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Experimental Study of Enhancing the Shear Strength of Hidden/Shallow Beams by Using Shear Reinforcement

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Abstract - The primary objective of this article is to study the effect of shear reinforcement on the performance of wide shallow beams. The investigated parameters include the crack patterns, mode of failures, load-deflection curves, load-strain curves of stirrups and the failure load. Nine tested specimens have 1800mm clear span and 500mm width with different thicknesses (150mm, 200mm, and 250mm), and type of the web reinforcement. The experimental results showed that there was a significant improvement in the shear strength due to using the traditional tied stirrups for beams with depth 250mm, but it seems that the vertical tied reinforcement does not work properly to resist the shear for beams with depth less than 250mm. While the welded link web reinforcement increases the shear capacity for beams with depth less than 250mm. A comparison between experimental shear capacities and the prediction of the ECP-203-2016, ACI 318-14, EN1992 and CSA 2004 codes are also presented in this research. It is recommended to re-evaluate the contribution of the shear reinforcement according to the Egyptian ECP-203. In addition, the tested beams specimens are analysed using the nonlinear finite element method (ANSYS). The results showed that the effect of web reinforcement on improving shear strength is more pronounced at higher depth of specimens.

***Keywords*:** Shallow Wide Beam, Shear Reinforcement, Welded Link Stirrups.

1. Introduction

In the design of buildings, modern architectural constraints are pushing engineers to provide longer clear spans at a reasonable cost. At the same time, there is a need to minimize the overall structural depth, which can be achieved through the use of wide beams or thick structural slabs. Wide shallow beams in concrete buildings are usually constructed as hidden beams in the sense that these wide beams have the same depth as the supported floor. The wide beams may be used to carry direct forces or to serve as primary transfer elements. However, the shear failure in reinforced concrete structures is highly brittle when compared with the flexural failure [1-5]. According to the Egyptian Code of practice (ECP 203-2016) [6], in case of beams with a total depth not greater than 250mm, 2.5 times thickness of flange, or half of the width of web, whichever is greatest, the shear stresses must be less than the concrete shear strength with no consideration of the contribution of shear reinforcement. As a consequence large cross-sectional areas of concrete have to be provided to meet one-way shear demands. While the code neglects the web reinforcement contribution in the shear strength, in practice a minimum web reinforcement is provided. These requirements of the code lead to a very conservative, uneconomic shear design of shallow wide beams. The target of this study was to investigate the effectiveness of shear reinforcement in increasing the shear strength of shallow wide beams by using different types of stirrups at different shear span-to-depth ratios (a/d).

2. Experimental Program

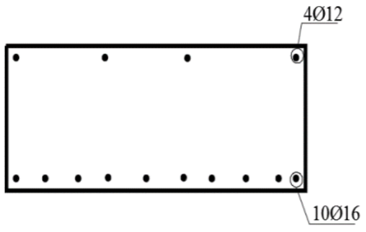
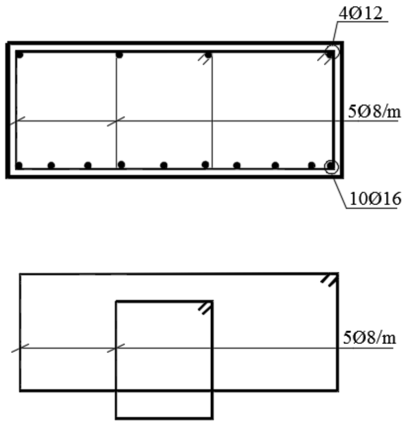
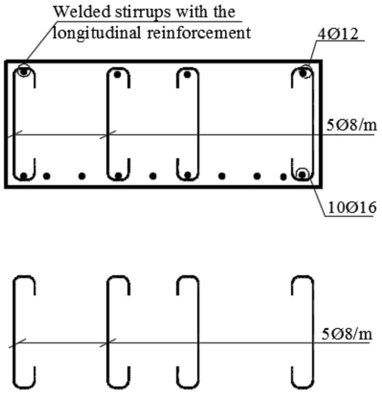
To investigate the effect of using different types of stirrups to enhance the shear capacity of reinforced concrete RC shallow wide beams and evaluate the allowable shear force with the shear reinforcement contribution, an experimental program consisting of eight simply supported RC shallow wide beams is conducted. The tested specimens have 500mm width, and 2000mm length with different thickness (150mm, 200mm and 250mm) as shown in Table 1. All tested specimens have longitudinal reinforcement10Ø16 bottom, and 4Ø12 top steel bars. The stirrups used are 5Ø8/meter with different configurations. All tested specimens were designed to fail in shear. The average concrete cube compressive strength of the concrete used in the cast of the tested specimens is shown in Table 1. The yield strength of top and bottom longitudinal steel, and vertical stirrups were equal to 360MPa, and 240 MPa respectively.

