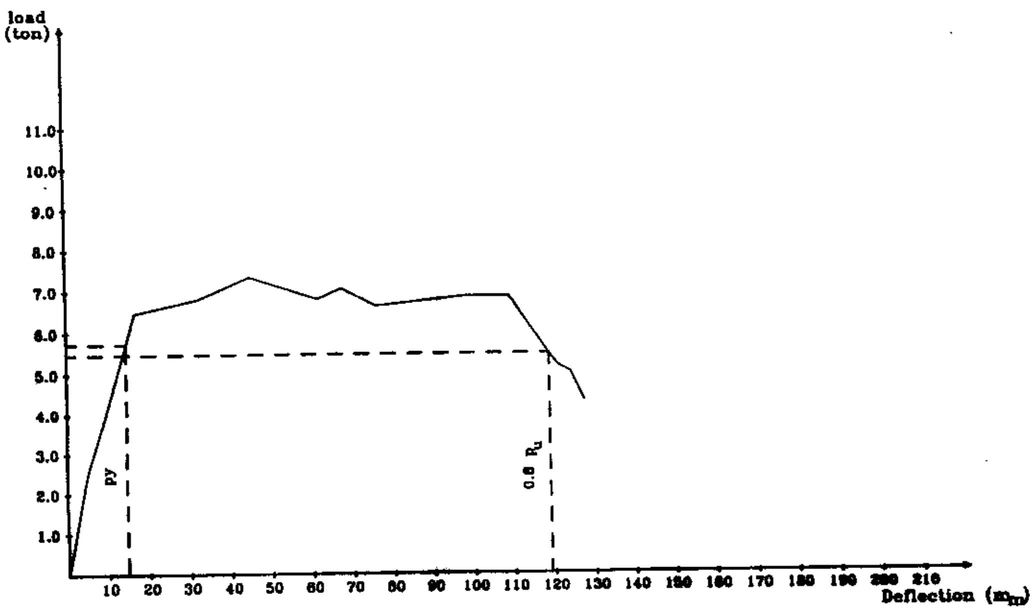

Fig.(7) Load- Deflection Curve For Beam B 6

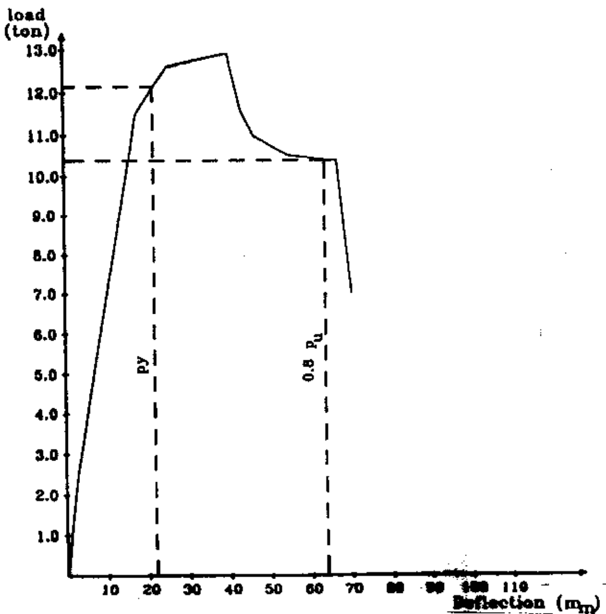

Fig.(8) Load- Deflection Curve For Beam B 7

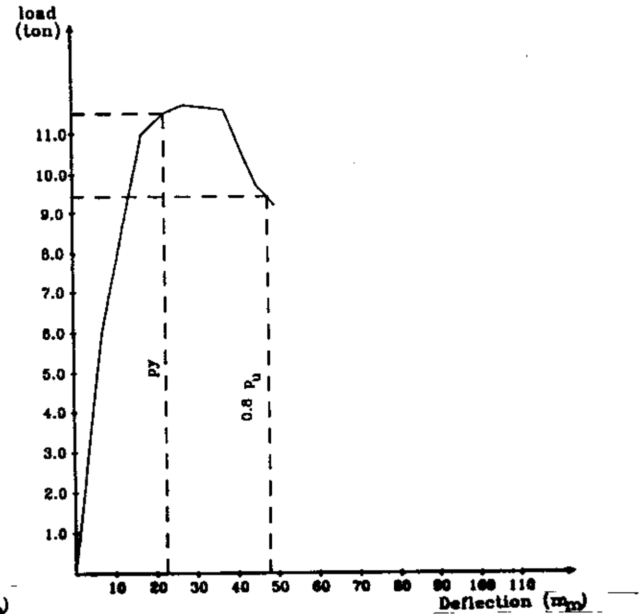

