ENHANCEMENT OF SHEAR STRENGTH AND DUCTILITY FOR REINFORCED CONCRETE WIDE BEAMS DUE TO WEB REINFORCEMENT

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ABSTRACT

In this research, the shear behavior of reinforced concrete wide beams was investigated. The experimental program consisted of nine beams of 29 MPa concrete strength tested with shear span-depth ratio equal to 3.0. One of the tested beams had no web reinforcement as a control specimen. The flexure mode of failure was secured for all of the specimens to allow for shear mode of failure. The key parameters covered in this investigation are the effect of the existence, spacing, amount and yield stress of the vertical stirrups on the shear capacity and ductility of the tested wide beams. The study shows that the contribution of web reinforcement to the shear capacity is significant and directly proportional to the amount and spacing of the shear reinforcement. The increase in the shear capacity ranged from 32% to 132% for the range of the tested beams compared with the control beam. High grade steel was more effective in the contribution of the shear strength of wide beams. Also, test results demonstrate that the shear reinforcement significantly enhances the ductility of the wide beams. In addition, shear resistances at failure recorded in this study are compared to the analytical strengths calculated according to the current Egyptian Code and the available international codes. The current study highlights the need to include the contribution of shear reinforcement in the Egyptian Code requirements for shear capacity of wide beams.

KEYWORDS: Stirrups, Shear strength, Wide beams, Ductility, Web reinforcement

1 INTRODUCTION

Large, wide reinforced concrete beams and thick slabs are frequently used as economical transfer elements where the total structural depth must be kept to a minimum. The wide beams may be used to carry direct forces, or to serve as primary transfer elements. A system of wide beams may provide a simple and economical solution to transfer column loads from the tower portion
over required column free spaces in the podium or parking areas below. Thick one-way transfer slabs can serve similar roles when the column layout to be transferred is irregular in the plan and for roofs of underground stations [1, 2].

Recently, some researchers directed their efforts to study the shear behavior of wide beams. Lubell et al. [2] investigated the influence of the shear reinforcement spacing on the one-way shear capacity of wide reinforced concrete members. Shear reinforcement spacing was a primary test variable. A series of 13 normal strength concrete specimens were tested. The specimens contained web reinforcement ratios close to ACI 318-02 [10] minimum requirements. The study concluded that the effectiveness of the shear reinforcement decreases as the spacing of web reinforcement legs across the width of a member increases, the use of few web reinforcement legs, even when widely spaced up to a distance of approximately 2d, has been shown to decrease the brittleness of the failure mode compared with a geometrically similar member without web reinforcement. Sherwood et al. [3] carried out an experimental study to investigate the shear behavior of the wide beams and thick slabs as well as the influence of member width. They tested five specimens of normal strength concrete with a nominal thickness of 470 mm and varied in width from 250 to 3005 mm. The study demonstrated that the failure shear stresses of narrow beams, wide beams, and slabs are all very similar. It is worth mentioning that the basic expression for one-way shear in ACI 318-02 [10] is the same for narrow beams and wide beams.

Hsiung and Frantz [4] concluded that no noticeable results on the ultimate shear capacity or differences in crack widths measured for wide beam having shear reinforcement ratios approximately 60% higher than the ACI 318 minimum limit. James et al. [5] investigated the shear behavior of reinforced concrete exterior wide beam-column-slab connections subjected to lateral earthquake loading. An experimental program of three reinforced concrete exterior wide beam-column-slab specimens was conducted. The wide beams were constructed with concrete strengths varying from 29 to 34.5 N/mm². Upon examining the beams after failure, they observed that the wide beams never exhibited any inclined cracking that could be characterized as related to shear. Observed cracks were narrow, vertical flexural cracks that opened very little. Stirrups strain gages never measured strains in the stirrups vertical legs greater than one-third of the yield strain, hence, they concluded that the wide beams performed well in the shear. On the other hand, the influence of member width on the shear stress at failure was investigated by Kani [6]. His test series compared the capacities of 610 mm wide by 305 mm deep beams with 162 mm wide by 305 mm deep companion beams, at shear span-to-depth ratios (a/d) of 3, 4, 5, and 6. The failure shear stresses in the wide beams were within 10% of the failure shear stresses of the corresponding narrow beams and as such he concluded that the width-to-depth ratio had no significant influence on the shear stress at failure. Khalil [7] carried out an experimental study to investigate the shear behavior of wide beams in hollow block slabs. His experimental investigation included nine medium-scale simply supported beams and five full-scale hollow block one way slabs with normal concrete strength. He concluded that the shear capacity of wide beam with shear reinforcement reached as high as 300% of those without shear reinforcement. The study did not mention any test results about the ductility of the tested beams.