Two types of stirrups were used as shown in Table 2. The first group of beams did not contain stirrups, the second group contained traditional stirrups (four branches), while the third group contained four link stirrups welded with the top and bottom longitudinal reinforcement.

Table 1: The results of the tested specimens.

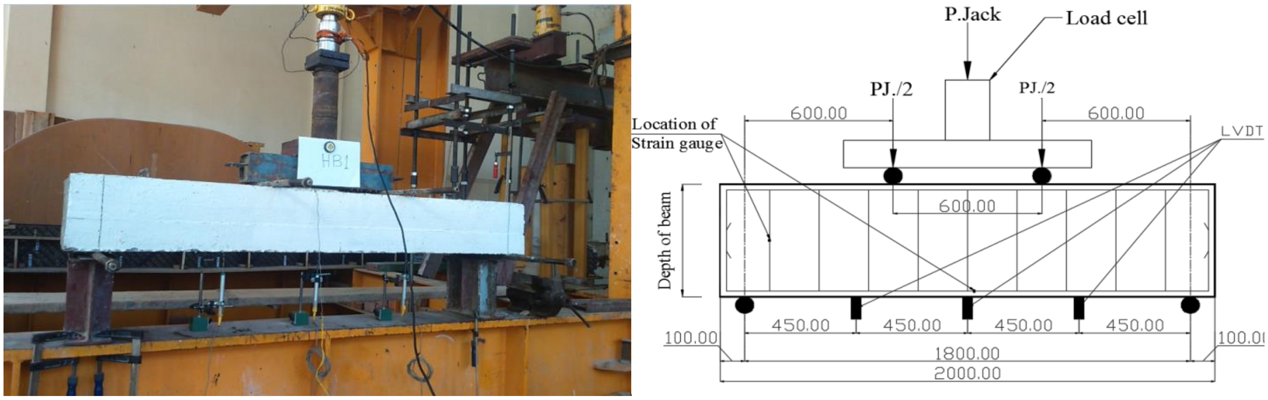
Group	Specimens	Depth	Type of stirrups	Depth (mm)	f_{cu} (MPa)	P_{cr} (kN)	P diag. (kN)	P_{max} (kN)	Pcr/ P_{max}	P_{diag}/ P_{max}	Area P-d (kN.mm)	Def. at P_{max} (mm)	defl/def control
G1	HBC 25	250	None	250	33.79	147.62	211.87	264.93	0.56	0.80	1938.8	4.38	1.00
	HBS 25	250	Traditional	250	28.04	131.79	239.58	345.26	0.38	0.69	3840.7	5.30	1.21
G2	HBC 20	200	none	200	33.79	163.6	189.60	239.30	0.68	0.79	2131.6	4.27	1.00
	HBS 20	200	Traditional	200	28.04	115.5	199.6	243.20	0.47	0.82	3018.7	5.38	1.26
	HBA 20	200	weld	200	33.43	111.3	203.90	317.50	0.35	0.64	3282.8	10.8	2.52
G3	HBC 15	150	none	150	33.79	93.9	139.20	178.20	0.53	0.78	1931.8	6.4	1.00
	HBS 15	150	Traditional	150	28.04	117.2	162.00	194.80	0.60	0.83	1333.2	7.6	1.19
	HBA 15	150	weld	150	33.43	118.2	172.70	225.00	0.53	0.77	3240.7	10.44	1.63

Table 2: Type of stirrups.

