International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 8 Issue 04 Series. I || April 2019 || PP 01-08

Effect of Cross-Section Shape on Shear Behavior of Reinforced Concrete Beams

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Abstract: *This paper presents the evaluation of the effect of different cross-section concrete shapes, relative dimensions and shear reinforcement of reinforced concrete beams. Six tests were conducted on full-scale beam specimens. Five rectangular beams of different relative dimensions and one T-shape beam were investigated. The performance of these beams is discussed in terms of crack load, failure load and crack width.*

Keywords: *Shear behavior; Cross-section relative dimensions; Shear strength; Width-to-depth ratio; Shear reinforcement ratio*

Date of Submission: 29-03-2019 Date of acceptance: 09-04-2019

I. Introduction

In spite of the numerous research efforts directed towards estimating the shear capacity of reinforced concrete beams [1-4], there is still a disagreement concerning the design principles that govern the shear design of RC beams.

Most of the previous studies which refer to the shear behavior of reinforced concrete beams do not consider the effect of different cross-section concrete shape and relative dimensions [5-8]. Little is therefore known about the effect of cross-section shape on the shear behavior of reinforced concrete beams. As such, there is a need for experimental data on the behavior of RC beams.

In this paper, an experimental program was conducted to investigate the effect of width-to-depth ratio (b_w/d), the cross-section shape, the shear reinforcement ratio (m_w), and the amount of longitudinal tensile reinforcement ratio on the shear resistance of normal strength reinforced concrete beams.

II. Research Significance

This paper examines the shear behavior through an experimental investigation.

The influence of cross-section concrete shape, and relative dimensions, as well as, different amounts of shear reinforcement and longitudinal tensile reinforcement on the shear capacity of reinforced concrete beams is investigated. In particular, crack widths and deflection of beams are studied.

Therefore, the information in this paper has a direct relevance to structural engineering design practices.

III. Experimental Program

3-1 Description of Beam Specimens

Six full-scale beam specimens were tested. The geometry and reinforcement details of the specimens are shown in Fig. 1 and in Table 1.

The main variables were the cross-section shape, width-to-depth ratio (b_w/d), the shear reinforcement ratio (m_w), and the amount of longitudinal tensile reinforcement.

The beam specimens were tested under monotonically increasing vertical loads.

All of the tested beam specimens have the same cross-section area which is 126000 mm^2. The beam specimens B1 through B5 have a rectangular cross section with width-to-depth, b_w/d, varying from 0.77 to 1.38. Beam specimen B6 has T-shape, its overall depth is 460mm, web width is 200mm, with flange thickness and width of 110 mm and 500 mm, respectively.

For all tested beam specimens, the overall length is 2000 mm with a clear span of 1800 mm between the two simple supports. The clear shear span, for all the specimens, is 780 mm. As such, the shear span-to-depth ratio, a/d, vary from 2.14 to 3.10. The shear span-to-depth ratio was chosen to be less than five, in order to produce a shear critical specimen.

B1 and B2 had the same dimensions and web reinforcement ratio (m_w), however B2 had higher longitudinal tensile reinforcement than B1 to examine the effect of longitudinal reinforcement on the shear capacity.
B4 and B5 had the same dimensions, but B5 has web reinforcement ratio equals 1.5 times that of B4 to examine the effect of web reinforcement ratio on the shear capacity.

It should be noted that the longitudinal steel ratios were higher in some specimens than that allowed by ECP 203-2007. The amount of flexural reinforcement was chosen to insure that a shear failure would occur before a flexural failure. The longitudinal steel was evenly distributed along the width of the specimens leaving a 20 mm clear cover on both sides and at the top, and 30 mm clear cover at the bottom except B6 which has 40 mm bottom cover. Specimens B1, B3, and B4 had one layer of bottom steel, while B2, B5, and B6 had two layers of bottom steel.

3-2 Material properties and Specimens Casting

Concrete compressive strengths were obtained by testing cube samples (158 mm side length). The average compressive strength (fcu) at the time of testing was 24.3 MPa.

