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Effect of the distribution of negative steel reinforcement on the behavior of RC continuous beams

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This paper presents results from an experimental study including testing nine reinforced concrete continuous beams. The main objective of the study is to investigate the effect of the distribution of negative steel reinforcement on the behavior of such beams. Firstly, three two-span continuous beams having rectangular cross-sections were considered. Three different negative steel reinforcement ratios were chosen for the three beams, which are 1.5, 1.0 and 0.47 times the positive steel reinforcement. Secondly, another three two- span continuous beams were considered having T-cross-sections with a slab width of the beam width plus six times the slab thickness. However, the reinforcement of these beams was the same as the three rectangular beams. Furthermore, another beam was considered having a T-cross-section and a negative reinforcement of 1.5 times the positive reinforcement. However, the negative reinforcement for this beam was uniformly distributed within the slab width. Finally, two continuous beams were considered having T-cross-sections, with a slab width of the beam width plus four times the slab thickness. It was found that the effect of increasing the negative steel reinforcement is not proportional to the increase in the overall strength of the beam for beams having either rectangular or T-cross-sections. As the negative steel reinforcement was increased to 1.5 times the positive steel reinforcement, the corresponding increase in the beam strength was only around 10%. Test results revealed that the negative steel reinforcement, in beams having T-cross-sections, either placed lumped or distributed within the slab width gave nearly the same strength. However, the case of distributed steel resulted in enhanced beam ductility. Also, it was found that beams having T-cross-sections had an overall strength much more than those with rectangular section for all cases of negative reinforcement distribution.

يعرض هذا البحث نتائج دراسة معملية تضمنت إختبار تسع كمرات خرسانية مسلحة مستمرة. كان الهدف الرئيسى لهذا البحث هو دراسة تأثير طريقة توزيع حديد التسليح السالب على سلوك هذه الكمرات. أولاً تم إختبار ثلاث كمرات خرسانية مسلحة مستمرة ذات قطاع مستطيل. تم إختيار ثلاث نسب لحديد التسليح السالب لهذه الكمرات وهو ١,٥، ١,٠، و٠,٤٧ مرة حديد التسليح الموجب. ثانياً تم إختبار ثلاث كمرات أخرى ولكن ذات قطاع على شكل حرف (T) وقد كان عرض البلاطة لهذه الكمرات مساوياً لعرض الكمرة بالإضافة إلى ستة مرات سمك البلاطة وتم تزويد هذه الكمرات بحديد تسليح موجب وسالب مثل الكمرات الثلاث الأولى تماماً. بالإضافة إلى ذلك تم إختبار كمرة أخرى ذات قطاع على شكل حرف (T) وتحتوى على حديد تسليح سالب مساوياً لـ ١,٥ مرة حديد التسليح الموجب ولكن فى هذه الحالة تم توزيع حديد التسليح السالب بالتساوى على كامل عرض البلاطة. أخيراً تم إختبار كمرتين أخرتين ذات قطاع على شكل حرف (T) ولكن كان عرض البلاطة بالنسبة لتلك الكمرتين مساوياً لعرض الكمرة بالإضافة إلى اربعة مرات سمك البلاطة. أوضحت النتائج أن تأثير زيادة نسبة حديد التسليح السالب لايتناسب مع الزيادة فى حمولة الكمرات سواء كانت ذات قطاع مستطيل أو ذات قطاع على شكل حرف (T). وقد أوضحت النتائج أيضاً أنه عند زيادة حديد التسليح السالب إلى ١,٥ مرة حديد التسليح الموجب كانت الزيادة فى حمولة الكمرة حوالى ١٠%. أيضاً تبين أن حديد التسليح السالب فى حالة الكمرات ذات قطاع على شكل حرف (T) سواء تم تركيزه فى منطقة عرض الكمرة أو تم توزيعه بالتساوى على كامل عرض البلاطة يؤدي الي نفس الحمولة. علي الرغم من ذلك فانه في حالة توزيع حديد التسليح السالب بالتساوي علي كامل عرض البلاطه فإن ذلك يؤدى إلى تحسن فى ليونة الكمرة. كذلك وجد أن حمولة الكمرات ذات قطاع على شكل حرف (T) أعلى من تلك الكمرات ذات قطاع مستطيل وذلك لجميع حالات توزيع حديد التسليح السالب.

Keywords: Behavior, Continuous beams, Ductility, Negative steel reinforcement, Reinforced concrete, Strength

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1. Introduction

Reinforced concrete flexural members such as girders and beams usually support a slab that is built integrally with their stems. Hence, they behave as if their sections were T-shaped [1]. When these members are subjected to positive bending moments, the existence of the slab part at the compression side enhances both cracking and post-cracking strength. On the contrary, when such members are subjected to negative bending moments, an enhancement in the cracking strength is only observed. However, in continuous spans, the existence of the slab part increases the rotational capacities at the positions of the plastic hinges forming at the locations of maximum positive and negative bending moments allowing more redistribution between them.

The bending moments in a continuous beam can be prescribed using a linear-elastic analysis, provided that the load level is such that the elastic limit is not exceeded in any of the constituent materials. When the elastic limit is exceeded, at any particular load level, the bending moments in the beam will likely differ from those predicted by a linear –elastic analysis. The difference for a particular load level between the actual moment at a section and that determined by a linear –elastic analysis is referred to as redistribution of moment [2]. The problem of moment redistribution in continuous reinforced concrete beams has long been of interest to researchers. With the introduction of plastic section design it was realized that inelastic beam behavior should be considered in the analysis and that such consideration could lead to economic benefits. A continuous reinforced concrete beam, entirely designed to elastic analysis, would be reinforced to suit the elastic moment envelope. However, considering inelastic beam behavior, peak moments of such an elastic envelope could be redistributed without detriment to the beam-carrying capacity [3]. The plastic rotation of reinforced concrete members can be estimated on the basis of the distribution of the mean curvature along the plastic zone. In this case as well, it is necessary to take into account several aspects of structural behavior that have not yet fully explained: the performance of concrete in compression, in particular, the effect of the section size on the ultimate strain (scale effect); the bond between steel and the concrete when the steel is in the plastic range (tension stiffening effect); and influence of shear [4].

The calculation of the slab contribution in practical design usually means the effective slab width conventionally used in estimating the flexural capacities of beams under sagging moments. Design for hogging moments is generally considered simpler because in this case the presence of slabs is conventionally ignored [5]. However the presence of slabs may play a vital role in the seismic response of reinforced concrete frame structures [6-11]. Through simulated cyclic load reversals applied on single or continuous slab-beam-column subassemblies, it was demonstrated that the slab, through diaphragms action, is primarily responsible for the three-dimensional characteristics of frame response under lateral loads. Most dramatic was the degree of participation measured when the slab was in the tension zone of the beam section, that is on the side where it was traditional design practice to consider slab effects negligible [5].

With respect to Code Provisions, the Egyptian code of Practice for construction and design of reinforced concrete structures [12] recommends that if the flanged part of the section is located at the tension side, part of the tension steel reinforcement but not more than one-third of such reinforcement may be distributed within the flange width or width equal to one-tenth the clear span of the beam whichever is smaller provided that an enough lateral steel reinforcement is placed to transmit the shear forces arised from the steel reinforcement located outside the web of the beam . In ACI code provisions [13], a similar recommendation for the distribution of the tension steel reinforcement along the flanged part of the section when located at the tension side is given. However, the ACI code recommends that if the flange width exceeds one-tenth the span of the beam, additional longitudinal steel reinforcement shall be provided in the outer portions of the flange. The British Standards [14] does not present any recommendations regarding the distribution of negative steel reinforcement within the flange width but the code recommends a minimum steel reinforcement to be provided when the flange is located at the tension side. Such minimum steel reinforcement is 1.5 to 2 times that of the case when the web is located at the tension side for the ratio of web width to flange width less than and greater than or equal 0.4, respectively.

In this paper, a detailed experimental investigation was conducted including fabrication, instrumentation, and testing nine reinforced concrete two-span continuous beams. The main objectives of the experimental investigation were: (i) to study the effect of varying the amount of negative steel reinforcement on the behavior of reinforced concrete continuous beams; (ii) to investigate the contribution of the slab part of beams having T-cross-sections with different slab widths; and (iii) to study the possibility of the uniform distribution of the negative steel reinforcement within the effective slab width of beams having T-cross-sections.

