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THE BEHAVIOR OF REINFORCED-CONCRETE DEEP BEAMS WITH WEB OPENINGS UNDER REPEATED LOADS

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The objective of the work is to investigate the structural behavior of reinforced-concrete flanged deep beams with web openings, particularly in regards to the web reinforcement effect. This paper reports on experimental work on five test specimens, with square openings 25% of web depth at mid-height, through a critical shear path, subjected to repeated loading on simply-supported T-beams with two-point loads. Results showed that increasing the ratio of reinforcement of web increased the cracking and ultimate load, while increasing the vertical and horizontal reinforcement of web gives better results. Thus an inclined reinforcing of web gives higher ultimate load.

Keywords: Reinforced concrete, Deep beams, Web opening, Web reinforcement, Repeated loads, Flanged, Beam.

1 INTRODUCTION

Reinforced concrete deep beams are widely used in many structural engineering applications, such as, transfer girders, piles cap, offshore structures (caisson), shear wall, wall footings, floor diaphragms, and complex foundation systems. When the span-to-depth ratio of simply-supported beams is less than 2, or less than 2.5 for any span of a continuous beam, then these beams are considered to be deep beams (Park and Paulay 1975). According to the ACI Building Code 318-08, deep beams are members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports, and have either:

- Clear spans, l_n, equal to or less than four times the overall member depth; or
- Regions with concentrated loads within twice the member depth from the face of the support.

Deep beams are structural element loaded as beams, but with a depth/thickness ratio and shear span/depth ratio not exceeding 2 for concentrated loads or 4 for distributed load. The shear span is the clear span of the beam for a distributed load. In many instances, reinforced concrete slabs together with the beams behave as a T-section. Stronger compression zones provided by flanges in the T-section generally preclude shear compression failure in T-beams, and as a result has shear strength higher than the shear strength of rectangular sections (Hawy 2005).

1.1 Behavior of Deep Beams

Deep beams differ from common flexural members in that they behave as two-dimensional rather than one-dimensional members, and are subjected to a two-dimensional state of stress. This difference in behavior is mainly attributed to the significant effects of vertical normal stresses and shear deformations in these members (Kani 1969). In deep beams, the stress distribution with depth is nonlinear even at the elastic stage (Subedi 1986). The strength of deep beams is usually controlled by shear, rather than flexure, provided that an adequate amount of longitudinal reinforcements are used. The main parameters governing the deep-beam behavior are the span/depth ratio, shear span/depth ratio, slenderness (depth/thickness) ratio, main and web reinforcement, and the loading and supporting condition (ACI 2008).

1.2 Effects of Main and Web Reinforcements

The main steel not only acts as tension reinforcement in flexure, but also contributes substantially to the shear strength of beams. Further, web reinforcement controls crack widths and deflection. Of all types of web reinforcement, the inclined-type placed perpendicular to the plane of rupture (critical diagonal crack) has been found to be the most effective arrangement to offer resistance to sliding. The next practical and effective type is horizontal web steel that, with nominal vertical web steel, may further increase the effectiveness of the beam and thus its strength. It was observed that in beams with web openings, horizontal-web reinforcement that was distributed equally on either side of the opening location showed better results. Failure will be gradual and slow in beams with web reinforcement, while sudden in beams without web reinforcement. From electrical-strain measurements on main steel, it was observed that the general trend of the stress-strain characteristics under different load levels resembled stress-strain behavior of steel. However, shear failure occurred at steel strains below the yield-point values normally expected in shear failures. It was further seen that after cracking of the beams, the steel strain rapidly increased at the location near the supports while steel strain in the flexural zone remained almost constant (i.e., tension was uniform). The inclined cracks began to develop at higher loads (CIRIA 1977).

2 EXPERIMENTAL TEST PROGRAM

2.1 Materials

All materials used in experimental investigations were available in local markets, including cement, natural gravel, natural silica sand, water, and deformed reinforcement bars. All materials were tested according to Iraqi specifications.

2.2 Concrete Mix

The quantities of cement, fine aggregate, and course aggregate based on dry weights were cement 1: sand 1.5: gravel 3. Water/cement ratio=0.55. The mix was designed to give a compressive strength of about 30 N/mm^2 at age of 28 days and slump of about 8 mm. The same concrete mix was used throughout the whole investigation. A tilting drum mixer was used. Mixing was carried out according to BS 1881.

2.3 Testing the Properties of Concrete

During the casting of each group of beams, three 150x150x150 mm cubes and three 100x200 mm cylinders were made. The cube compressive and splitting tensile strength were obtained by testing three cubes and three cylinders as per to BS 1881.