The longitudinal reinforcement bars were of nominal proof strength 400 MPa deformed bars (denoted by Y). All stirrups were 6-mm diameter mild steel (denoted by R) of nominal yield stress of 240 MPa.

The reinforcing bars were cut to the desired lengths and were bent according to the Egyptian Code. In addition, the longitudinal reinforcement was extended and bent beyond the support sections to ensure sufficient anchorage capacities. Reinforcement cages were placed on rigid floor in wooden forms. Concrete was compacted in the forms using a hand-held vibrator. Specimens were water cured.

3-3 Instrumentation

The specimens were heavily instrumented to provide detailed strain readings. Three electrical wire strain gages of 6 mm length were installed on stirrups in the shear span and two strain gages of 10 mm length were attached to the longitudinal bars in the bottom layer to measure the tensile strains. These gauges were glued to the reinforcement and were covered by waxing material to protect them during handling and casting

Three linear voltage differential transducers (LVDT), of accuracy 0.01 mm, were used to measure the deflection of the specimens during the test. The LVDTs were attached to independent wooden bar between the two piers of the testing frame.

Fig.2, shows the LVDT attached to the side-face of the beams to enable the determination of the concrete strain and crack widths. Additionally, demec points were attached to the other side-face of the beams for more precise measurements of crack widths.
Crack widths were determined at each load stage, and photographs at each load step were taken to enable the following of crack development.

3-4 Test Procedure

The test program was conducted in the Reinforced Concrete Laboratory of Ain Shams University. The beam specimens were tested in three points bending, as shown in Fig 1. The load was applied at mid-span of the specimens. The load transfer from the loading frame to the specimens was through bearing plates and steel rigid beam. The loading was applied using a manually operated hydraulic jack with a capacity of 600 kN and an accuracy of 10 kN. The vertical load was applied at an increment of 50 kN for beam specimens B1, B2, B3, B4, B5 and at an increment of 30 kN for B6. At each load increment, the load was held constant for a period of about three minutes to allow for measurements and observations. The loading was continued up to failure of the test specimens.

During testing, the general deformational behavior was tracked. The development of cracks was marked along the sides of the test specimens. In addition, specimen deflections, concrete strains, longitudinal reinforcement strains, and stirrup strains were measured.

IV. General Behavior Of Test Specimens

The general behavior of all the tested specimens was relatively similar. In this respect, the crack development in all tested beams followed a similar pattern. First, nearly vertical flexural cracks initiated at approximately mid-span sections of the tested specimens. After the first crack formation, additional vertical cracks appeared near the mid-span sections. At intermediate loading stages, inclined flexural cracks initiated in the shear span and propagated with increased inclination towards the supports at one end and the loading point at its other end.

Table 2 and Fig. 3 give the measured loads at flexural cracking, shear cracking, ultimate for all the tested beam specimens, it also shows the maximum crack widths in pre-failure stage. Fig. 4 and Fig. 5 show photographs of the specimens after their failure.

It should be noted that tested beam specimen B6, the T-shape beam, had higher ratio between diagonal cracking loads to failure load than the other specimens. This is probably because of the enhancement of shear strength due to the presence of compression flange.

Tested beam Specimens B1 and B2 shared the same concrete dimensions and shear reinforcement ratio (m_w), however B2 had higher amount of tensile reinforcement than B1. At failure, the shear capacity of B2 was not higher than B1. No apparent reason was thought to explain the difference in failure loads between B1 and B2. As noted from Fig. 4, B2 had more uniform distribution of cracks, and higher margin between shear cracking to failure cracking, leading to more ductile nature of failure.

Specimens B4 and B5 had the same concrete dimensions. Shear reinforcement ratio (m_w) in B5 was increased by one half that in B6. The increase of shear capacity of B4 than B5 is clearly attributed to the increase in the shear reinforcement ratio. The beneficial nature of failure was noticed as the shear reinforcement ratio increased. This is evident through the larger number and more uniform distribution of cracks. Apparently, increasing the stirrups ratio boosted the ratio of failure loads to shear cracking loads. These trends can be attributed to the increase in the tensile resistance of the section due to the composite action of stirrups and concrete.