HBC (without stirrups)	HBS (with four branches stirrups)	HBA (with four link welded stirrups)
		

The eight tested specimens are divided into three groups with the different studied parameters. In the first group, the two tested specimens named "HBC25" and "HBS25" with and with without stirrups, were tested to study the effect of stirrups contribution in tested beams with the 250mm thickness in shear strength. In the second group, the three tested specimens with the 200mm thickness named "HBC20", "HBS20" and "HBA20" presented the three types of stirrups used to study the effect of type of stirrups in enhancing the shear strength. In the third group, the three tested specimens with 150mm thickness named "HBC15", "HBS15" and "HBA15" presented the three types of stirrups used to study the effect of type of stirrups in enhancing the shear strength.

The beams were tested using a hydraulic jack with 1000kN capacity, manually operated by an oil pump. The test set-up and instrumentation used are shown in Figure 1. An electrical load cell (accuracy of 0.1 kN) connected to a digital load indicator is used to measure the applied vertical loads. The deflection of the tested beams was recorded using three electric dial gauges LVDT, one at mid-span, and the second, and the third located at quarter-span from each support of the tested beam located at the bottom face of the beam supports. The strain of the main steel reinforcement and the first stirrups beside support were measured using two strain gauges. The three electric dial gauges, two electric strain gauges, load cell were connected to the data acquisition system attached to the computer. Continuous recording of the load, displacements, and reinforcement strains were provided throughout each test beam up to failure.



a) Test Set-up b) Schematic of test Set-up

Fig. 1: Test set-up and instrumentation of tested specimens.

3. Test Results and Analysis

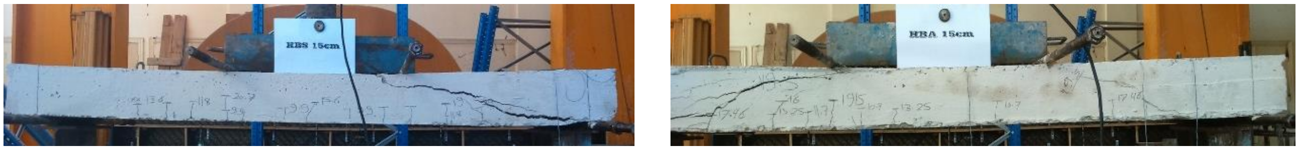
3.1. Crack Pattern and Mode of Failure

The crack patterns for all tested specimens are shown in Figure 2. In general, it was observed that the first crack (P_{cr}) was a vertical flexural crack occurring near mid span. After that, additional diagonal shear cracks appeared and propagated towards the top compression flange or the bottom and continued propagating horizontally. The first diagonal cracking load ($P_{diag.}$) and maximum failure load (P_{max}) are listed in Table 1. The cracking loads ranged from 35% to 68% of the maximum loads, while the diagonal cracks appeared at loads ranging from 64% to 83% of the maximum failure loads. By comparing between traditional stirrups and welded stirrups, it was found that the welded type did not effect on the cracking load. However, the diagonal cracking loads were slightly delayed and the maximum failure loads increased.