In Egypt, the use of wide beams is popular in hollow block reinforced concrete slabs for constructional and architectural advantages. It is apparent that the shear design procedures for wide beam are not covered adequately in the current Egyptian Code of practice ECP-203[9]. According to the ECP-203, the contribution of shear reinforcement in wide beam is totally discarded and the shear strength provided by concrete equals 67% of the concrete shear strength for slender beams. The current ECP-203 provides specified minimum shear reinforcement to impart reserve shear strength by preventing sudden shear failure upon first diagonal tension cracking as a result of unexpected tensile forces or catastrophic loading. In addition, the ECP-203 requires the stirrups to be arranged so that the distance between stirrups branches across the beam section does not exceed
250 mm. All the previous requirements of the code may lead to a highly conservative and uneconomic shear design of wide beams. On the other hand, four international codes [8-12] requirements were reviewed and no similar provisions were found. As such, there is a need for experimental data on the shear behavior of wide beams.

The objective of this study is to evaluate the effect of the existence, spacing, yield stress and amount of the vertical stirrups on the shear resistance of reinforced concrete wide beams. The test results not only fill the gap of full-scale test data, but also contribute to the future development of design guidelines for contribution of the shear reinforcement for wide beams. Also, the study addressed the adequacy of ECP 203[8], ACI 318-11 [9], AASHTO [10], CSA 2004 [11] and EN1992 [12] requirements for shear design of wide beams.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens

The experimental program consisted of nine beams of 29 MPa concrete strength each tested in a four-point loading arrangement. All beams were constructed in the R.C. laboratory of the Housing and Building National Research Center. All beams were 700 mm wide, 250 mm deep, 1750 mm long and were tested at a shear span of 650 mm. This gives a shear span-depth ratio (a/d) equal to 3.0. High strength steel, grade 40/60, of 10, 12 and 22 mm diameter (denoted by T) was used in the experimental tests. Mild steel, grade 24/35, of 6 and 8 mm diameter (denoted by R) was also used. All the specimens were reinforced with identical longitudinal steel bars. In order to investigate the shear behavior, the specimens were designed to fail in shear (i.e., the flexural capacity was designed to exceed the shear capacity of the tested beams). Beam SB1 represents the control specimen with no web reinforcement. The amount of transverse reinforcement in the other specimens was varied by varying the spacing or the diameter of the stirrups. Typical concrete dimensions and reinforcement details of the test specimens are illustrated in Fig. 1. Table 1 shows the details of the test specimens.

Fig. 1: Test setup and details of tested beams
Table 1: Details of test specimens and test results

<table>
<thead>
<tr>
<th>Beam</th>
<th>Stirrups</th>
<th>Shear* cracking loads (kN)</th>
<th>Ultimate load, $P_u$ (kN)</th>
<th>#Increase in ultimate load%</th>
<th>$\Delta u$ mm</th>
<th>$\Delta f$ mm</th>
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<td>----</td>
<td>400</td>
<td>449.92</td>
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<td>SB2</td>
<td>R6/200 mm</td>
<td>420</td>
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<td>32.4</td>
<td>4.7</td>
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<td>R8/200 mm</td>
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<td>653.60</td>
<td>45.2</td>
<td>9.2</td>
<td>13.1</td>
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<tr>
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<td>R6/150 mm</td>
<td>430</td>
<td>622.96</td>
<td>38.2</td>
<td>7.6</td>
<td>11.6</td>
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<td>SB5</td>
<td>R8/150 mm</td>
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<td>50.2</td>
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<td>R6/100 mm</td>
<td>443</td>
<td>650.30</td>
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<td>R8/100 mm</td>
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<td>693.70</td>
<td>54.1</td>
<td>7.1</td>
<td>28.40</td>
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<tr>
<td>SB8</td>
<td>T10/200 mm</td>
<td>432</td>
<td>807.10</td>
<td>79.3</td>
<td>10.1</td>
<td>16.8</td>
</tr>
<tr>
<td>SB9</td>
<td>T10/100 mm</td>
<td>464</td>
<td>927.37</td>
<td>106.2</td>
<td>11.9</td>
<td>96.6</td>
</tr>
</tbody>
</table>

*approximate value with ±10 kN error

#Increase in ultimate load due to the presence of web reinforcement comparing with SB1

$\Delta f$ = Deflection at 80% of the ultimate load on the descending branch of the load-deflection curve.

