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Improved Shear Performance of Bent-Up Bars in Reinforced Concrete Beams

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Abstract

Shear failure of reinforced concrete beams is often sudden and catastrophic. This sudden failure, due to shear, made it necessary to explore more effective ways to design reinforced concrete beam for shear. The reinforced concrete beams show different behavior at the failure stage in shear compare to the bending, which is considered to be unsafe mode of failure. The shear cracks progressive rapidly without sufficient advanced warning, and the diagonal cracks that develop due to excess shear forces are considerably wider than the flexural cracks. The cost and safety of shear reinforcement in reinforced concrete beams led to the study of other alternatives. Bent-up bars have been used in the past. New form of bent-up bars will be used. Cross bars will be welded to these bent-up bars making rectangles capable of resisting shear in a plane compared to single bar performance. The main purpose is to identify the most efficient shape to carry shear forces at the lowest cost. Several reinforced concrete beams were carefully prepared and tested in the lab. The results of these tests will be presented and discussed. The deflection of each beam is also measure at a given applied load. The propagation of shear cracks was also closely monitored.

Keywords: Bent-up, Deflection, Beam, Crack, Stirrup

Introduction

Reinforced concrete beams are structural members used to carry loads primarily by internal moments and shears. In the design of a reinforced concrete member, flexure is usually considered first, leading to the size of the section and the arrangement of reinforcement to provide the necessary resistance for moments. For safety reasons, limits are placed on the amounts of flexural reinforcement to ensure ductile type of failure. Beams are then designed for shear. Since shear failure is frequently sudden with little or no advanced warning, the design for shear must ensure that the shear strength for every member in the structure exceeds the flexural strength. The shear failure mechanism varies depending upon the cross-sectional dimensions, the geometry, the types of loading, and the properties of the member.

Reinforced concrete beams must have an adequate safety margin against bending and shear forces, so that it will perform effectively during its service life. At the ultimate limit state, the combined effects of bending and shear may exceed the resistance capacity of the beam causing tensile cracks. The shear failure is difficult to predict accurately despite extensive experimental research. Retrofitting of reinforced concrete beams with multiple shear cracks is not considered an option.

Diagonal cracks are the main mode of shear failure in reinforced concrete beams located near the supports and caused by excess applied shear forces. Beams fail immediately upon formation of critical cracks in the high-shear region near the beam supports. Whenever the value of actual shear stress exceeds the permissible shear stress of the concrete used, the shear reinforcement must be provided. The purpose of shear reinforcement is to prevent failure in shear, and to increase beam ductility and subsequently the likelihood of sudden failure will be reduced.

Normally, the inclined shear cracks start at the middle height of the beam near support at approximately 45^0 and extend toward the compression zone. Any form of effectively anchored reinforcement that intersects these diagonal cracks will be able to resist the shear forces to a certain extent. In practice, shear reinforcement is provided in three forms; stirrups, inclined bent-up bars and combination system of stirrups and bent-up bars.

In reinforced concrete building construction, stirrups are most commonly used as shear reinforcement, for their simplicity in fabrication and installation. Stirrups are spaced closely at the high shear region. Congestion near the support of the reinforced concrete beams due to the presence of the closely spaced stirrups increase the cost and time required for installation.

Bent up bars are also used along with stirrups in the past to carry some of the applied shear forces. In case where all the tensile reinforcement is not needed to resist bending moment, some of the tensile bars where bent-up in the region of high shear to form the inclined legs of shear reinforcement. The use of bent-up bars is not preferred nowadays.

In this study, four reinforced concrete beams were tested using new shear reinforcement bent-up bar system and the traditional stirrups. Several shapes of bent-up bars are used to study the effect of bent-up bar configuration on the shear load carrying capacity of the beams. The first beam, B1, is used as a reference beam where no shear reinforced of any kind is provided. The other three beams were reinforced by bent-up bars in one side and the other side is reinforced by stirrups. Extra stirrups were used to make sure that beam will fail by shear in the bent-up bars side. In this investigation, all of the beams are supposed to fail solely in shear, so adequate amount of tension reinforcement were provided to give sufficient bending moment strength. This study aims at investigating a new approach of design of shear reinforcement through the use of bent-up bars provided in the high shear region. The main advantages of this type of shear reinforcement system are: flexibility, simplicity, efficiency, and speed of construction.

Piyamahant (2002) showed that the existing reinforced concrete structures should have stirrup reinforcement equal to the minimum requirement specified the code. The theoretical analysis shows that the amount of stirrup of 0.2% is appropriate. The paper concluded that small amount of web reinforcement is sufficient to improve the shear carrying capacity. The study focused on the applicability of the superposition method that used in predicting shear carrying capacity of reinforced concrete beam with a small amount of web reinforcement at the shear span ratio of 3. Also the failure mechanisms were considered when small amount of stirrup used.

Sneed, and Julio (2008) discussed the results of experimental research performed to test the hypothesis that the effective depth does not influence the shear strength of reinforced concrete flexural members that do not contain web reinforcement. The results of eight simply supported reinforced concrete beam tests without shear and skin reinforcement were investigated. The beams were designed such that the effective depth is the variable while the values of other traditionally-considered parameters proven to influence the shear strength (such as the compressive strength of concrete, longitudinal reinforcement ratio, shear span-to-depth ratio, and maximum aggregate size) were held constant. The values selected for the parameters held constant were chosen in an attempt to minimize the concrete shear strength.