As can be seen from Table 2, the diagonal crack widths just before failure increase with the increase of the width-to-depth ratio in rectangular specimens B1 through B5.

4-1 Mid-Span Deflection

Fig. 6 shows the load-deflection relationships at mid span for the tested specimens. Inspecting the load-deflection behavior revealed that specimens with bigger depths had stiffer responses to loading in all loading stages. Expectedly, the deflection increased almost linearly with loading in the pre-cracking stage. In this stage, the strains in steel and concrete are relatively small and both materials are in the elastic portion of their respective responses. In the post-cracking stage, there are slight changes of slope in the load deflection curves due to cracking. Cracking moved the neutral axis towards the compression flanges, and thus, increased the curvature and deflections. Again, each specimen exhibited different post-cracking load deflection response depending upon its reinforcement ratio.

Specimens B2 and B4 had the same shear reinforcement ratio (m_w) and same amount of longitudinal steel in both compression and tension. It can be noted that B2 with lower width-to depth ratio (0.77) than that of B4 (1.38) experienced less deformations at the same load levels.

4-2 Reinforcement Strains

Fig. 7 shows the load-strain relationships in the flexural bottom tensile steel of the tested specimens. A common observation from the figure is that all specimens failed before their tensile reinforcement reached their proof limit (2000 microstrain), indicating the shear nature of failure in all test specimens. Comparing the responses of specimens revealed that specimens with higher reinforcement ratios had lower strains at the same load level compared to specimens with lower reinforcement ratios.

4-3 Stirrups Strains

Fig. 8 plots the load-strain relationships in the vertical branches of stirrups around quarter span section of the tested specimens. During early loading stages (before shear cracking), the strains were compressive with small values (less than 100 micro-strain). This Compressive strains resulted from the fact that the load was applied on the top surface of the test specimens. After shear cracking, the stirrups developed tensile strains.

Comparing specimens B1 and B2 which share the same concrete dimensions and shear reinforcement ratio, it is clear that higher amount in tensile reinforcement in B2 than B1 , had an impact on stirrups strain.

On the other hand, it can be observed from Fig.7 that the decrease in width-to-depth ratio was relevant to the increase of strain of the stirrups.