2. Experimental study

2.1. Test beams

The experimental program included testing nine reinforced concrete two-span continuous beams. The span length for all tested beams was 1700 mm. Three tested beams B1, B2 and B3 had a rectangular cross section of 120 mm width and 250 mm height. Four tested beams B4, B5, B6 and B7 had cross section of T-shape with web width 120 mm and total height of 250 mm. The slab thickness was 50 mm and the slab width was 420 mm. Tested beams B8 and B9 had also cross section of T-shape as the previous ones. However, their slab width was 320 mm.

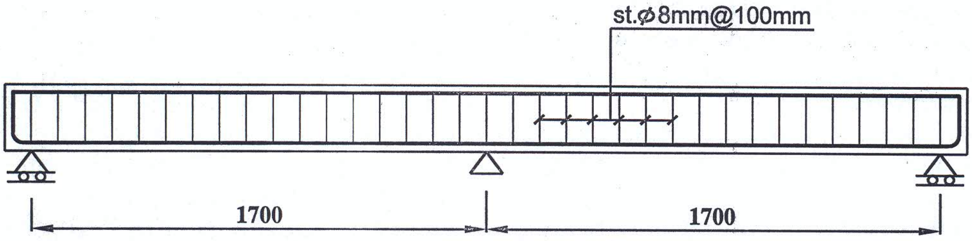
All tested beams were provided with bottom positive reinforcement consisting of two bars diameter 12 mm high tensile steel. However, the top negative reinforcement was varied from a beam to another as follows: (i) tested beams B1, B4 and B8 were provided with three bars diameter 12 mm high tensile steel along their web width; (ii) in the case of tested beam B7, such top negative reinforcement was replaced by ten bars diameter 8 mm mild steel distributed within the slab width of the cross section; (iii) tested beams B2 and B5 were provided with two bars diameter 12 mm high tensile steel within their web width; and (iv) tested beams B3, B6 and B9 were provided with two bars diameter 10 mm high tensile steel within their web width. For all tested beams of T-shape, the slab part was reinforced with 6 mm diameter ordinary mild steel spaced at 100 mm and fixed with longitudinal bars of the same 6 mm diameters at corners and mid of the flange arms at each side. To ensure flexural failure rather than shear failure, all tested beams were provided with vertical stirrups of diameter 8 mm mild steel at a spacing 100 mm. Fig. 1 shows the dimensions and reinforcement details for all tested beams.

2.2. Materials

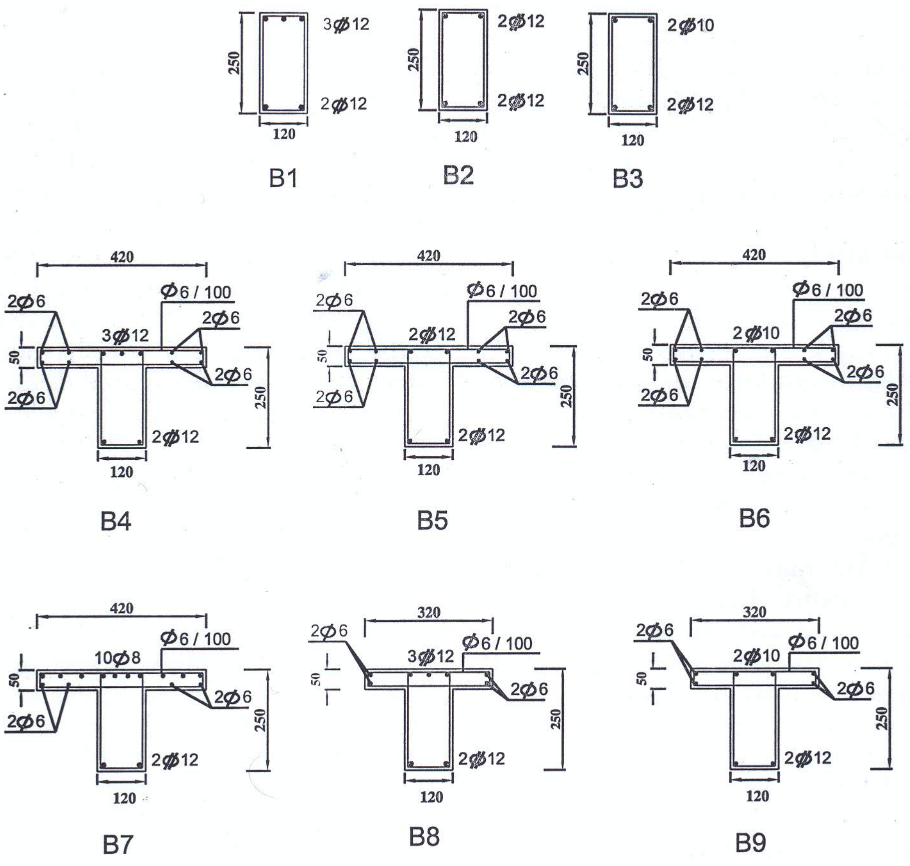
The concrete mix used for casting all tested beams was made using ordinary Portland cement, natural sand, and gravel having a maximum size of 25 mm. The mix proportions were 1.0: 1.48: 2.95, respectively by weight. The water cement ratio w/c was kept in the range of 0.5. The average concrete cube compressive strength was 35 MPa. The steel bars used for tested beams longitudinal reinforcement were high tensile steel (diameter 12 mm and 10 mm) and the steel used for the stirrups and the negative reinforcement of beam B7 was ordinary mild steel 8 mm diameter. The yield stress and the ultimate strength were 380 MPa and 600 MPa for diameter 12 mm, respectively and the yield stress and the ultimate strength were 390 MPa and 580 MPa for diameter 10 mm, respectively. The yield stress and the ultimate strength of mild steel bars of 8 mm diameter were 250 MPa and 400 MPa, respectively and the yield stress and the ultimate strength of mild steel bars of 6 mm diameter were 240 MPa and 400 MPa, respectively.

2.3. Loading setup and instrumentation

All beams considered in the experimental study were tested to failure under the effect of two concentrated loads as shown in fig. 2. The load was applied using a hydraulic jack of



(a) Typical Steel Arrangements in Longitudinal Direction



(b) Cross sections and reinforcement of tested beams

Fig. 1. Dimensions and reinforcement details of tested beams.

500 kN capacity and was transmitted to the beam by means of distributing steel beam. The load was monitored using an electrical load cell. Deflections of tested beams were measured at the mid-span locations by means of mechanical dial gauges. Electrical strain gauges of 10 mm gauge length were used to measure the strain in the longitudinal bottom and top flexural reinforcement at mid- span and support locations. Fig. 2 shows the loading setup and instrumentations for all tested beams.

3. Test results and discussions

The choice of the nine reinforced concrete two-span continuous beams which were included in the current experimental program aimed to achieve many objectives through detailed comparisons of the behavior of these beams. For example, tested beams B1, B2, and B3 revealed the effect of varying the amount of negative steel reinforcement on the behavior of continuous beams having rectangular cross sections. Also, tested beams B4, B5, B6, B8, and B9 revealed the effects of varying the amount of negative steel reinforcement and slab width on the behavior of continuous beams having T-cross-sections. Furthermore, tested beam B7 revealed the possibility of distributing the negative steel reinforcement within the effective slab width rather than lumping it within the web width. The behavior of all tested beams will be discussed in the following sections. Necessary comparisons will be made between different beams in order to achieve the objectives of this study. The experimental results for all tested beams are summarized in table 1. The experimental results included negative cracking loads, positive cracking loads, ultimate failure loads, and modes of failure. Figs. 3 and 4 show cracking patterns for tested rectangular beams and those having T-cross-sections, respectively. Figs. 5 and 6 show load-deflection relationships for all tested beams measured at mid right span and mid left span, respectively. Figs. 7- 9 show load-steel strain relationships measured at mid left span, mid right span, and at the support, respectively. Figs. 10- 13 show load-steel strain relationships for tested beams B1, B2, B4, and B5, respectively. Fig. 14 presents the effect of negative steel reinforcement distribution on the load-strain relationships.