$\Delta u$ = Deflection corresponding to the ultimate load.

2.2 Materials

Table (2) shows mix proportions by weight of the quantities needed for one cubic meter of concrete to achieve the target cube compressive strength.

Table 2: Mix proportions of the concrete

<table>
<thead>
<tr>
<th>Cement (kg/m$^3$)</th>
<th>Dolomite Kg/m$^3$</th>
<th>Sand Kg/m$^3$</th>
<th>W/C</th>
<th>Target compressive strength, $f_{cu}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1300</td>
<td>650</td>
<td>0.45</td>
<td>30</td>
</tr>
</tbody>
</table>

2.3 Instrumentation and Test Procedure

Test specimens were instrumented to measure the applied load, mid-span deflection, and strains of vertical reinforcement in the constant shear force region. A general view of the instrumentation is shown in Fig.1. A linear variable displacement transducer (LVDT) for measuring deflection was mounted at the bottom side of the midspan for each specimen. Two electrical resistance strain gauges mounted on the vertical stirrups were used to measure the steel strains up to yielding. The locations of the strain gauges are also shown in Fig1. Load was applied using a hydraulic jack of 2000 kN capacity in compression. The jack was equipped with a calibrated load cell of ± 1200 kN capacity to measure the applied load. The load was distributed equally by a spreader beam to two points along the specimen. The test was continued after the ultimate load in order to evaluate the post peak behavior of the tested beams. During testing, the general deformational behavior was tracked. The development of cracks was marked along the sides of the specimens. At each load stage, the electrical strain gauges, load cells and (LVDT) voltages were fed into the data acquisition system. The voltage excitations were read, transformed and stored as micro strains, force, and displacement by means of a computer program that runs under the Lab
View software. Data obtained from these gauges were later used to estimate the cracking, the yield and the ultimate loads of the test specimens.

3 TEST RESULTS

3.1 Cracking Behavior

Typical behavior of beams is introduced through cracks pattern distributions recorded at applied load increments as shown in Fig. 2. For all specimens, the first crack development, crack propagation, and plane of failure were observed during the test. As stated before; all tested specimens were designed to fail in one way shear and this presumption was investigated for all tested specimens. The general behavior of all tested specimens was relatively similar and the crack development followed a similar pattern in all tested specimens. The tested beams were free of cracks in the early stages of loading. All beam specimens failed in shear and shear cracks crossed the compression zone of beam section. For specimens SB1 to SB5 the shear cracks started without appearance of flexural cracks. For specimen SB6 to SB9, it was observed that the first early cracks were vertical flexural cracks occurred in the specimens mid span and near mid span section and upon increasing the applied load, a series of flexural cracks was formed at the bottom in the shear span region and gradually propagated towards the two loading points while no crack had been observed at beam ends. By increasing the applied load and at intermediate loading stages, a new series of flexural cracks was formed in the shear span region then rotated to form flexural-shear cracks joining the loading and supporting points. During subsequent loading stages, additional diagonal shear cracks appeared and developed through a substantial depth of the specimen section and propagated towards the top of the specimen.
Table 1 summarizes the results of the tested beam specimens. The table gives the main characteristics of each specimen, the shear cracking load, the ultimate load and the corresponding displacement.

3.2 Mode of Failure

The Specimens SB1 to SB5 failed in a mode of shear failure characterized by diagonal shear tension mode of failure as shown in Fig. 2. The typical behavior of the SB6, SB7 and SB8 was characterized by diagonal shear mode of failure accompanied with crushing of the web concrete and this failure may be called shear compression failure. On the other hand, the failure of Specimen SB9, having the higher web reinforcement (T10/100mm) was characterized by crushing of concrete in compression fiber. Failure of beam SB9 exhibited the role of steel stirrups in changing the mode of failure and increasing the ultimate load.