a) HBC25 b) HBS25

c) HBC20 d) HBS20

e) HBA20 f) HBC15

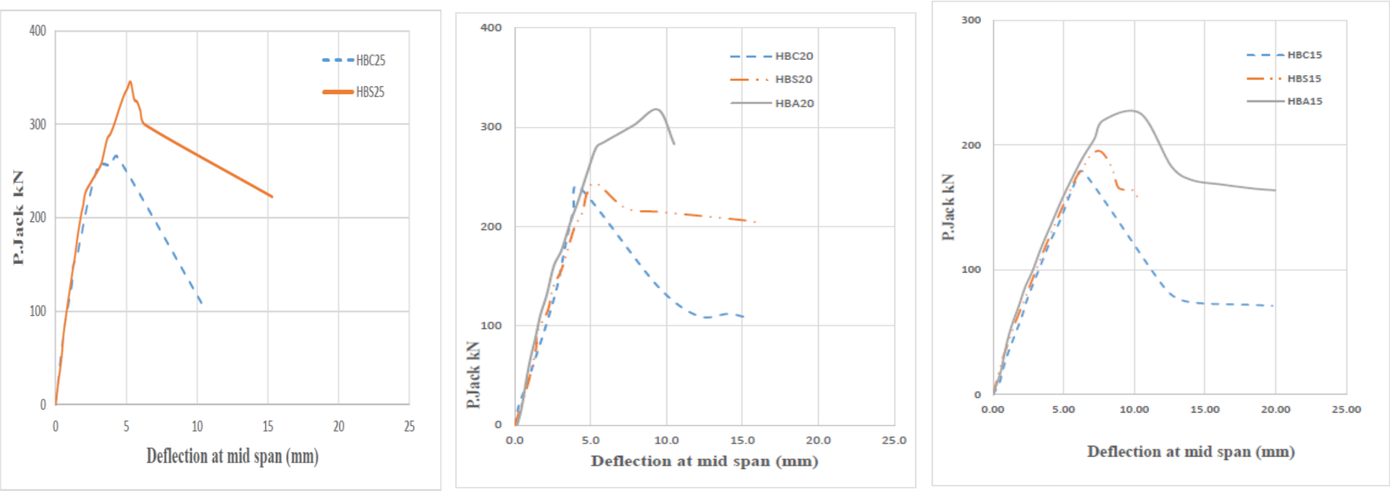


g) HBS15 h) HBA15

Fig. 2: The crack pattern of tested specimens.

3.2. Load Deflection Curves

The load deflection curves measured at the mid-span are shown in Figure 3. In general, using stirrups increases the maximum failure load of the tested specimens and enhances the behaviour.



thickness=250mm b) thickness=200mm b) thickness=150mm

Fig. 3: The effect of type of stirrups on the load deflection curves at different beam thickness.

As shown in Table 1, for the shallow wide beams of 250mm, 200mm, and 150 thickness, the traditional stirrups with four branches increased the maximum load by about 30.0%, 2.0% and 9.0% compared to the control beam without stirrups. On the other hand, for the shallow beams with 200mm and 150 thicknesses, the welded link stirrups increased the maximum loads by about 33%, and 26.0% compared to the control beam without stirrups respectively. From this it can be concluded that using weld stirrups significantly increases the shear resistance of the shallow wide RC beams. By comparing between using traditional stirrups, and welded stirrups it can be concluded that the welded stirrups are much more efficient than the traditional stirrups for the beams with thicknesses 150mm and 200mm. By calculating the energy absorption (the area under load-deflection curves) as shown in Table 1 it can also be concluded that the energy absorption increases by using traditional stirrups and even more increases if welded stirrups are used.

3.3. The Effect of Shear Span-To-Depth Ratio (A/D)

The inclination of the diagonal cracks depended on the shear span to depth ratio as the angle decreased with increasing span-to-depth ratio (a/d). Figure 4 shows the relation between stress and deflection taking the effect of the thickness of tested specimens into consideration.