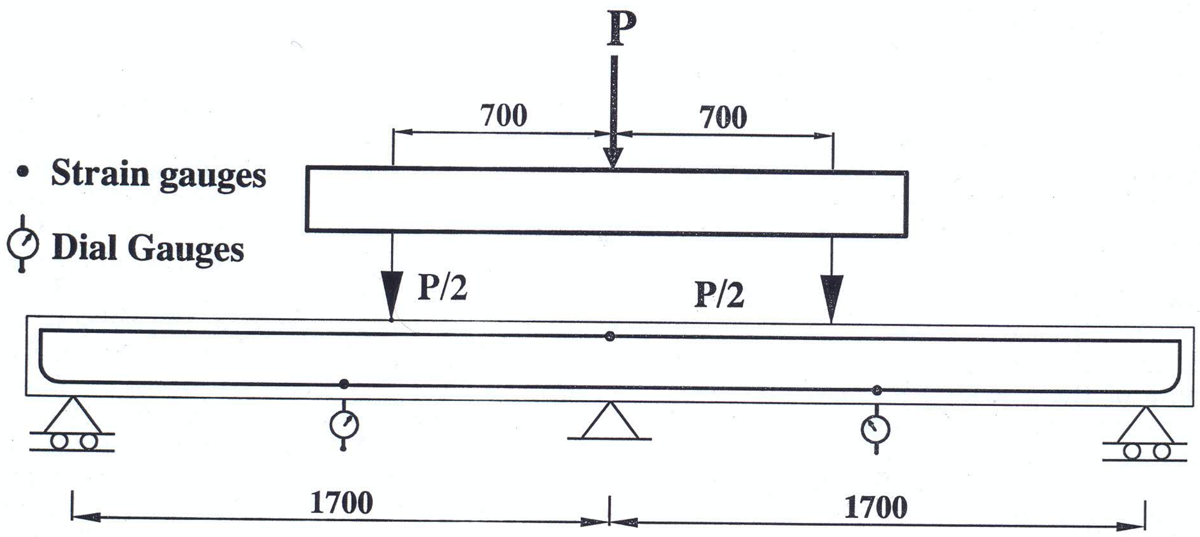


Fig. 2. Loading set-up and instrumentation of tested beams.

Table 1
Test results

Beam number	Cross section type	First negative cracking load (kN)	First positive cracking load (kN)	Ultimate load (kN)	Mode of failure
B1	Rectangular	40	60	205	Flexure
B2	Rectangular	35	55	190	Flexure
B3	Rectangular	30	50	175	Flexure
B4	T-Section	80	70	280	Flexure
B5	T-Section	75	65	260	Flexure
B6	T-Section	70	60	240	Flexure
B7	T-Section	80	65	270	Flexure
B8	T-Section	70	65	255	Flexure
B9	T-Section	65	60	220	Flexure

3.1. Cracking patterns and ultimate strength

Different cracking patterns were observed for different beams according to beam's cross section shapes and the change in the amount of negative steel reinforcement. For tested beams having rectangular cross sections B1, B2 and B3, the first flexural crack was observed at the position of maximum negative bending moment at the middle support and was followed by a positive flexural crack under the position of the concentrated load at each span at higher level of loading. For tested beam B1, the first negative flexural crack was observed at a total load of 40 kN whereas the positive flexural crack was observed at a total load of 60 kN. For tested beam B2, the first negative flexural crack was observed at a total load of 35 kN whereas the positive flexural crack was observed at a total load of 55 kN. For tested beam B3, the first negative flexural crack was observed at a total load of 30 kN whereas the positive flexural crack was observed at a total load of 50 kN. Comparing the results of the cracking strength of those beams revealed that the negative cracking strength was improved by about 17% and 33% whereas the enhancement in the positive cracking strength was 10% and 20% when the negative steel reinforcement was increased by about 43% and 115%, respectively. Different observations were found for tested beams provided with flanged slab of thickness 50 mm and width of 420 mm including the beam web width, (tested beams B4 to B7). In this case the first flexural crack was observed at the position of the maximum positive bending moment under the concentrated load at each span and was then followed by the negative flexural crack at the position of middle support at higher range of loading. The first positive cracks for those beams were observed at total load of 70 kN, 65 kN, 60 kN and 65 kN whereas the first negative cracks were observed at total load of 80 kN, 75 kN, 70 kN, and 80 kN for tested beams B4, B5, B6 and B7 respectively.

Comparing the results of cracking strength of beams B4, B5, and B6 revealed that the negative cracking strength was improved by about 7% and 12.5% whereas the enhancement in the positive cracking strength was 8% and 16.7% when the negative steel reinforcement increased by about 43% and 115%, respectively. It should be noted that the enhancement in the cracking strength as a result of increasing the negative steel reinforcement was much more significant in the case of rectangular beams than that in the case of beams having T-cross-sections. Also, in the case of rectangular beams the negative cracking strength was much more affected by the change in the amount of negative steel reinforcement than the positive cracking strength. However, in the case of beams having T-cross-sections, the positive cracking strength was much more sensitive to a change in the amount of negative steel reinforcement than the negative cracking strength. Furthermore, a comparison between cracking loads for the rectangular beams B1, B2, and B3 to those for the corresponding beams having T-cross-sections B4, B5, and B6 showed a significant enhancement in the negative cracking load in the case of beams having T-cross-sections as a result of the existence of the flanged slab. Much less enhancement in the positive cracking load was observed as a result of the existence of the flanged slab. Moreover, one of the main objectives of this study was to check the possibility of the distribution of the negative steel of the beam within the slab width. This was achieved when comparing the results of beam B4 with lumped negative steel with those of beam B7 having the same amount of negative steel but distributed within the slab width. Results for cracking loads supports the possibility of distributing the negative steel reinforcement along the slab width since the cracking loads were almost the same for both beams B4 and B7.

Significant effects on the cracking loads were also observed when decreasing the flange width from 420 mm (beams B4 and B6) to 320 mm (beams B8 and B9). The negative cracking loads decreased from 80 kN and 70 kN for beams B4 and B6 to 70 kN and 65 kN for beams B8 and B9 representing about 12.5% and 7.1% decrease, respectively. Also, the positive cracking loads decreased from 70 kN for beam B4 to 65 kN for beam B8 representing about 7.1% decrease.

Beyond cracking of tested beams and as the applied load was increased, bands of cracks were formed at the positions of maximum positive and negative moments. The crack widths were observed and they were varied and alternated as the applied load was increased as a result of redistribution of forces between positive moment and negative moment zones. All tested beams either having rectangular cross-sections or having T-cross-sections failed in a flexural mode of failure. The cracking of concrete was observed at the compression sides at maximum positive and negative moment locations. Fig. 3 shows cracking patterns of all tested rectangular beams after failure. Fig. 4 shows cracking patterns for all tested beams having T-cross-sections after failure.

It can be observed from the results presented in table 1. That with the same positive steel reinforcement and as the negative steel reinforcement increases, the ultimate load capacity increases for all cases of beams having rectangular cross-sections or beams having T-cross-sections. In the case of rectangular beams B1, B2, and B3 the ultimate load was 205, 190, and 175 kN, respectively. Therefore, the enhancement in the ultimate load capacity was about 8.6% and 17.1% as a result of increasing the amount of negative steel reinforcement by 43% and 115%, respectively. Also, in the case of beams having T-cross-sections B4, B5, and B6 the ultimate load was 280, 260, and 240 kN, respectively. Therefore, the enhancement in the ultimate load was about 8.3% and 16.7% as a result of increasing the amount of negative steel reinforcement by 43% and 115%, respectively.

The effect of the presence of slab on the ultimate load can be detected when comparing rectangular beam B1, as an example, with beam B4 having T-cross-section. The ultimate load increased from 205 kN to 280 kN, representing about 36.6% enhancement in the ultimate load as a result of the presence of the slab. Furthermore, the effect of slab width on the ultimate load of beams having T-cross-sections can be detected when comparing the results of testing beams B4 and B6 (slab width = 420 mm.) to those of beams B8 and B9 (slab width= 320 mm.). The ultimate load decreased from 280 kn and 240 kN for beams B4 and B6 to 255 kN and 220 kN for beams B8 and B9, representing about 9.8% and 8.3% decrease as a result of the reduction in the slab width.