3.3 Load-Deflection Relationship

The applied load was plotted against the vertical deflection measured at midspan for all tested beams as shown in Fig 3. The load-deflection curves of the specimens show that shear reinforcement had no significant impact on the deflection values at pre-cracking stage. On the other hand, the transverse reinforcement had noticeable impact on the ultimate load and the failure displacement $\Delta_f$. Beyond the ultimate load, the descending branch of the curves had a real relation with the amount and spacing of web reinforcement. In addition to the previous remarks, the following findings can be noticed:

1- Expectedly, the control beam SB1 with no web reinforcement had a sudden shear failure with rapid stiffness degradation beyond its ultimate load accompanied with the lowest value of $\Delta_f = 6.8$ mm.

2- Beam SB6, with vertical stirrups of R6/100 mm, showed improved ultimate load and post peak behavior. The ultimate load of this beam is higher than those of beams SB2 (R6/200mm) and SB4 (R6/150mm) by 12% and 6% respectively comparing with the control beam which indicates the
beneficial effect of decreasing the spacing between stirrups. Also, the failure displacement of SB6 is higher than those of beams SB2 and SB4 by 190% and 150% respectively comparing with the control, Table 1 and Fig 3-a.

3- Regarding Fig 3-b, Beam SB7, with vertical stirrups of R8/100 mm, significantly showed improved ultimate load and post peak behavior. The ultimate load of this beam is higher than those of beams SB3 (R8/200mm) and SB5 (R8/150mm) by 10% and 5% respectively comparing with the control beam SB1. The failure displacement of SB7 is higher than those of beams SB3 and SB5 by 225% and 190% respectively comparing with the control beam, see Table 1.

4- From Fig. 3-c, Beam SB9, with vertical stirrups of T10/100 mm, showed the highest ultimate load which was higher than beam SB8 (T10/200mm) by 27% comparing with the control beam. Among the tested specimens, beam SB9 recorded the highest value of failure displacement =96 mm

5- The ultimate load of beams SB3, SB5 and SB7 is higher than those of beams SB2, SB4 and SB6 by 12.5%, 13% and 9.5% respectively comparing with the control beam SB1. The failure displacement of SB3, SB5 and SB7 is higher than those of beams SB2, SB4 and SB6 by 67%, 55% and 91% respectively comparing with the control beam indicating the fruitful effect of increasing the amount of stirrups, see Table 1.

3.4 Ductility

Ductility is the ability of the reinforced concrete member to sustain large inelastic deformations without excessive strength deterioration. The ductility can either be represented in terms of the ratio of maximum displacement to the yield displacement, both measured at mid span, or in terms of the displacement energy consumed by the specimen during the test measured as the area under the load displacement curve till the failure load which can be considered 80% of the of the ultimate load on the descending branch of the load-deflection curve. Since the flexure mode of failure was prevented for all specimens to allow for shear mode of failure, it was found more suitable to use the second measure of ductility. Fig. 4 shows displacement energy measured for all tested specimens. The figure undoubtedly shows that the increase in web reinforcement amount and yield stress generally increases the ductility. Also, as the spacing between web reinforcement decreased, the ductility of specimen increased.

![Fig 3-a: Load-deflection relationship for specimens with R6 web reinforcement](Image)

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Fig 3-b: Load-deflection relationship for specimens with R8 web reinforcement

Fig 3-c: Load-deflection relationship for specimens with T10 web reinforcement
3.5 Strains in Web Reinforcement

Two electrical strain gages were attached to stirrups vertical branches per specimen, see Fig.1. The readings of strain gauges in all the test specimens indicated that the transverse reinforcement developed yielding before failure of specimens and also entered the strain hardening range exhibiting strains much higher than the yield strain which indicates that the stirrups were successful in resisting the shear stresses in test specimens. The rate of steel strain increase was small just after formation of first shear crack and increased rapidly when specimens approached failure load. Unfortunately, the strain gauges situated along the transverse reinforcement of beams SB2 and SB3 were inoperative. Fig. 5 plots the load strain relationships of the vertical stirrups for tested specimens. Examining Fig.5, some of the strain gages output were compression with small values in the early loading stage and this may be attributed to applying the load on the top surface of the beams.
3.6 Effect of Transverse Reinforcement