Fig.(9) Load- Deflection Curve For Beam B 8

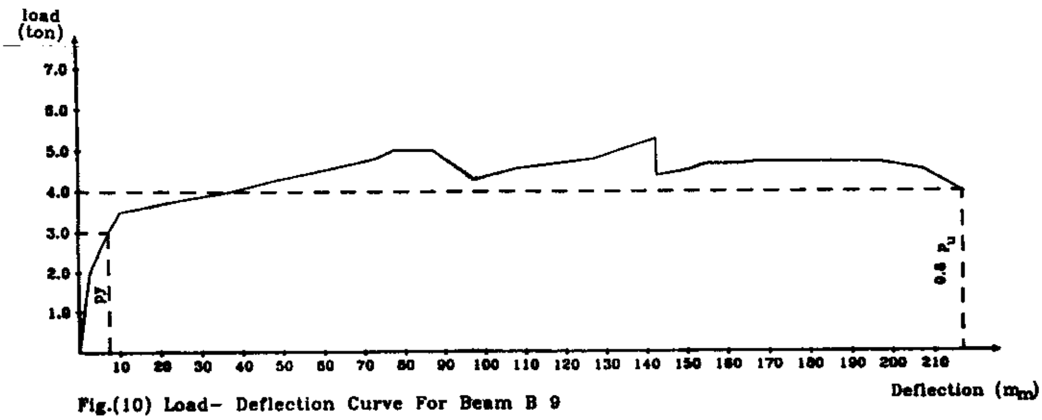

Fig.(10) Load- Deflection Curve For Beam B 9

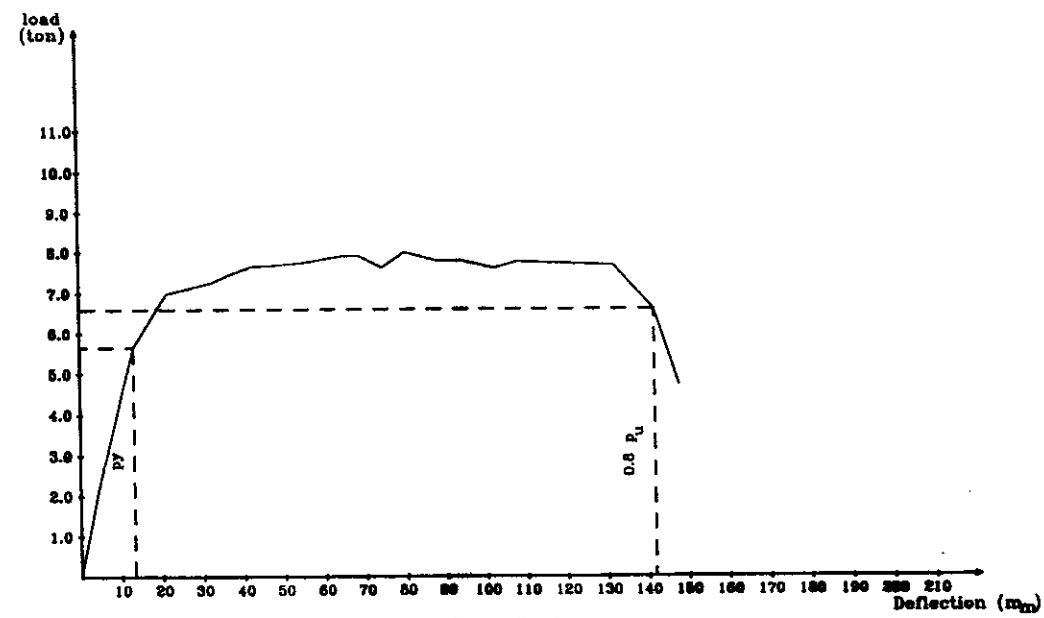

Fig.(11) Load- Deflection Curve For Beam B 10