Moreover, in order to detect the effect of the distribution of negative steel reinforcement on the ultimate load of beams having T-cross-sections a comparison was made between beam B4 with lumped negative steel and beam B7 with distributed negative steel within the slab width. Marginal effect was observed which indicates that the slab reinforcement near to the beam section contributes to the negative steel reinforcement of the beam at the negative moment zone. Such contribution increases the negative moment capacity of the beam section.

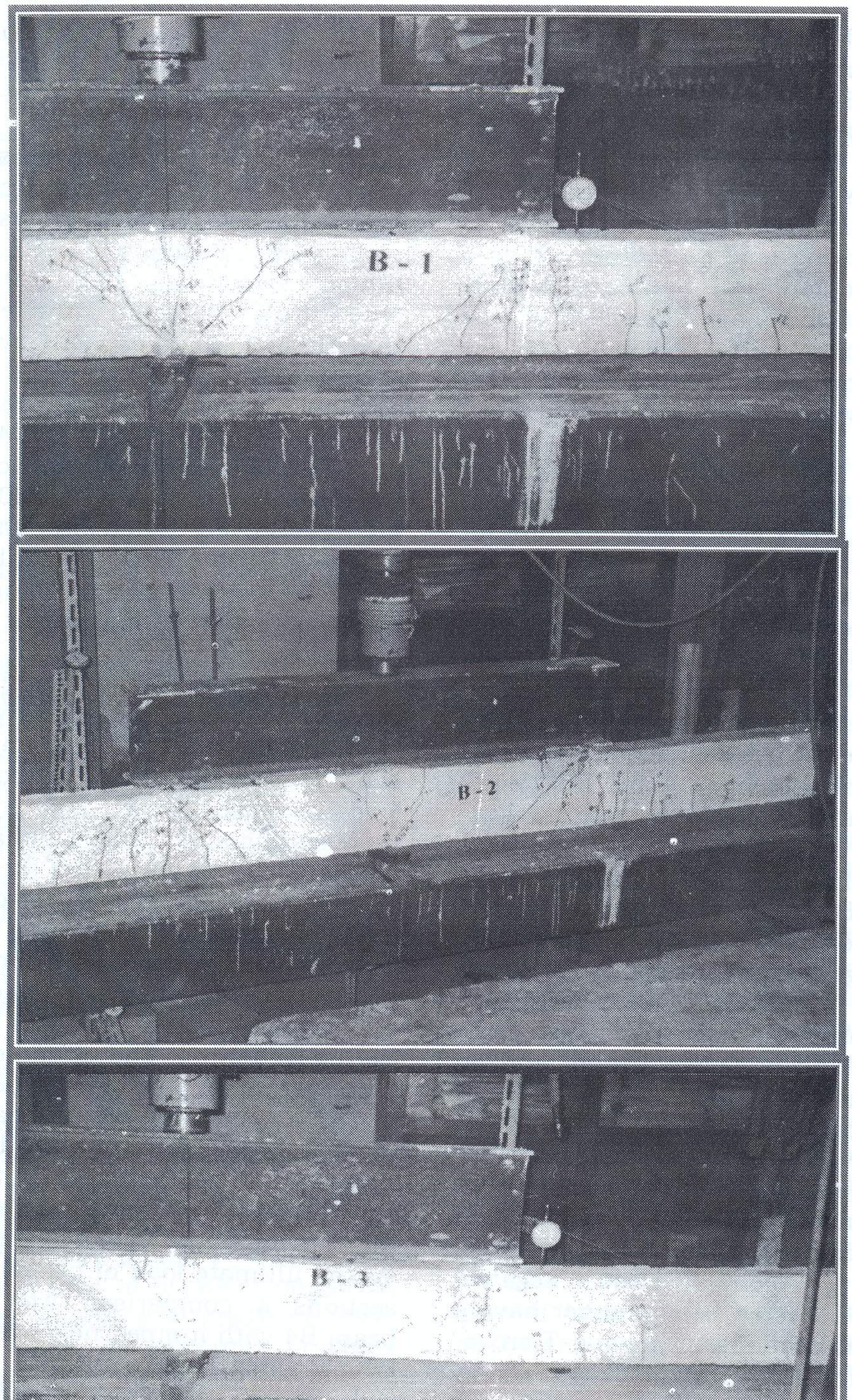


Fig. 3. Cracking patterns of tested rectangular beams after failure.

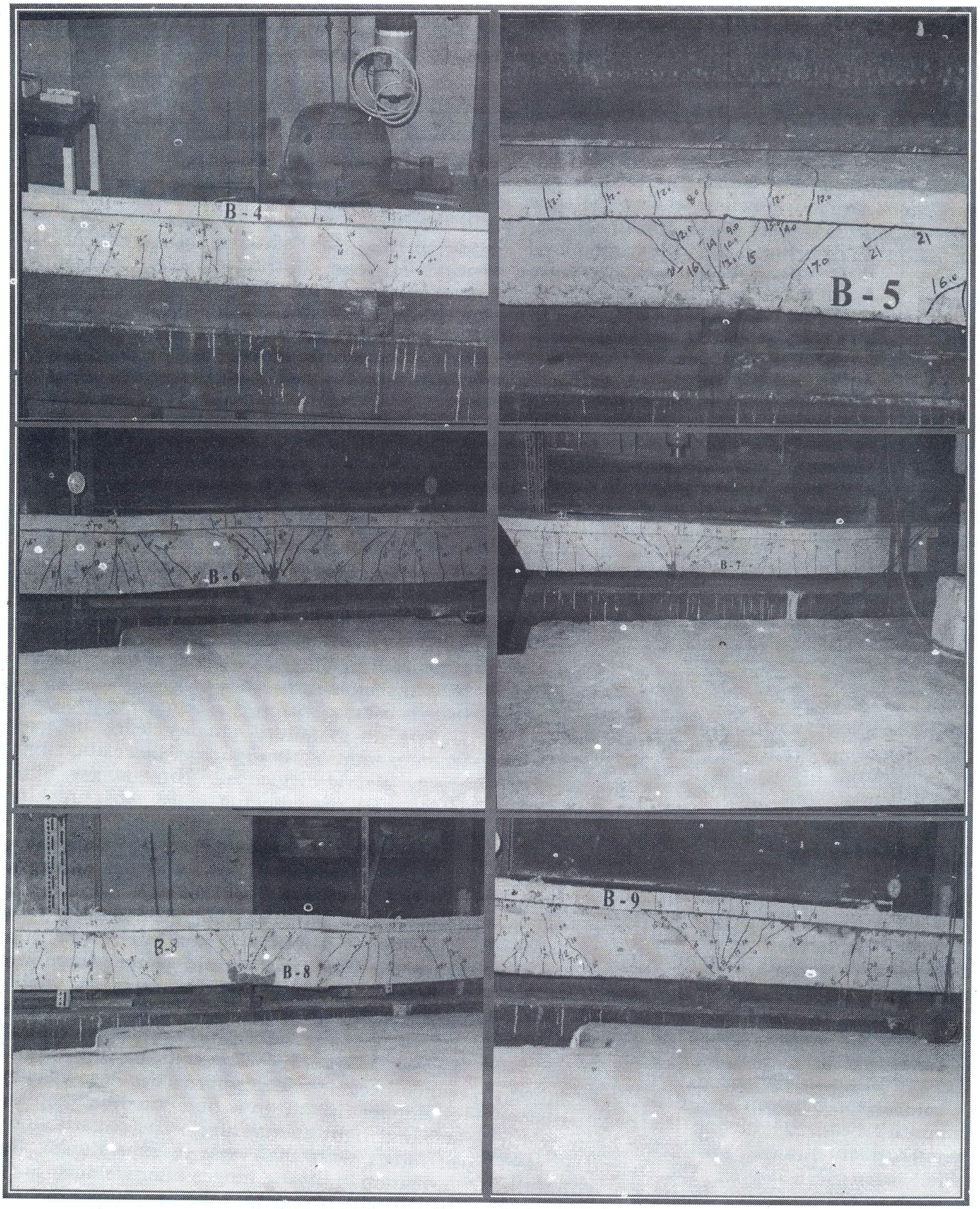


Fig. 4. Cracking patterns of tested beams having T-cross-sections after failure.