V. Tables And Figures

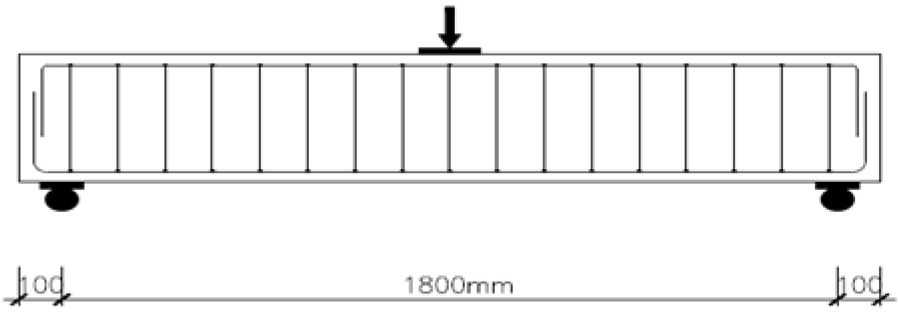

Figure 1- Details of tested beam specimens

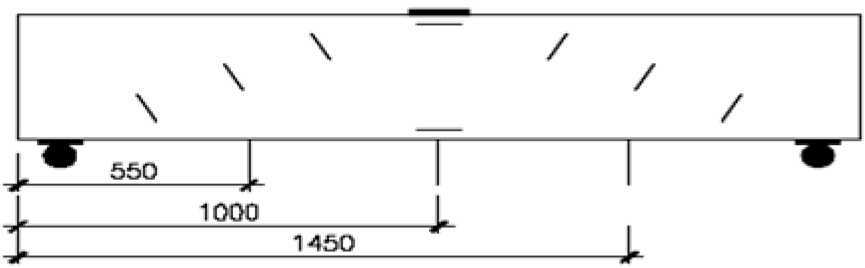

Figure 2- LVDTs on beam specimens

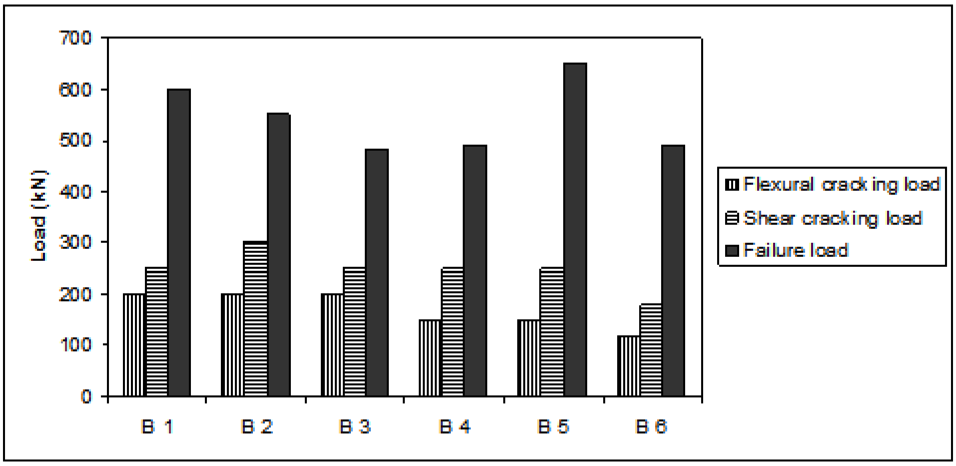

Figure 3- Cracking and failure loads of beam specimens

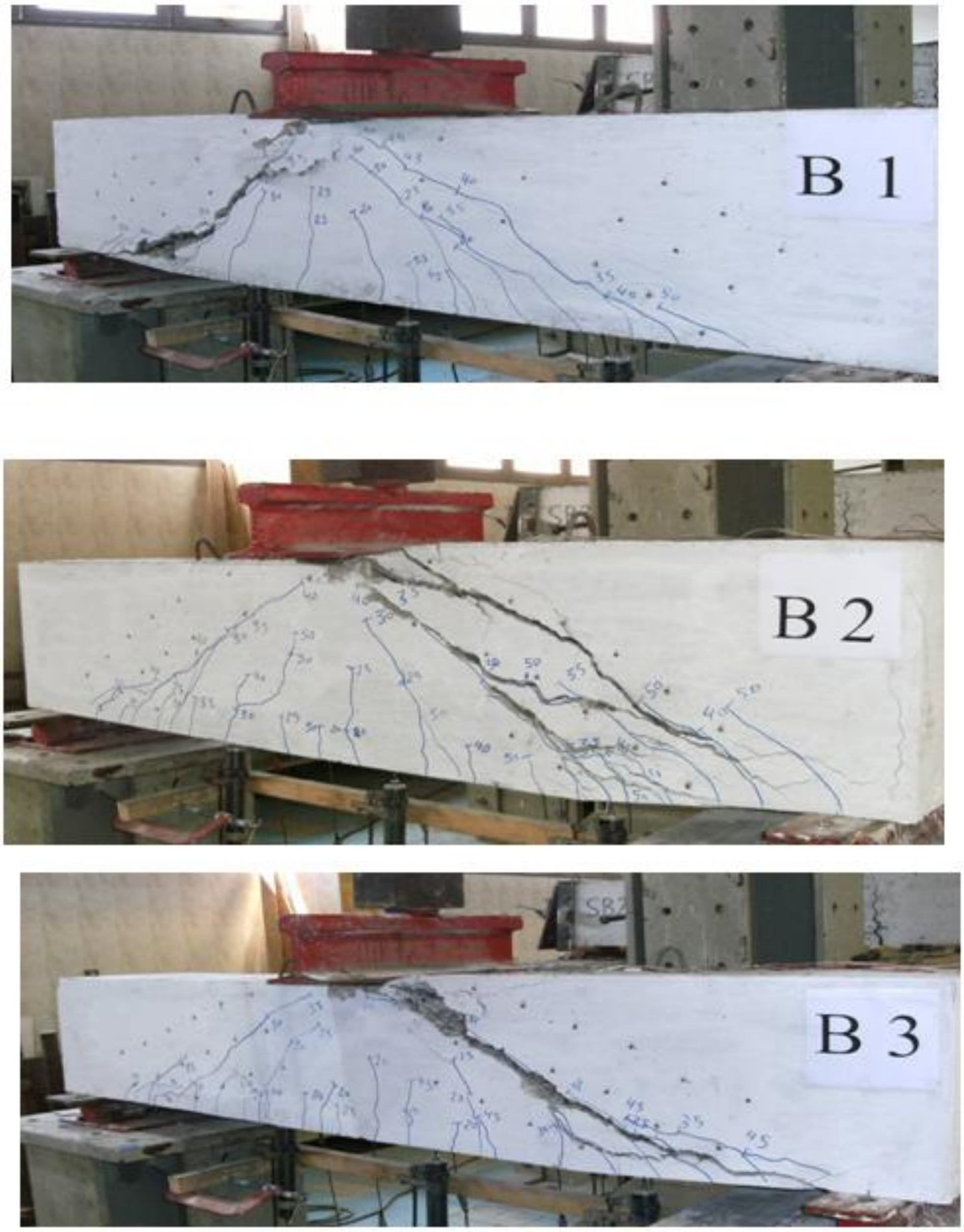

Figure 4- Crack patterns of beam specimens (B1, B2 and B3) after failure

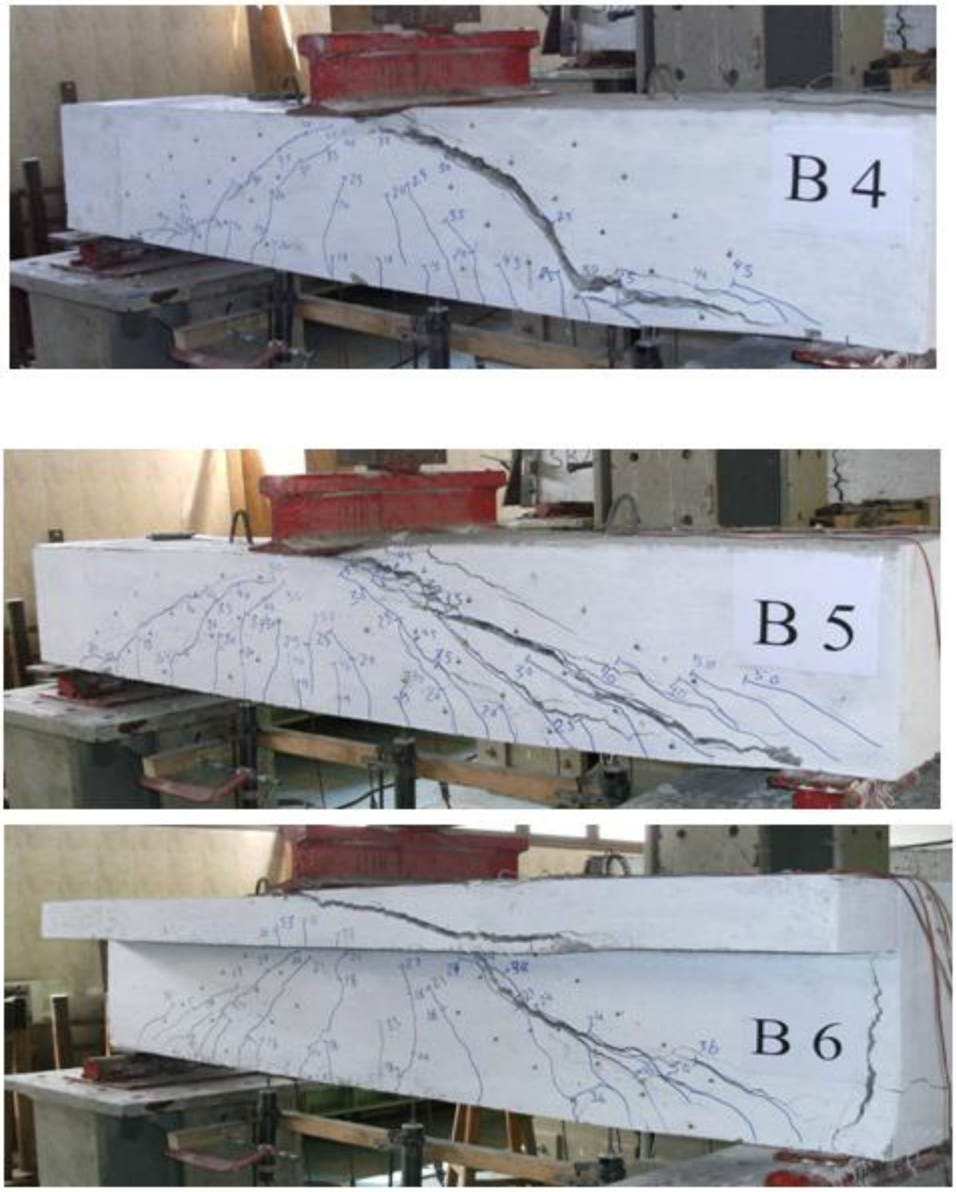

Figure 5- Crack patterns of beam specimens (B4, B5 and B6) after failure

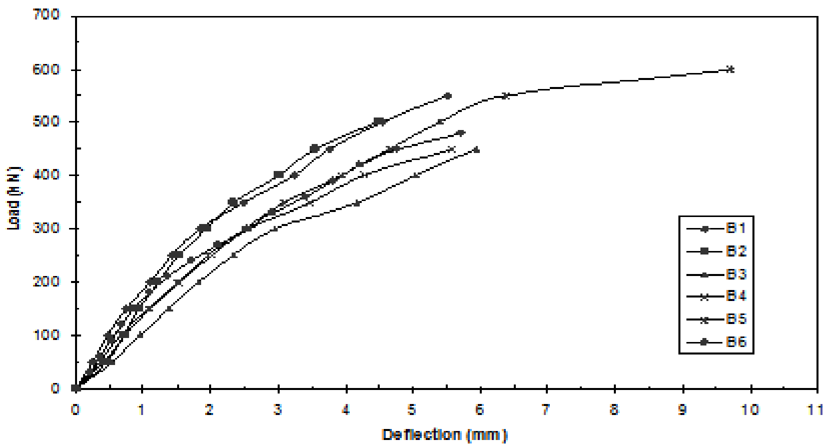

Figure 6- Load-Deflections At Mid Span Of Tested Specimens

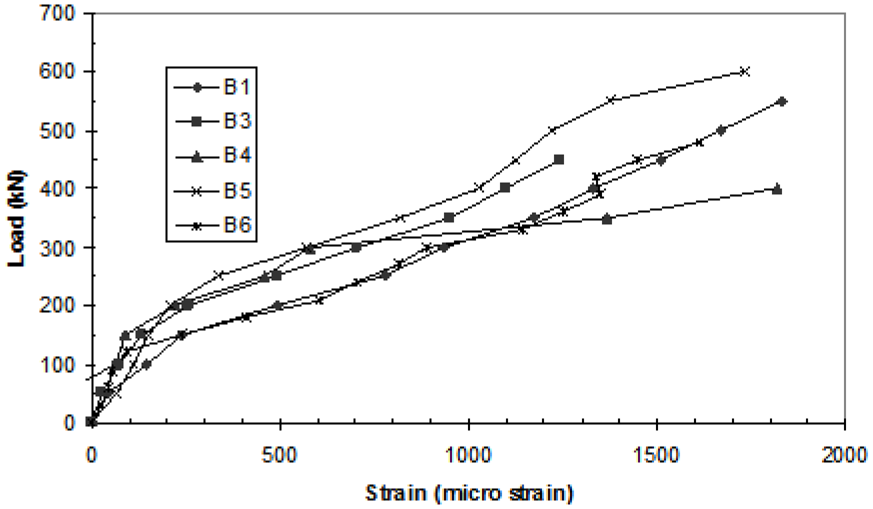

Figure 7- Load- strain for tensile reinforcement