2.4 Description of Tested Deep Beams

TB#1 was designed according to CIRIA guide 2, which gives 4-ø10 mm for main reinforcement, ø6 at 150 mm for vertical web reinforcement and ø6 at 200 mm for horizontal web reinforcement. All beams have a length of 1300 mm, a depth of 400 mm, a flange width of 300 mm, a flange thickness of 60 mm, a web thickness of 120 mm and a distance between the supports center/center 1000 mm, with web square opening of 100x100 mm. In this study, four parameters changed: 1) vertical web reinforcement changed from ø6 at 150 mm in TB#1 to ø10 at 150 mm in TB#5; 2) horizontal web reinforcement changed from θ6 at 200 mm in TB#1 to ø10 at 200 mm in TB#6; 3) vertical and horizontal web reinforcement changed from ø6 to ø10 at spacing 150,200 mm for vertically and horizontally in TB#7; 4) inclined web reinforcement with ø10 at 180mm in TB#8 was used. All changes above were with same main reinforcement at TB#1 (see Table 1 and Figure 1).

Table 1. Details of reinforcement for specimens.

I	Specimen Symbol	Main Reinforcing	Web Reinforcing Vertical	Web Reinforcing Horizontal	Flange Reinforcing	Loading Type
1	TB#1	4 ø 10 mm	ø 6@150 mm	ø 6@200 mm	ø 6@200 mm	repeated
2	TB#5	4 ø 10 mm	ø10@150 mm	ø 6@200 mm	ø 6@200 mm	repeated
3	TB#6	4 ø 10 mm	ø 6@15 mm	ø 10@200 mm	ø 6@200 mm	repeated
4	TB#7	4 ø 10 mm	ø10@150 mm	ø 10@200 mm	ø 6@200 mm	repeated
5	TB#8	4 ø 10 mm	ø 10@180 mm Inclined		ø 6@200 mm	repeated

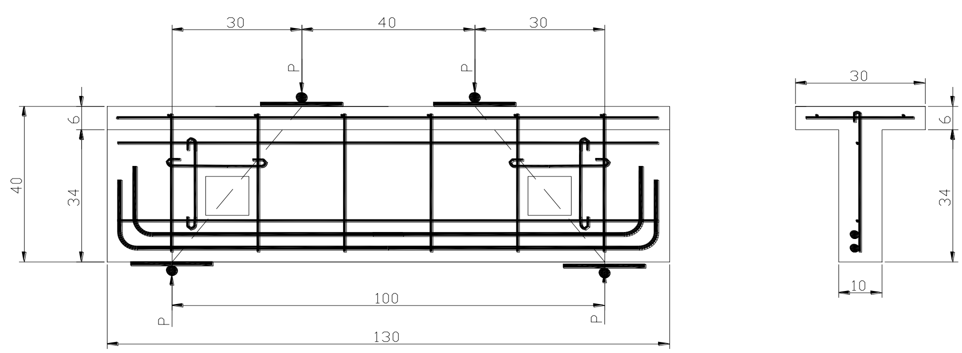

Figure 1. Description of tested specimens.

2.5 Fabrication and Casting of Beams

Timber forms with a plywood face were used in casing beams. The interior face of forms were coated with oil prior to casting and before the reinforcement cage was placed in position. Plastic spacers were used to maintain the concrete covers. The concrete mix was then placed in layers, and each layer compacted by means of a Poker vibrator. The top surface of the beam was finished level by a hand trowel. After the mold was stripped, beams were cured for seven days after casting with damp canvas.

2.6 Testing Equipment and Instrumentations

Below is a list of equipment and instrumentation used during the experiments:

- Machine for load applying: Torsee Universal Testing Machine with a capacity of (2000) (kN).
- Electrical strain gauges: TML strain gauges.
- Data acquisition system: Includes a personal laptop computer and a strain indicator with 16 channels named Data Taker (data logger) DT85, made in Australia in 2010.
- Measurement of deflection: The mid-span deflection of each beam was measured by using a dial gauge with a magnetic base. The accuracy of the dial gauge was 0.01 mm.
- Micro-crack reader: The width of concrete cracks were monitored using a hand microscope of accuracy 0.02 mm per division.

2.7 Test Procedure

- **Loading for first crack**: Loading was initiated from zero at a slow rate of about 1 kN, and recorded the data readings for strains and deflection until it detected the first crack. Then loading was stopped to measure the values of crack width through the crack detector device and the load value. If that crack was a diagonal crack, then item 2 below was performed (see Table 2 and Figure 2). If not, the loading continued until the first diagonal crack was detected.
- **Loading repeating**: When detecting the first diagonal crack, some cycles of loading and unloading were performed during this stage for a minimum of five times. The loading and unloading were performed in gradual increments and decrement at a suitable rate. During these individual steps, deflections, strains, and crack-width readings were recorded. If specimen did none of these, the loading was increased by 25 kN, some cycles were performed about five times. If specimen did not fail, the test continued to failure.
- **Loading to failure**: When the loading was increased to the next loading step some specimens failed. Tests terminated when the total load applied on the specimens started to drop off.

3 RESULTS AND DISCUSSION

3.1 Effect of Web Reinforcement on Cracking and Ultimate Load

Cracking load was increased by 50% for TB#5 and 25% for TB#6, TB#7, and TB#8 and comparing with TB#1. Ultimate load was increased by 25% for TB#5, 18% for TB#6, 28% for TB#7, and 69% for TB#8. This means the use of inclined web reinforcement gave a higher ultimate load, but had little effect on the cracking load compared to other specimens (see Table 2 and Figure 2).