3.2. Deflections

Figs. 5 and 6 show load-mid span deflection relationships for all tested beams. Generally, load-deflection relationships for all tested beams were divided into two zones, linear zone followed by non-linear zone. Within the linear zone load-deflection relationships were similar for beams having the same cross-section. However, in the non-linear zone the effect of a change in the amount of negative steel reinforcement on the load-deflection relationships can be clearly detected. It can be observed from figs. 5 and 6 that as the amount of negative steel reinforcement decreases the deflection of beams increases. Such observation can be detected for rectangular beams when comparing load-deflection relationships for beams B1, B2, and B3, having different amounts of negative steel reinforcement. Also, the observation can be detected for beams having T-cross-sections when comparing load-deflection relationships for beams B4, B5, and B6. Also, the difference in the behavior of rectangular beams and beams having T-cross-sections can be observed from figs. 5 and 6. The presence of the slab in the case of beams having T-cross-sections results in a significant enhancement in the beam stiffness. Such enhancement in the beam stiffness which results in significant reduction in the beam deflection can be observed from figs. 5 and 6 when comparing load-deflection relationships for the rectangular beams B1, B2, and B3 with the corresponding beams having T-cross-sections B4, B5, and B6.

Furthermore, for beams having T-cross-sections it was found that as the width of the slab increases the enhancement in the beam stiffness significantly increases which results in reduced deflection. This can be clearly detected from figs. 5 and 6 when comparing load-deflection relationships for beams B4 and B6 (slab width = 420 mm.) to those for beams B8 and B9 (slab width = 320 mm.). Moreover, a comparison between load-deflection relationships for beam B4 having the negative steel reinforcement lumped within the beam width and beam B7 having the negative steel reinforcement uniformly distributed within the slab width revealed that the load-deflection relationships are nearly the same in the two cases. However, a significant enhancement in the beam ductility was observed in the case of beam B7 having distributed negative steel reinforcement.

The load-deflection behavior of tested beams indicates that the presence of the slab part in the case of beams having T-cross-sections results in a significant enhancement in the overall stiffness of the beam. Also, the presence of the slab reinforcement at the negative zones contributes with the negative steel reinforcement of the beam which results in a significant enhancement in both the beam overall stiffness and the ultimate strength. Regarding the practical situation, usually beams are provided with slabs. The presence of such slabs enhances the beam stiffness and ultimate strength of the beam.

3.3. Strains

Figs. 7 and 8 present load-strain relationships for the bottom flexural steel reinforcement for all tested beams, at mid left span and mid right span, respectively. Fig. 9 shows load-strain relationships for the top flexural reinforcement of tested beams at the support (position of maximum negative bending moment). The general behavior of tested beams within the complete range of loading up to failure can be clearly detected when examining the figures. The relationships can be clearly divided into three stages. Such stages are: pre-cracking stage; post-cracking stage; and post-yielding stage.

Fig. 9 shows the effect of changing the amount of negative steel reinforcement on the load-strain behavior of tested beams. It is clear from the figure that as the amount of negative steel reinforcement decreases, the corresponding steel strain values increase, which reflects an improvement in the global stiffness of the beam. Examining figs. 7 and 8 together, one can observe the redistribution of forces between positive and negative zones which becomes much more clear near yielding where positive strain is fluctuated between the left and right spans due to the redistribution of forces with the negative zone during the formation of plastic hinges after yielding. Such redistribution was affected by the presence of

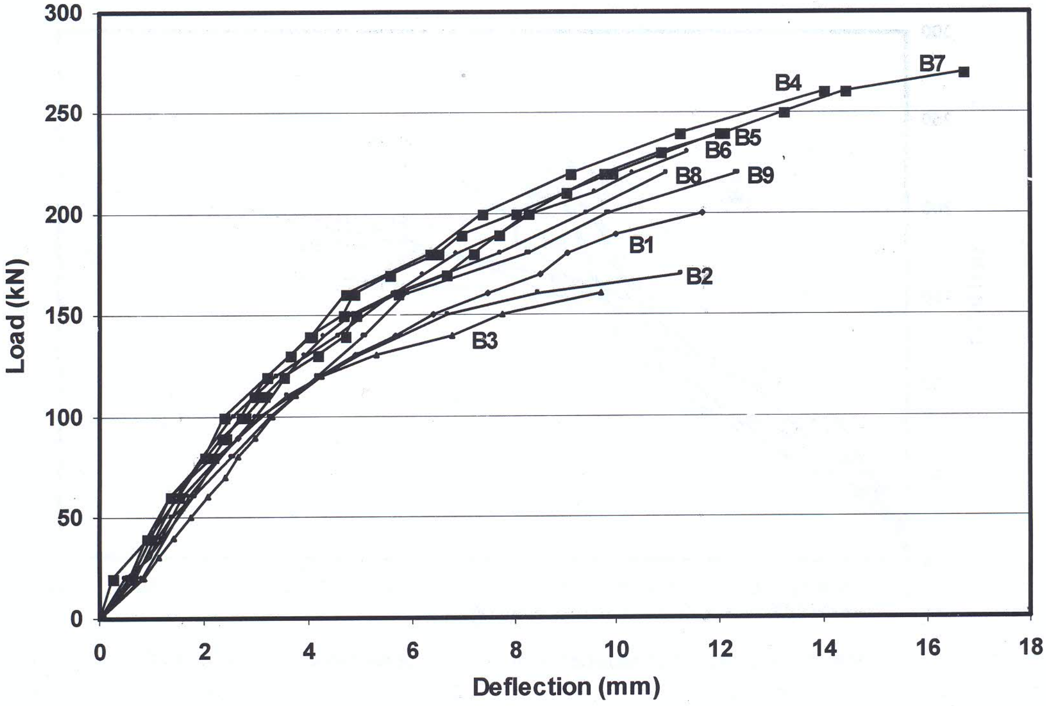


Fig. 5. Load-mid right span deflection relationships for all tested beams.

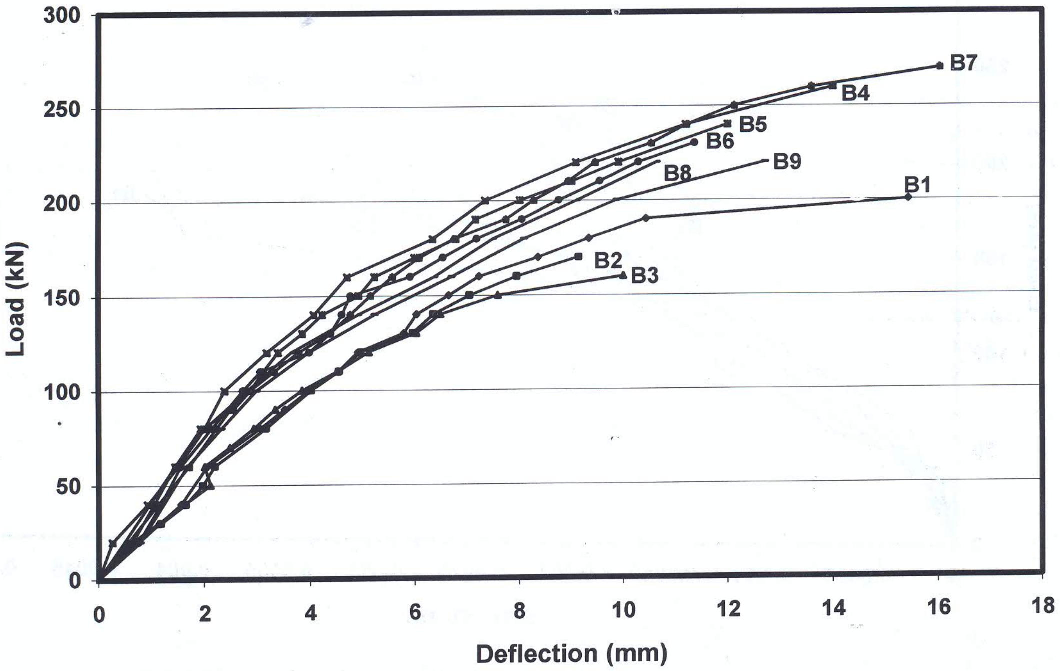


Fig. 6. Load-mid left span deflection relationships for all tested beams.