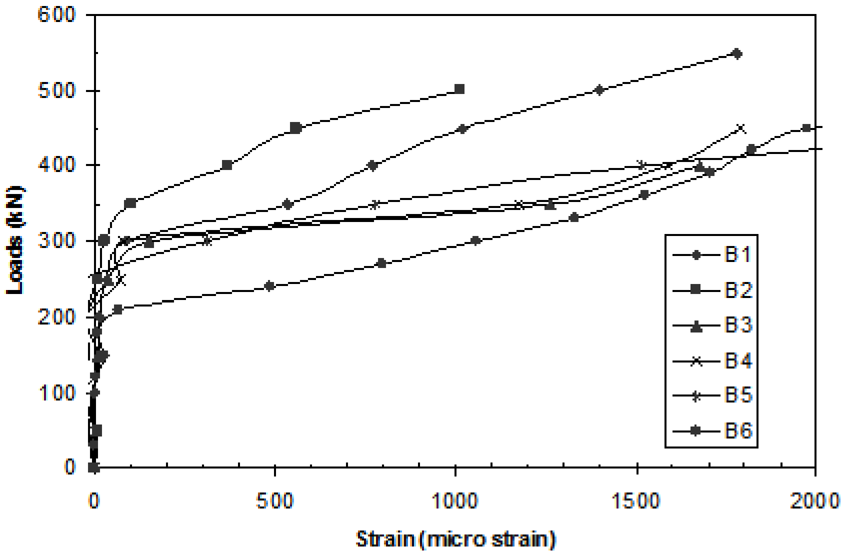

Figure 8- Load-strain for stirrups

Table 1- Details of test beam specimens

	Cross-section					Longitudinal reinforcement				Shear reinforcement	
	Shape	b_w	d	b_w/d	a/d	Bottom Rft	Top Rft	As	m_{sl}	Stirrups	m_w
B 1	R-sec	300	390	0.77	2.31	6Y22	5Y16	19	1.62%	R6-110	0.17%
B 2	R-sec	300	390	0.77	2.31	8Y22	9Y16	26.6	2.27%	R6-110	0.17%
B 3	R-sec	350	330	1.06	2.73	7Y22	7Y16	22.8	1.97%	R6-95	0.17%
B 4	R-sec	400	290	1.38	3.10	8Y22	9Y16	26.6	2.29%	2R6-160	0.17%
B 5	R-sec	400	290	1.38	3.10	9Y22	10Y16	30.4	2.62%	2R6-110	0.26%
B 6	T-sec	200 B=500	420 ts=110	0.48	2.14	5Y22	4Y10	19.01	2.26%	R6-165	0.17%

Table 2- Cracking and failure loads for the tested beam specimens