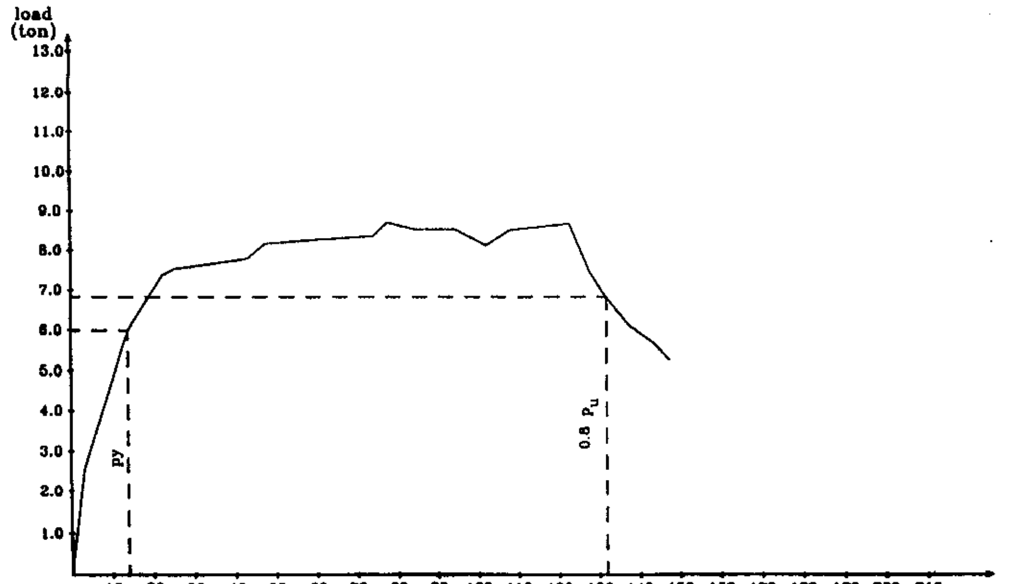

Fig.(12) Load- Deflection Curve For Beam B11

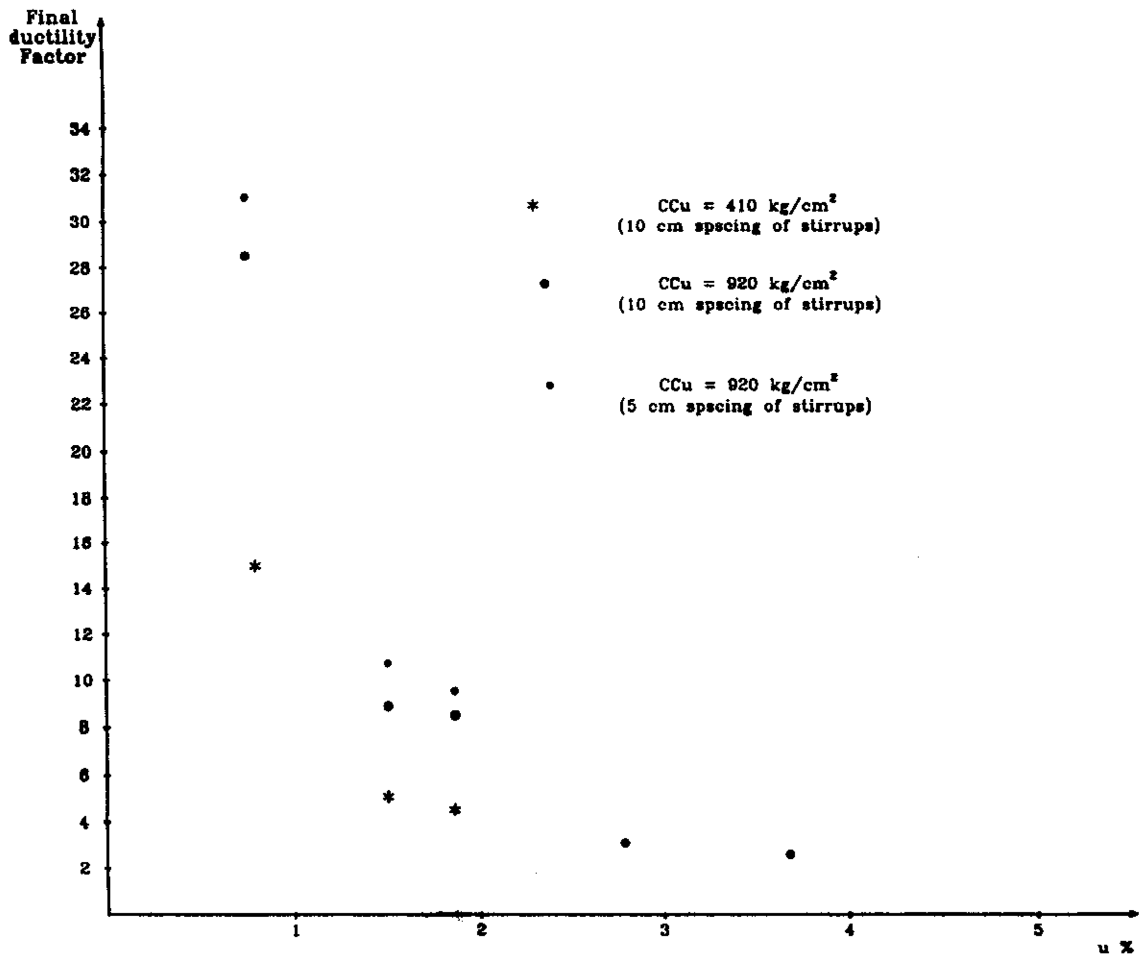

Fig.(13) Final ductility factor versuss percentage of tensile steel.