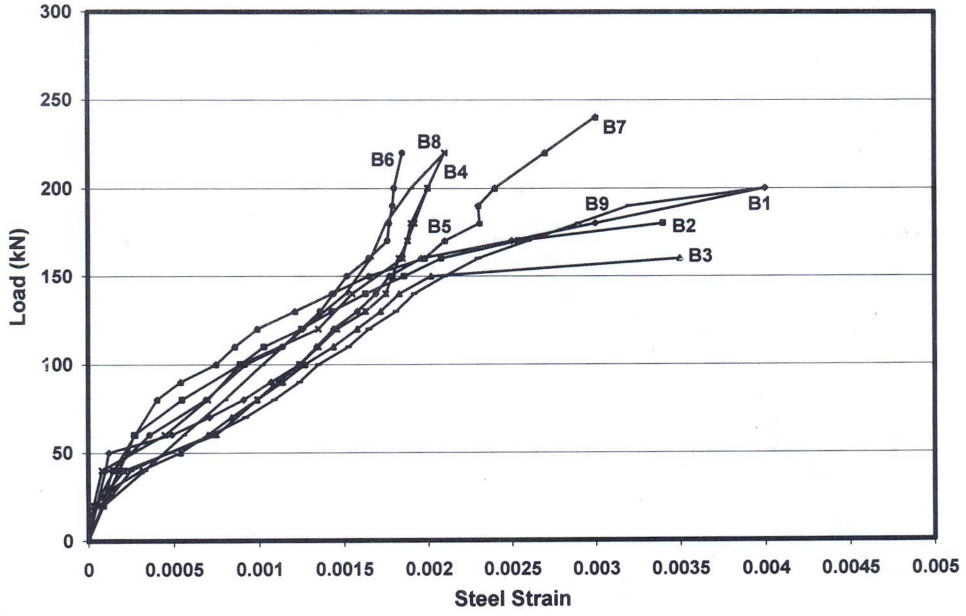


Fig. 7. Load-strain relationship at mid left span for all tested beams.

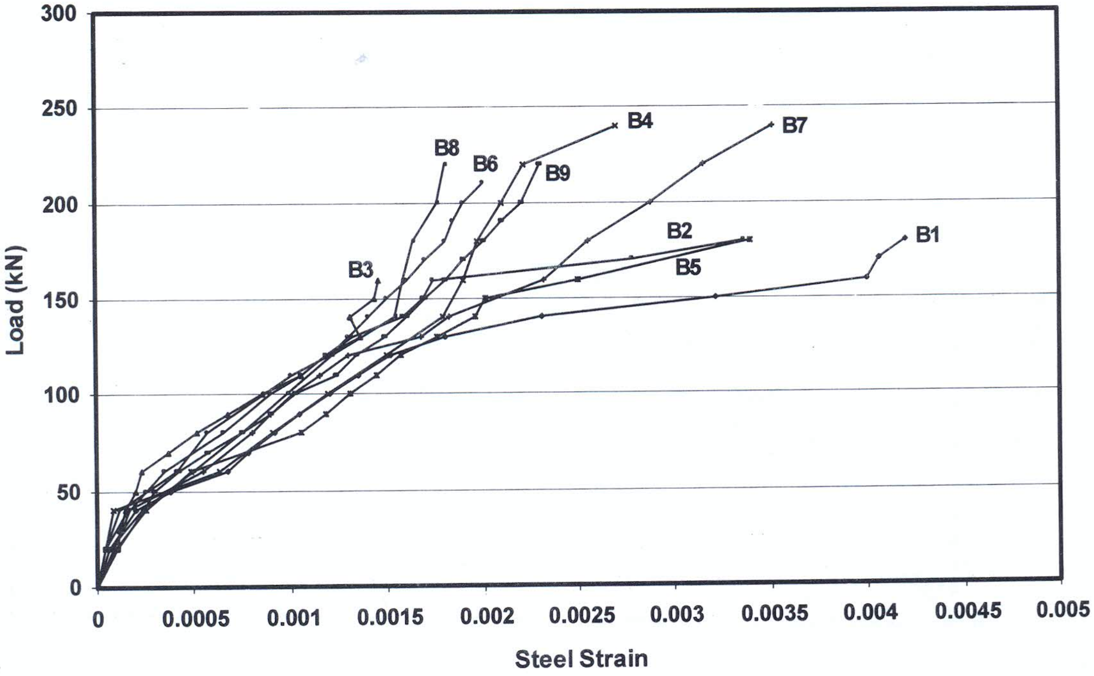


Fig. 8. Load-strain relationships at mid right span for all tested beams.

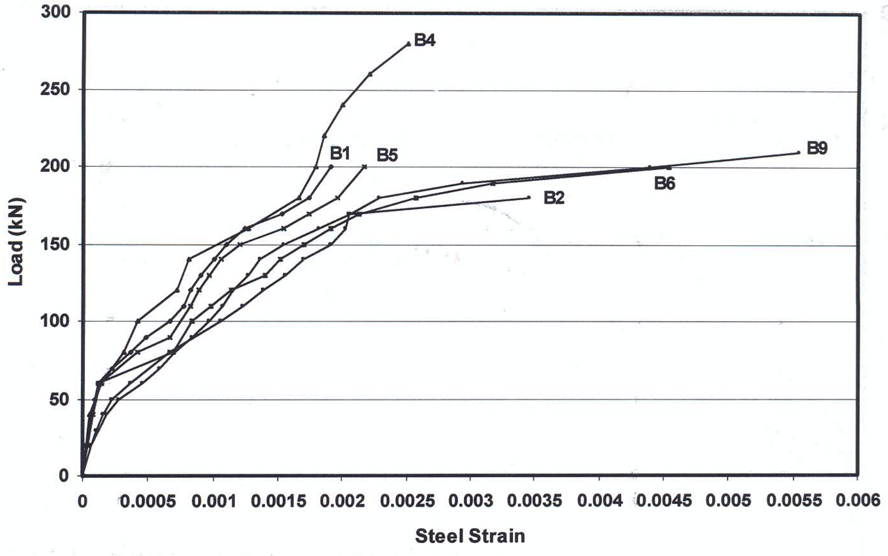


Fig. 9. Load-strain relationships at support for all tested beams.

flanged slab and the change in the amount of negative steel reinforcement.

Figs. 10 and 11 show load-strain relationships for rectangular beams B1 and B2, respectively. For beam B1 the negative steel reinforcement was 1.5 times the positive steel reinforcement. In this case, it is clear from fig. 10 that positive steel reinforcement showed higher strain values than negative steel reinforcement. Also, it is clear from the figure that the positive steel strain is fluctuated between the left and right spans at post yielding zone reflecting redistribution of forces between the two positive zones. For beam B2 the negative steel reinforcement was equal to the positive steel reinforcement in each span. In this case, the load-strain behavior of both positive and negative steel reinforcement was almost similar.

Figs. 12 and 13 present load-strain relationships for tested beams having T-cross-sections B4 and B5, respectively. Beam B4 had a negative steel reinforcement of 1.5 times the positive steel reinforcement whereas beam B5 had a negative steel reinforcement equal to the positive steel reinforcement. Comparing the load-strain relationships for beams B4 and B5 with those for the rectangular beams B1 and B2 revealed that the presence of slab part at the tension side for beams having T-cross-sections results in a noticeable reduction in the negative steel strain at the position of maximum negative bending moment. Such observation reflects the importance of the existence of such slab part even if it was located at the tension side in order to enhance and increase the potential energy of the plastic hinge formed at the support.

Fig. 14 shows load-strain relationships at the position of maximum positive bending moment at left span and right span for tested beams B4 and B7 in order to detect the effect of negative steel reinforcement distribution on the load-strain relationships. Beam B4 had the negative steel reinforcement lumped within the beam width, whereas beam B7 had the negative steel reinforcement uniformly distributed within the slab width. It can be observed from the figure that load-strain relationships are almost similar which supports the possibility of distributing the negative steel reinforcement within the slab width. Furthermore, it can be concluded that the slab reinforcement within the effective part, up to the beam width plus six times the slab thickness, will contribute to the negative steel reinforcement of the beam and leads to a higher negative moment capacity for the beam. Fig. 14 also shows that for beam B7 having the negative steel reinforcement uniformly distributed within the slab width a more ductile behavior was observed than that for beam B4 having the negative steel reinforcement lumped within the beam width.