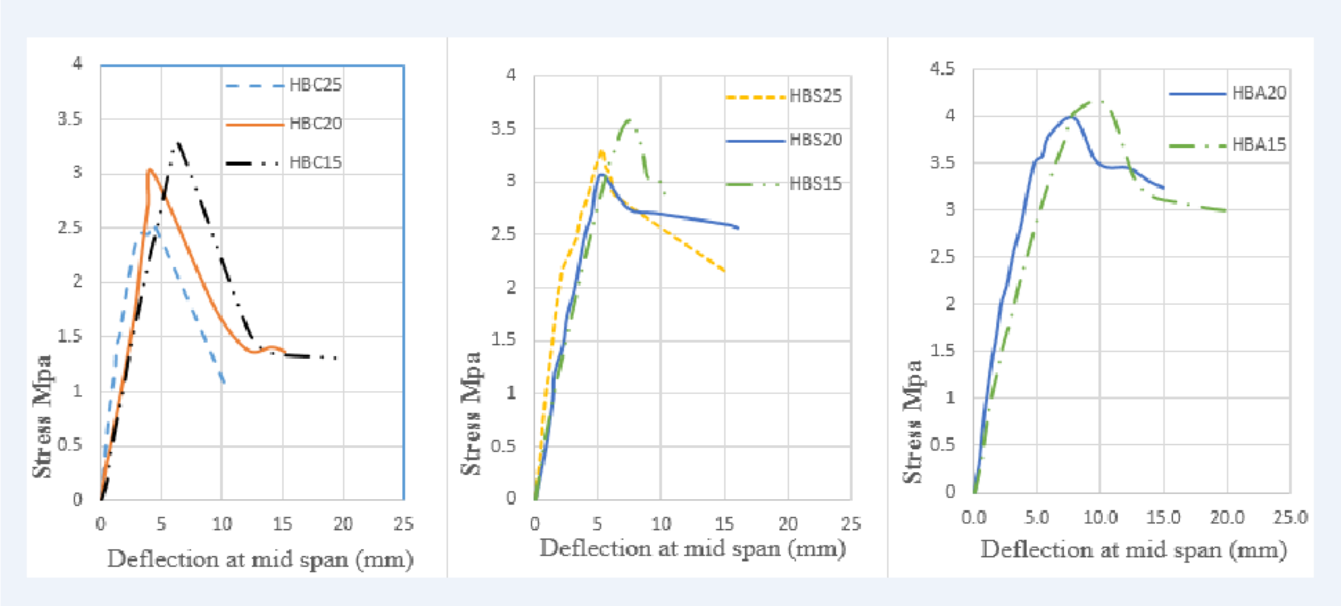
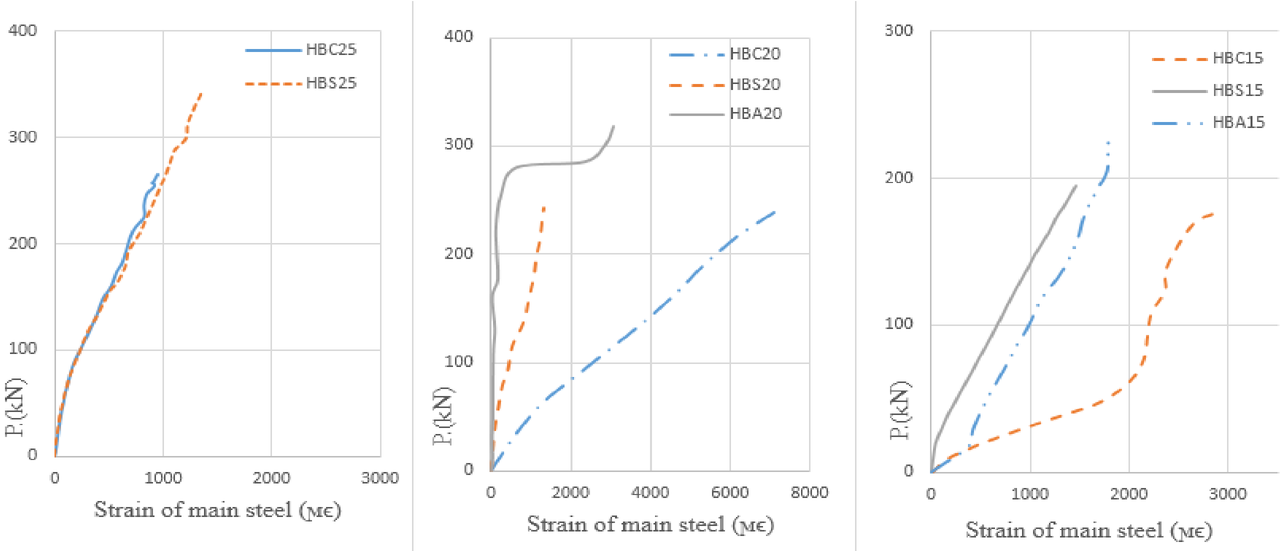