Table 2. Experimental cracking load and ultimate loads for the tested specimens.

Specimen Symbol	Cracking Load V_{cr} (kN)	Ultimate Load V_u (kN)	V_{cr} / V_u
TB#1	20	74	0.27
TB#5	30	92.5	0.32
TB#6	25	87	0.29
TB#7	25	95	0.26
TB#8	25	125	0.20

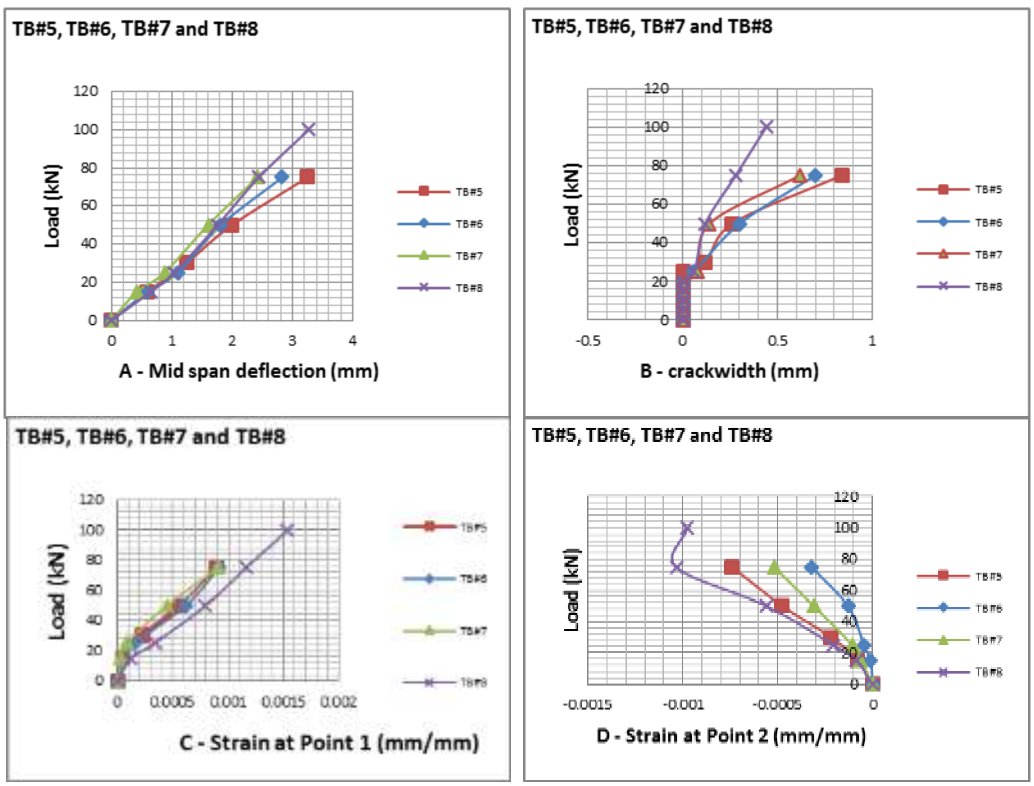

Figure 2. Charts of test results (A: Mid-span deflection, B: Crack width, C: Strain at point 1, D: Strain at point 2).

3.2 Effect of Web Reinforcement on Deflection

It was observed that increasing web reinforcement reduced the deflection. Increasing vertical web reinforcing gave better results than increasing horizontal web reinforcement. Increasing the vertical and horizontal web reinforcing gave better results than both of the above, close to increasing only the vertical web reinforcing. Increasing the vertical and horizontal web reinforcement gave less deflection than for specimens with other changes in web reinforcement.

3.3 Effect of Web Reinforcement on Crack Width

It was observed that increasing web reinforcement reduced the deflection. Increasing vertical web reinforcing gave better results than increasing the horizontal web reinforcement. Increasing the vertical and horizontal web reinforcing gave better results than both of the above. The use of inclined web reinforcement reduced crack width.

3.4 Effect of Web Reinforcement on Main Reinforcement Strain

It was observed that increasing web reinforcement vertically and/or horizontally decreased the strain for main reinforcement at point 1 (on main reinforcement at mid-span).

3.5 Effect of Web Reinforcement on Concrete Strain

It was observed that increasing web reinforcement vertically and/or horizontally decreased the strain for concrete at point 2 (on concrete face under the web opening on the shear path).

4 CONCLUSIONS

An increased ratio of web reinforcement vertically or horizontally increased the two ways that increased cracking and ultimate loading and reduced the deflection and crack width. By increasing the web reinforcement vertically, and/or horizontally decreasing the strain for main reinforcement and concrete strain, the reduction was higher than when increasing it both vertically and horizontally. Inclined web reinforcement increased cracking, and ultimate load and reduced crack width, with a slight effect on deflection. Inclined-web reinforcing has very little effect on main reinforcement and concrete strain.

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