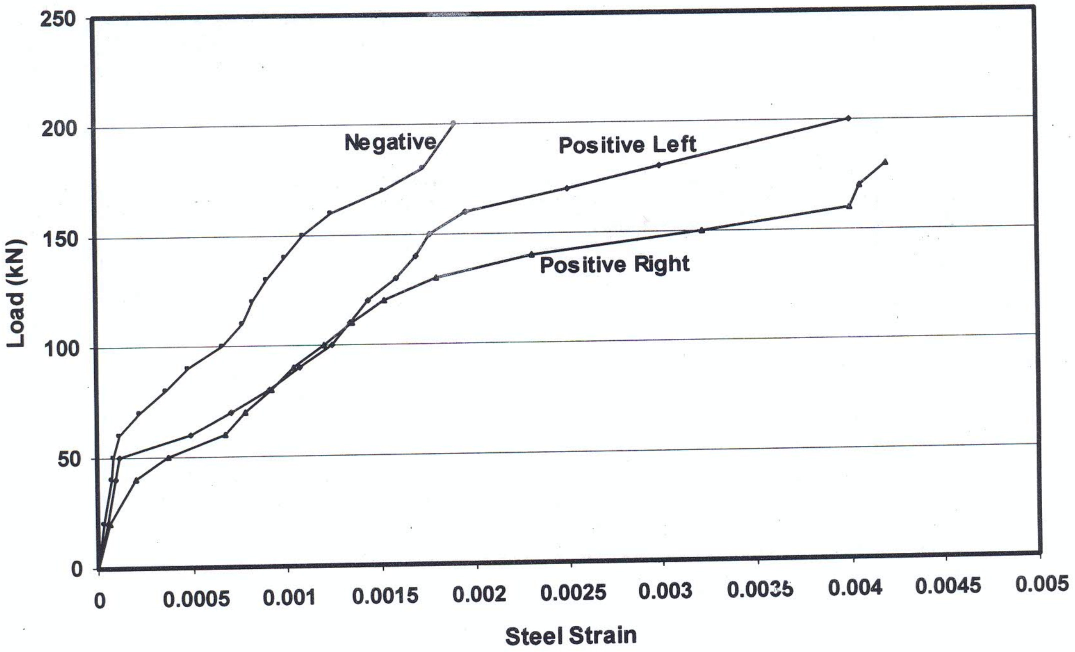


Fig. 10. Load-strain relationships for tested beam (B-1).

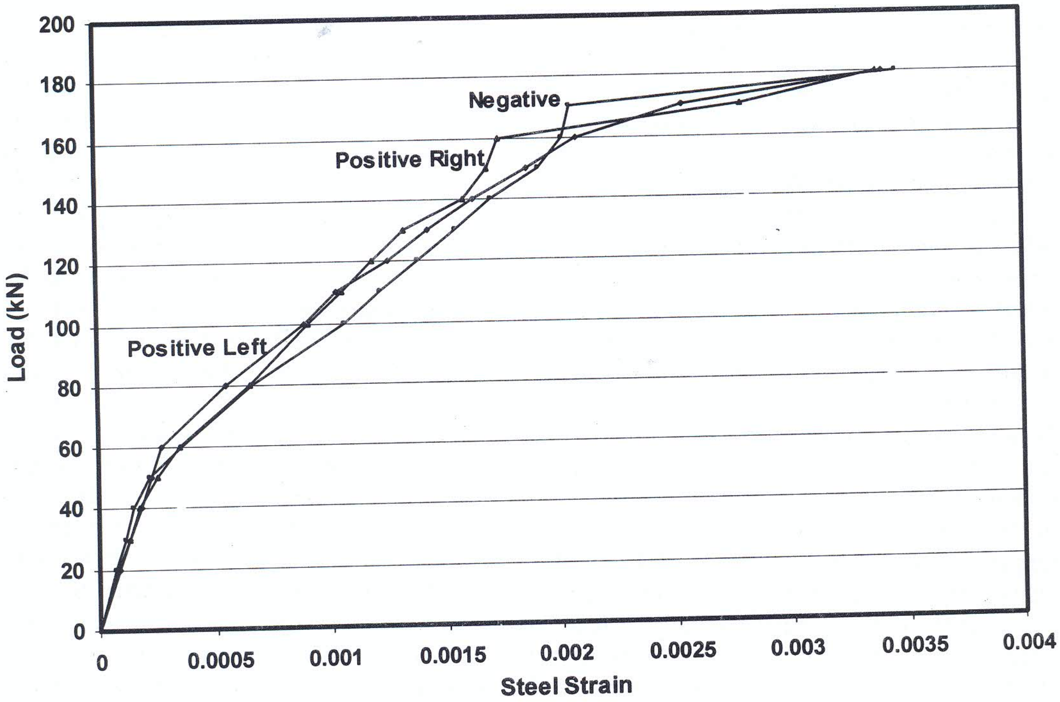


Fig. 11. Load-strain relationships for tested beam (B-2).

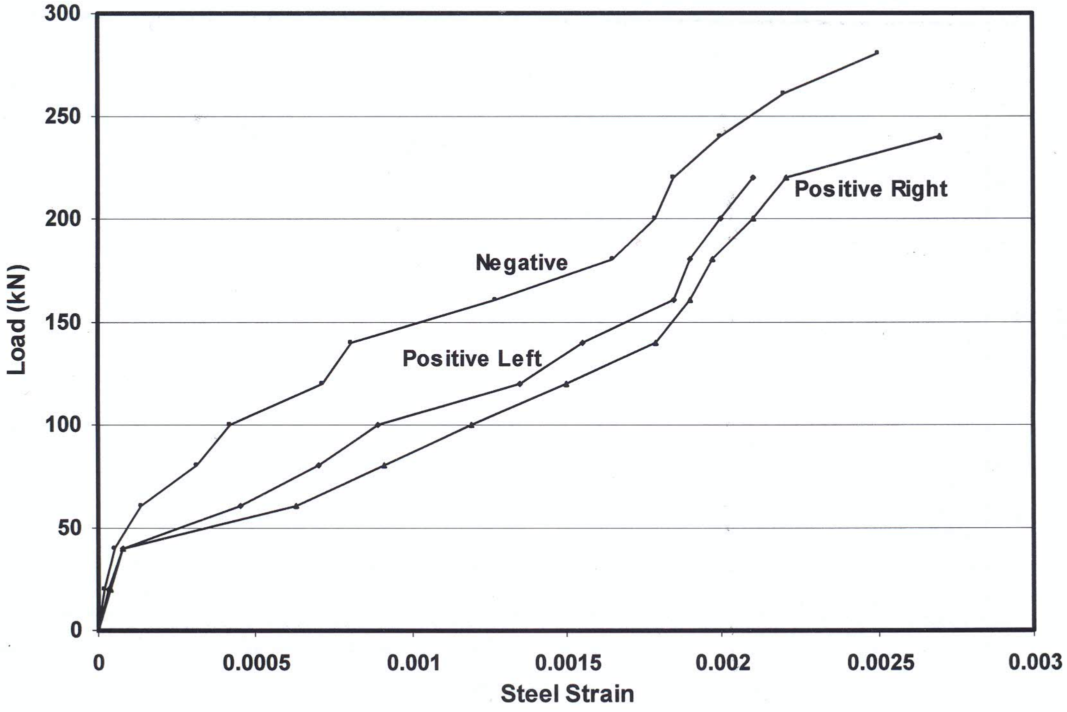


Fig. 12. Load-strain relationships for tested beam (B-4).