Fig. 4: The effect of variation thickness of tested beam on the load-deflection curve.

3.4. Load Strain Curves

The load-strain curves of steel bars at the mid-span section is shown in Figure 5. The strains of the main steel bars are larger in tested specimens without stirrups compared to the tested specimens with stirrups at the same loads except group1. The welding of the stirrups resulted in earlier yielding compared to the traditional stirrups.



a) thickness =250mm b) thickness =200mm c) thickness =150mm

Fig. 5: The effect of variation thickness of tested beam on the load-strain curves of the steel bar at the mid-span section.

4. Comparing Between Experimental Results and Analytical Ultimate Load of Different Codes

4.1. The Shear Capacity of Shallow Wide RC Beams without Shear Stirrups

According to ECP 203-2011 [6], ACI 318-14 [7], EN1992 [8], and CSA 2004 [9], the concrete contribution in the shear resistance is calculated by Eqs. 1, 2, 3 and 4 respectively.

$$V_c = bd \times \left[0.16 \times \sqrt{\frac{f_{cu}}{\gamma_c}} \right] \tag{1}$$

$$V_c = bd \times \left[0.17 \times \sqrt{f'_c} \right] \tag{2}$$

where f_{cu} is the concrete cube compressive strength at 28day, and f'_c is the concrete cylinder compressive strength after 28day

$$V_c = bd \times \left[0 \frac{0.18}{\gamma_c} k(100 \times \rho_1 \times f_{ck})^{1/3} \right] \geq 0.035 k^{2/3} f_{ck}^{0.5} \tag{3}$$

$$V_c = bd \times \left[\beta \times \sqrt{f'_c} \right] \tag{4}$$

Where f_{ck} = characteristic concrete cube strengthMPa); k = 1+ $\sqrt{\frac{200}{d}} \leq 2$; $\rho = \frac{Asl}{b \ * d} \leq \ 0$: β = factor indicating the ability of diagonally cracked concrete to transmit tension; f'_c is the concrete cylinder compressive strength after 28day.

Table 3 includes a comparison between the experimental shear force and allowable shear force calculated according to the different codes. All investigated codes give conservative values for the failure loads. EN-1992 is the most accurate in predicting the experimental failure loads because it accounts for the size effect (thickness) of the tested beams.

Table 3: Comparison between the experimental and code failure shear for beams without stirrups.

Specimens	Experimental shear capacity	Predicted Shear Capacity "$V_{code.}$" (kN)							
		ECP203-2011		ACI 318-14		EN-1992		CSA-2004	
	$V_{exp.}$ (kN)	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$
HBC 25	132.47	104.65	1.27	99.45	1.33	143.10	0.93	110.56	1.20
HBC 20	119.65	81.40	1.47	77.34	1.55	119.10	1.00	86.00	1.39
HBC 15	98.10	58.13	1.69	55.24	1.78	85.10	1.15	61.40	1.60

4.2. The Shear Capacity of Shallow Wide RC Beam with Shear Stirrups

ECP 203-2011 [6] neglects the effect of vertical stirrups for RC beam with depth less than 250mm. ACI 318-14 [7], CSA 2004 [9], and EN1992 [8] accounts for the contribution of the shear reinforcement by Eqs. 5, 6 and 7 respectively.