	P_{fl-cr} (1) (kN)	P_{sh-cr} (2) (kN)	P_{ult} (3) (kN)	W_{max} (4) (mm)	P_{ult}/P_{sh-cr}
B 1	200	250	600	1.08	2.40
B 2	200	300	550	1.12	1.83
B 3	200	250	480	1.74	1.92
B 4	150	250	490	1.38	1.96
B 5	150	250	650	1.58	2.60
B 6	120	180	490	1.66	2.72

(1) P_{fl-cr} = flexural cracking load
(2) P_{sh-cr} = shear cracking load
(3) P_{ult} = failure Load
(4) W_{max} = max. diagonal crack width at pre-failure stage

VI. Conclusions

The following conclusions are drawn from the results of the experimental program:

a- Using compression flange in RC beams results in higher ratio between diagonal cracking load to failure load.

b- Higher amount of tensile reinforcement, results in more uniform distribution of cracks, provide further evidence of the more favourable failures.

c- For beams with lower width-to depth ratio experienced less deformation at the same load level.

d- As width-to depth ratio increases, the width of diagonal cracks increases.

e- Increasing the amount of shear reinforcement increases the shear stress at failure.

f- Increasing the stirrups ratio boosted the ratio of failure loads to shear cracking loads.

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Omar A. El- Nawawy" Effect of Cross-Section Shape on Shear Behavior of Reinforced Concrete Beams" International Journal of Engineering Science Invention (IJESI), Vol. 08, No. 04, 2019, PP 01-08