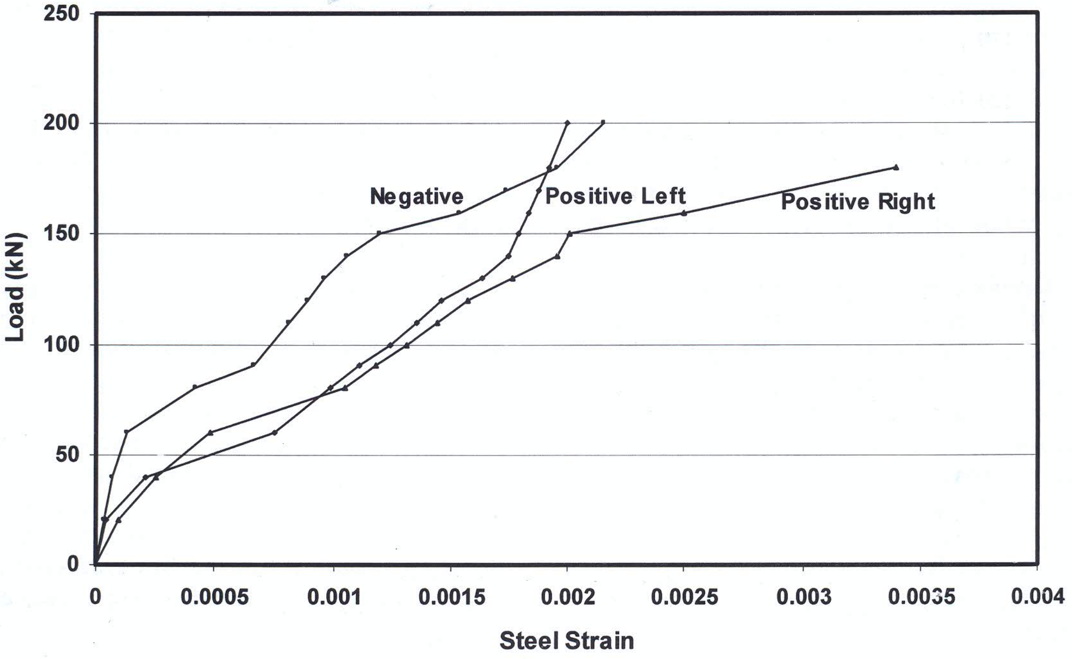


Fig. 13. Load-strain relationships for tested beam (B-5).

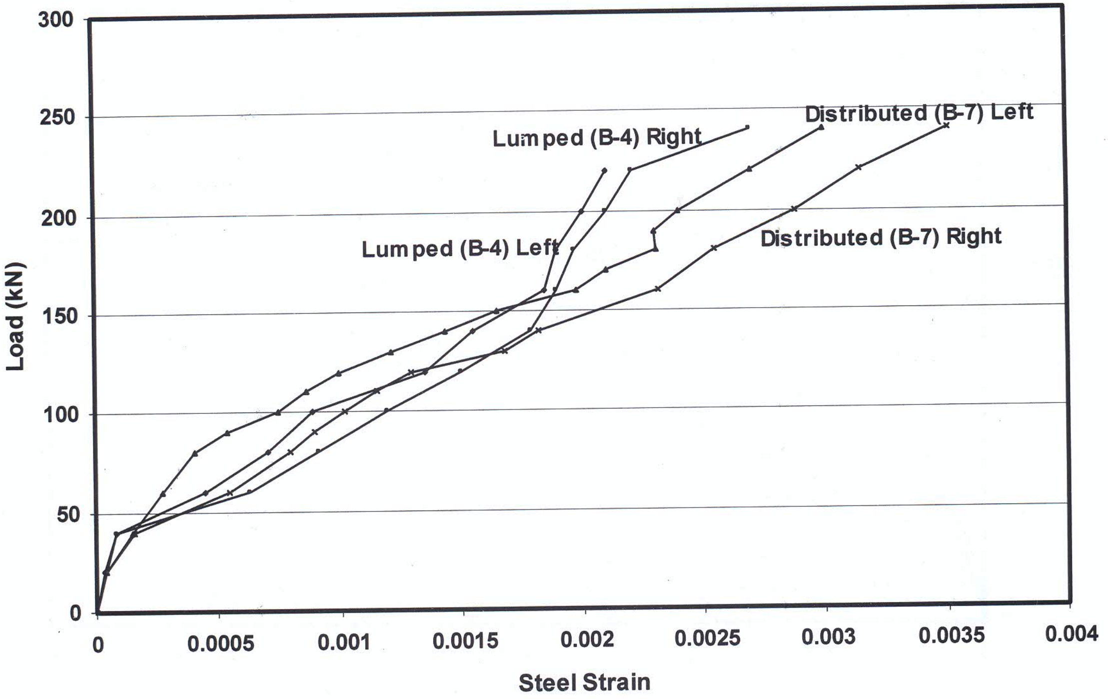


Fig. 14. Effect of negative steel reinforcement distribution on the load-strain relationships.

4. Summary and conclusions

An experimental study was conducted in this paper including testing nine reinforced concrete continuous beams. The main objective of the study was to investigate the effect of the distribution of negative steel reinforcement on the behavior of such beams. Other objectives of the experimental investigation were: (i) to study the effect of varying the amount of negative steel reinforcement on the behavior of reinforced concrete continuous beams; and (ii) to investigate the contribution of the slab part of beams having T-cross-sections with different slab widths. Firstly, three two-span continuous beams having rectangular cross-sections were considered. Three different negative steel reinforcement ratios were chosen for the three beams, which are 1.5, 1.0 and 0.47 times the positive steel reinforcement. Secondly, another three two-span continuous beams were considered having T-cross-sections with a slab width of the beam width plus six times the slab thickness. However, the reinforcement of these beams was the same as the three rectangular beams. Furthermore, another beam was considered having a T-cross-section and a negative reinforcement of 1.5 times the positive reinforcement. However, the negative reinforcement for this beam was uniformly distributed within the slab width. Finally, two continuous beams were considered having T-cross-sections, with a slab width of the beam width plus four times the slab thickness. Based on this study the following conclusions can be drawn:

1. For tested beams having rectangular cross sections, the first flexural crack was observed at the position of maximum negative bending moment at the middle support and was followed by a positive flexural crack under the position of the concentrated load. However, in the case of tested beams having T-cross-sections the first flexural crack was observed at the position of the maximum positive bending moment under the concentrated load and was then followed by the negative flexural crack at the position of middle support at higher range of loading.
2. The enhancement in the cracking strength as a result of increasing the negative steel reinforcement was much more significant in

the case of rectangular beams than that in the case of beams having T-cross-sections.

3. In the case of rectangular beams the negative cracking strength was much more affected by the change in the amount of negative steel reinforcement than the positive cracking strength. However, in the case of beams having T-cross-sections, the positive cracking strength was much more sensitive to a change in the amount of negative steel reinforcement than the negative cracking strength.

4. Negative cracking loads increase significantly in the case of beams having T-cross-sections as a result of the existence of the flanged slab. Much less enhancement in the positive cracking load was observed as a result of the existence of the flanged slab. Also, the presence of the flanged slab results in significant increase in the beam ultimate load capacity. The increase in the slab width enhances both cracking loads and the ultimate load capacity of the beam.

5. Results for cracking loads and ultimate loads support the possibility of distributing the negative steel reinforcement along the slab width rather than lumping the negative steel within the beam width. Also, the load-deflection and load-strain relationships are nearly the same in the two cases. However, a significant enhancement in the beam ductility was observed in the case of beam having distributed negative steel reinforcement.

6. The slab reinforcement within the effective part, up to the beam width plus six times the slab thickness, will contribute to the negative steel reinforcement of the beam and leads to a higher negative moment capacity for the beam.

7. As the amount of negative steel reinforcement decreases the deflection of beams increases for rectangular beams and also for beams having T-cross-sections. Also, the presence of the slab in the case of beams having T-cross-sections results in a significant enhancement in the beam stiffness. Such enhancement in the beam stiffness results in significant reduction in the beam deflection. Furthermore, for beams having T-cross-sections it was found that as the width of the slab increases the enhancement in the beam stiffness significantly increases which results in reduced deflection.

8. Redistribution of forces between positive and negative zones were observed which becomes much more clear near yielding where positive strain is fluctuated between the left and right spans due to the redistribution of forces within the negative zone during the formation of plastic hinges after yielding. Such redistribution was affected by the presence of flanged slab and the change in the amount of negative steel reinforcement.

9. The presence of slab part at the tension side for beams having T-cross-sections results in a noticeable reduction in the negative steel strain at the position of maximum negative bending moment. Such observation reflects the importance of the existence of such slab part even if it was located at the tension side in order to enhance and increase the potential energy of the plastic hinge formed at the support.

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