The experimental program was conducted to study the effect of the presence, amount and spacing of transverse steel on the shear behavior of wide beams. Although it had no significant effect on the initial stiffness, provision of the steel stirrups is shown to enhance the ultimate capacities and the ductility of the tested beams. The enhancement increases with increasing the amount of stirrups and decreasing the spacing between them, see Fig. 3. Compared to Specimen SB1, the maximum increase in the shear cracking load was 16%, and the increase in the ultimate load ranged between 32% and 106% depending on the configuration of vertical stirrups, Table 1. Inspecting Fig. 4, the specimens provided with steel stirrups exhibited more ductile behavior compared to that of Specimen SB1. The energy dissipation for specimen SB9 was about forty times specimen without shear reinforcement. The shear reinforcement in the form of stirrups contributes to the behavior of the shear mechanism by improving the contribution of the dowel action and limiting the opening of inclined shear cracks, thus enhancing and persevering shear transfer by aggregate interlock. Shear reinforcement is used in concrete beam to preserve the overall integrity of the concrete contribution allowing the development of additional shear forces. As shown in Fig. 3, high grade steel was more effective in the contribution of the shear strength of wide beams than mild type. It is obviously concluded that the effect of the transverse reinforcement in shear resistance of the wide beams should not be ignored.

4. COMPARISON BETWEEN TEST RESULTS AND AVAILABLE CODES FORMULAS FOR SHEAR STRENGTH

In this section, the experimental results were used to examine the applicability of the shear design formulas for wide beams given in different design codes. The codes examined are ECP 203[8], ACI 318-11 [9], AASHTO [10], CSA 2004 [11] and EN1992 [12]. As stated before, the current Egyptian Code of practice, ECP 203-2007, determines the concrete shear capacity of shallow wide beams equal to two-third of slender concrete with no dependence on any form of web reinforcement while stressing the need to provide specified minimum web reinforcement. It should be noted that ACI 318, AASHTO, EN1992 and CSA treat with shear capacity of wide beams as
slender beams. In other words, these codes completely acknowledge the effect of web reinforcement. On the other hand, the EN1992 code neglects the concrete contribution when shear stress exceeds the contribution of concrete in shear. All the partial factors of safety for materials and the resistance factors included in the codes formulas are set to unity. This will give an unbiased comparison of the capacities predicted by the five codes. It should be mentioned that the given values of the experimental strength $P_{exp}$ in Table 2 represent half of the ultimate loads in Table 1.

As shown in Table 3, prediction of shear capacity for specimen SB1, without steel stirrups, clarified that The ECP203[8], ACI318-08[9], AASHTO LRFD[10] and CSA A23.3 [11]provisions resulted in acceptable predictions of the ultimate load with a safety factor above 1.6 while the EN1992 code [12] results are shown to be less conservative. Comparison between the experimental and predicted shear capacity of specimens with shear stirrups by ECP203 is showing that contribution of steel stirrups should not be discarded as the average value of $(P_{exp}/P_{the})$ is 2.7 while the average value of $(P_{exp}/P_{the})$ is 1.5 for ACI 318-08, 1.4 for CSA-A23.3, 1.6 for AASHTO-LRFD and 1.3 for EN1992 which indicates better agreement with test results and this is attributed to the fact that these codes totally consider the contribution of web reinforcement.

Table 3: Calculated shear strength of the tested beams according to the available codes versus experimental values, kN

<table>
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</table>

5. CONCLUSIONS

Based on the study presented herein, the following conclusions have been drawn:

[1] The shear reinforcement in the form of stirrups significantly contributes to the shear behavior of wide beams by improving the contribution of the dowel action, and limiting the opening of inclined shear cracks, thus its effect in form of vertical stirrups on shear capacity of wide beams should be considered.

[2] The contribution of web reinforcement to the shear capacity is proportional to the amount of shear reinforcement. The increase in the shear capacity ranged from 32% to 132% for the range of the tested beams.
The shear reinforcement amount significantly enhances the ductility of the wide beams. Also, as the spacing between web reinforcement decreased, the ductility of specimen was increased.

High grade steel was more effective in the contribution of the shear strength and ductility of wide beams.

Among the used codes, the ECP 203-2007 formula for estimating the shear capacity of wide beams achieved the highest average value of the ratio \( \frac{P_{\text{exp}}}{P_{\text{th}}}=2.7 \) indicating that this formula is highly conservative and should be revised to account for the existence of the web reinforcement.

For the other used codes, the ratio of \( \frac{P_{\text{exp}}}{P_{\text{th}}} \) ranged from 1.3 to 1.6 as they totally acknowledge the effect of the web reinforcement in wide beams.

REFERENCES

[8] Building Code Requirements for Structural Concrete(ACI 318-08) and Commentary (318R-05),” American Concrete Institute, Farmington Hills, Mich.