$$V_s = \frac{A_{st} \times f_y/\gamma_s \times d}{s} \tag{5}$$

$$V_s = \frac{A_v f_y d_v \times \cot\theta}{S} \tag{6}$$

A_{st}, or A_v = area of shear reinforcement (mm^2); Θ= Angle of inclination of the diagonal compressive struts;

$$V_{RD} = V_{RD,s} = \frac{A_{sw}}{S} \times Z \times f_{ywd} \times \cot\theta \le V_{RD,max} = \frac{\alpha \times \nu_1 \times f_{cd}}{\cot\theta + \tan\theta} \times b \times Z \tag{7}$$

A_{sw} = cross-sectional area of the shear reinforcement (mm2), S = spacing of the stirrups (mm); f_{ywd} = yield strength of the shear reinforcement (MPa) for vertical shear reinforcement; Θ= angle between compression strut and the longitudinal axis; equal to 45°; z = the inner lever arm for a member with constant depth (mm).

A comparison between experimental and numerical shear resistance calculated by ECP 203-2011 [6], ACI 318-14 [7], EN1992 [8], and CSA 2004 [9], is presented in Table 4, taken into consideration the stirrups contribution in the shear resistance.

As shown in Table 4, all investigated codes give conservative results. In addition, the ratio between the experimental shear force and calculated by ECP-203 considering the vertical stirrups contribution ranges from 1.35 to 1.62.

Table 4: Comparison between the experimental shear forces with stirrups and predicted by different codes.

Specimens	Experimental shear capacity	Predicted Shear Capacity "$V_{code.}$" (kN)							
		ECP203-2011		ACI 318-14		EN-1992		CSA-2004	
	$V_{exp.}$ (kN)	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$	V_{code} (kN)	$V_{exp.}/V_{code}$
HBS 25	172.63	98.05	1.76	147.50	1.55	48.89	3.53	158.00	1.09
HBS 20	121.60	74.20	1.64	112.70	1.08	38.03	3.20	120.56	1.01
HBA 20	158.75	80.95	1.96	119.20	1.33	38.03	4.17	127.75	1.24
HBS 15	97.40	53.00	1.84	80.50	1.21	27.16	3.59	86.11	1.13
HBA 15	112.50	57.82	1.95	85.13	1.32	27.16	4.14	91.25	1.23

5. Theoretical Study Using Finite Element Program (ANSYS)

The nonlinear finite element method (ANSYS) is used to study the effect of increased shear reinforcement with welded links stirrups. A solid element, SOLID65, Link 180, and SOLID185 is used for concrete, reinforcement steel bars, and element used for steel plate respectively to model the beam in ANSYS, as shown in Figure 5.