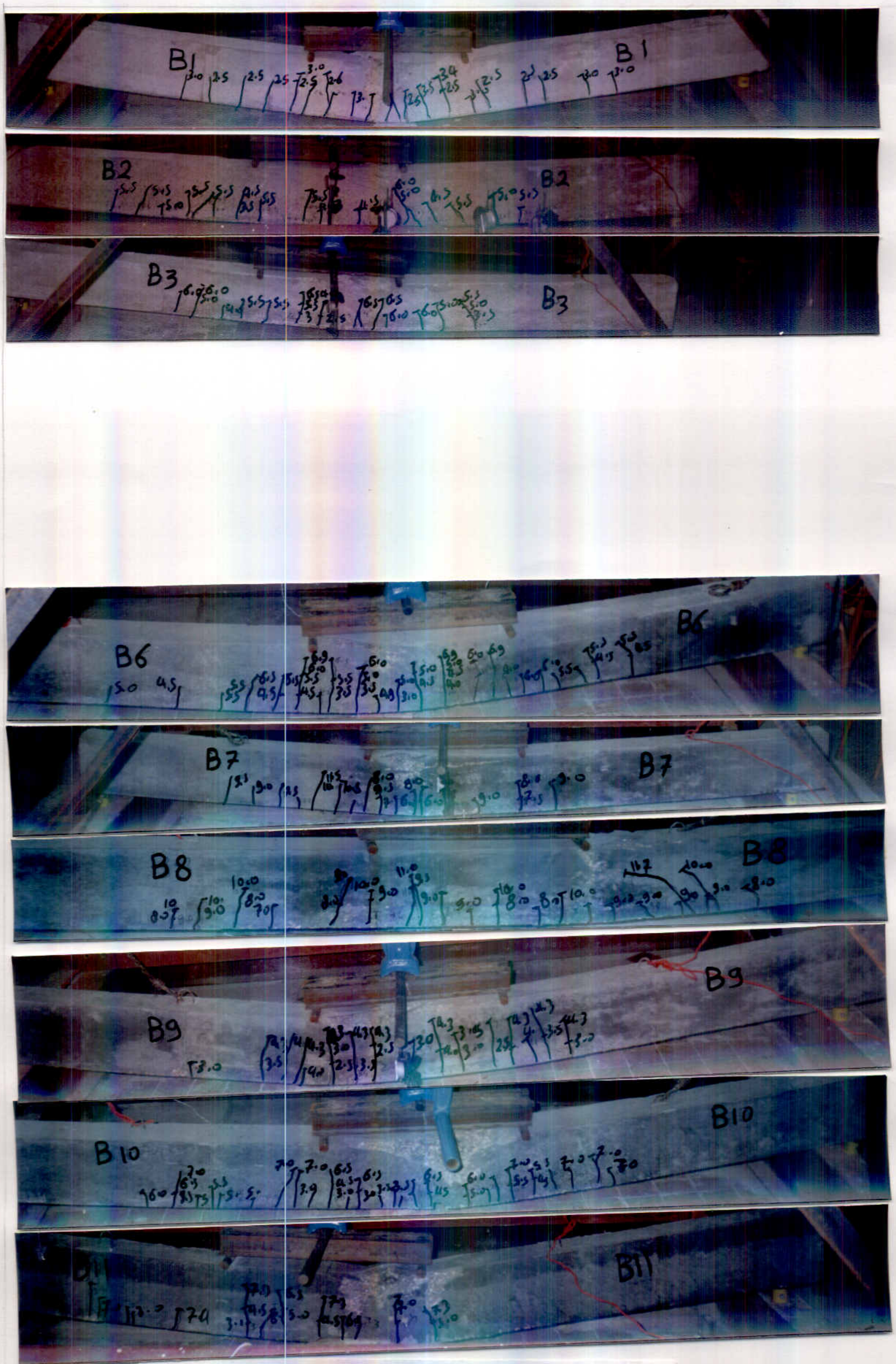

Fig. (14) Crack-Pattern of tested beams

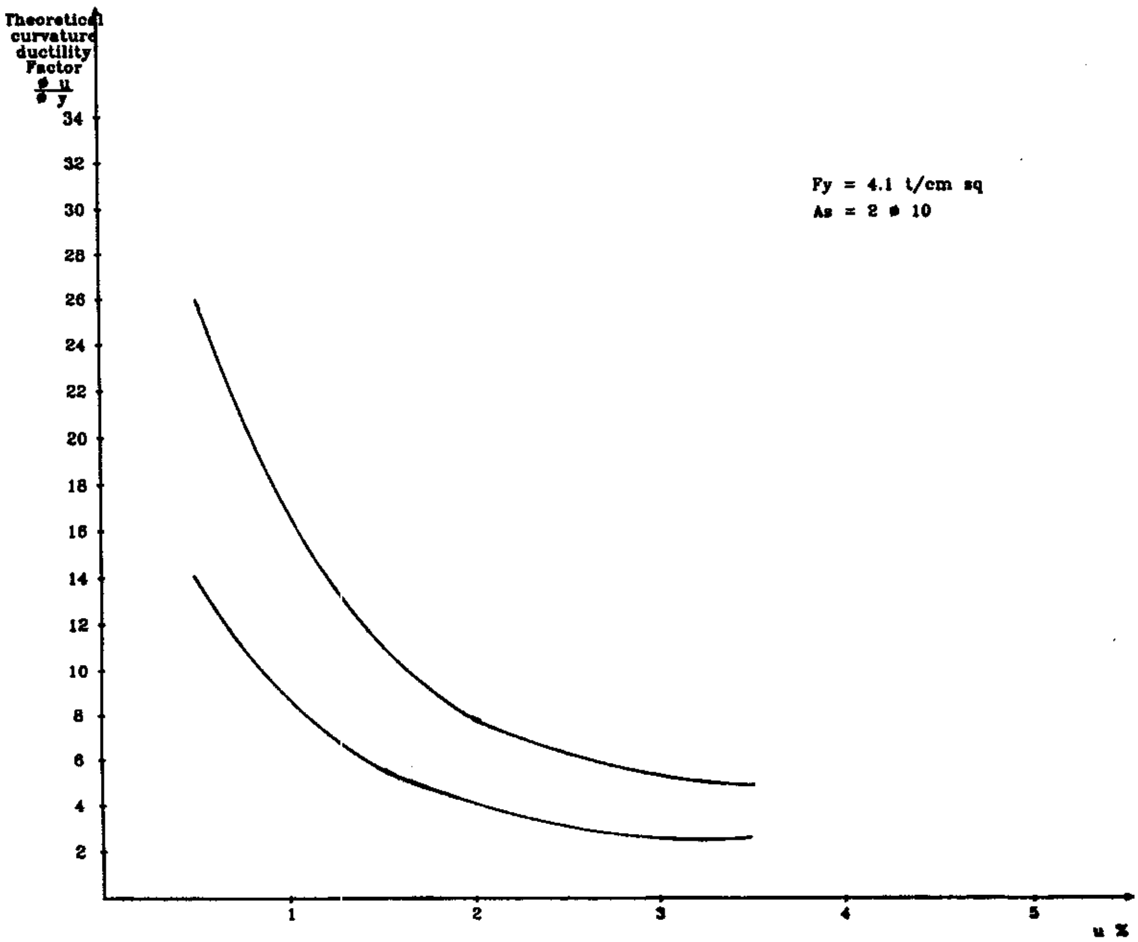

Fig.(15) Theoretical curvature ductility factor versus percentage of tensile steel.