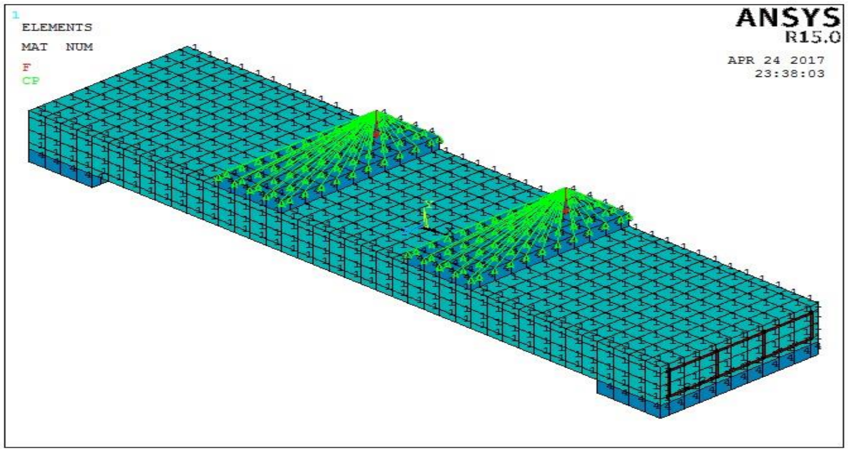
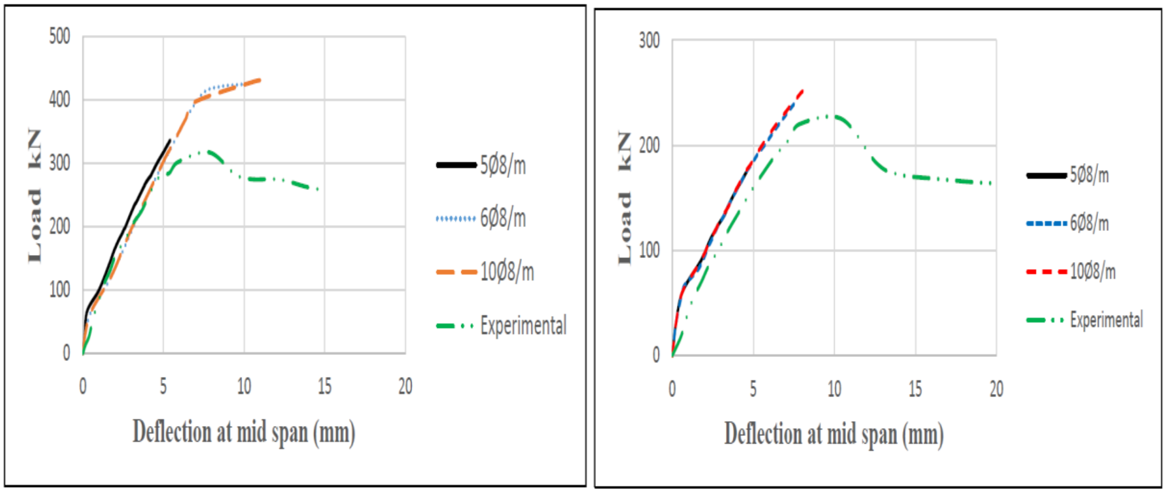


Fig. 5: Modelling of the tested specimen.

The verification is carried out on the experimental control tested specimen in order to check the validity and accuracy of the finite element model with different factors. For all theoretical specimens, the bond between the concrete and steel reinforcing is assumed to be perfect in the finite element models.

The theoretical results show that the crack patterns detected in the ANSYS models is quite similar to the experimental ones. The load-deflection curves of the theoretical tested specimens and experimental specimens HBA15 and HBA 20 are shown in Figure 6. The results shown that the theoretical stiffness is more than the experimental stiffness.



a) Depth 200mm b) Depth 150mm

Fig. 6: Comparison between theoretical load-deflection curves with different web reinforcement and experimental.

6. Conclusions

Based on the experimental and theoretical studies, the following conclusions can be drawn:

1.The different types of stirrups investigated cause an increase in the maximum failure load and corresponding deflection and slightly delayed the occurring of the diagonal cracking.

2.Using welded stirrups significantly increases the shear resistance of the shallow wide beams tested. By comparing between using traditional stirrups (four branches stirrups) and welded link stirrups, it was found that using welded stirrups increased the ultimate load by about 31% and 16% compared to traditional stirrups, with thickness equal to 200mm and 150mm respectively.

3.The ductility of the shallow wide beam has a significant enhancement by using stirrups and more enhancement can be achieved with changing the configuration types of steel.

4.The angle of diagonal shear crack decreases by increasing the shear span-to-depth ratio.

5.The ECP-203 is conservative in ignoring the shear reinforcement contribution in the resistance of shear stress in hidden RC beams. It is recommended to re-evaluate the contribution of the shear reinforcement in ECP-203 especially for welded stirrups.

6.Welded stirrups used proofed to be an efficient shear reinforcement for wide shallow RC beams.

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