Noor (2005) presented several results of experimental investigation on six reinforced concrete beams in which their structural behavior in shear was studied. The research conducted was about the use of additional horizontal and independent bent- up bars to increase the beam resistance against shear forces. The main objectives of that study were studying the effectiveness of adding horizontal bars on shear strength in rectangular beams, the effectiveness of shear reinforcement, and determining the optimum amount of both types of shear reinforcement to achieve a shear capacity similar to that of a normal links system. From experimental investigation of the system it was found that, the use of independent horizontal and bent-up bars as shear reinforcement were stronger than conventional shear reinforcement system.

Gaun (2008) focused on the effectiveness of independent inclined bars as shear reinforcement in rectangular beams where these bent-up bars were linked to the tension and support reinforcement then the anchorage length and the amount of the independent bent-up bars on its capacity in carrying shear were investigated. Results of five rectangular beams were presented in which the effect of using short anchorage of the independent bent-up bars on the capacity of the beam in carrying shear. The influence of various amounts of bent-up bars was also investigated.

All the beams, in that study were provided with identical longitudinal reinforcement but with different sets of shear reinforcement. In one of the beams, the shear reinforcement was in the form of closely spaced vertical links, while the other three beams had nominal link combined with independent bent-up bars of various amount and anchorage lengths. Test results indicated that the anchorage length of the bent-up bars is insignificant to the capability of the bars in carrying shear. It is also suggested that the provision of the large amount of bent-up bars does not produce the corresponding advantage to the beams shear capacity. It may, therefore, be concluded that independent bent-up bars be used effectively and economically in reinforced concrete beams.

ACI Code Provision for Shear Design

According to the ACI Code, the design of beams for shear is to be based on the following relation:

$$V_u \le \varnothing V_n \qquad (1)$$

Where: V_u is the total shear force applied at a given section of the beam due to factored loads and $V_n = V_c + V_s$ is the nominal shear strength, equal to the sum of the contribution of the concrete and the web steel if present. Thus for vertical stirrups

$$V_u \le \varnothing V_c + \frac{\varnothing A_v f_{yt} d}{s} \qquad (2)$$

and for inclined bars

$$V_u \le \varnothing V_c + \frac{\varnothing A_v f_{yt} d(\sin\alpha + \cos\alpha)}{s} \qquad (3)$$

Where: A_v is the area of one stirrup, α is the angle of the stirrup with the horizontal, and S is the stirrup spacing.

The nominal shear strength contribution of the concrete (including the contributions from aggregate interlock, dowel action of the main reinforcing bars, and that of the un-cracked concrete) can be simplified as shown in Eq. 4.

$$V_c = 0.17\lambda\sqrt{f'_c}\, b_w d \qquad (4)$$

Where: b_w and d are the section dimensions, and for normal weight concrete, $\lambda = 1.0$. This simplified formula is permitted by the ACI code expressed in metric units.

Tested Beams

The study was based on experimental investigation of four beams. All specimens were of the same size and reinforced with identical amount of longitudinal steel. The beams were tested to fail due to two point loads by shear given the ratio of a shear span to effective depth of 2.5. The compressive strength of concrete is measured according to ASTM C 192-57. Fifteen concrete samples were prepared. The compressive strength of concrete is measured at the 28th day. The concrete compressive strength results range between 34.9 N/mm^2 to 37.2 N.mm^2. The variables in these specimens are the shear reinforcement systems.

Four reinforced concrete beams were prepared for the test, B1 through B4. All of the same dimension 2000 mm length, 200 mm width and 250 mm depth. The effective length was also kept at constant value of 1800 mm. Summary of shear reinforcement system for each specimen is given in Table (1). Beam, B1, was designed without any shear reinforcement, but with 2ø10 top steel and 6ø10 bottom steel reinforcement. The Beams, B2, B3, and B4 were designed with 2ø10 top steel and 8ø10 bottom steel reinforcement out of which two of the bottom bars were kept straight while the others were bent, then welded with ø10 steel piece forming different shapes. In the other side of the beam 1ø6mm at 50mm spacing vertical stirrups were used. Figure (1) shows details of steel reinforcement used in beams B2, B3, and B4. Figure (2) shows the cage used in beam, B2. Beams B3, and B4, cages are similar, but beam, B3, bent-up bars are for forming three crossed rectangles, while beam B4 bent-up bars are forming three simple rectangles.

Table 1: Steel reinforcement details

No	**Wt. of Steel Cage (N)**	**Main Reinforcement**		**Shear Reinforcement**	
		Bottom	Top	Vert. stirrup	Bent-up
B1	106	6ø10	2ø10	-	-
B2	177	2ø10 straight + 6 ø10 bent-up at left side only	2ø10	1 ø 6 @ 50 mm at right side only	6 ø 10 bent-up at left side only
B3	179	2ø10 straight + 6 ø10 bent-up at left side only	2ø10	1 ø 6 @ 50mm at right side only	6 ø 10 bent-up at left side only
B4	168	2ø10 straight + 6 ø10 bent-up at left side only	2ø10	1 ø 6 @ 50 mm at right side only	6 ø 10 bent-up at left side only

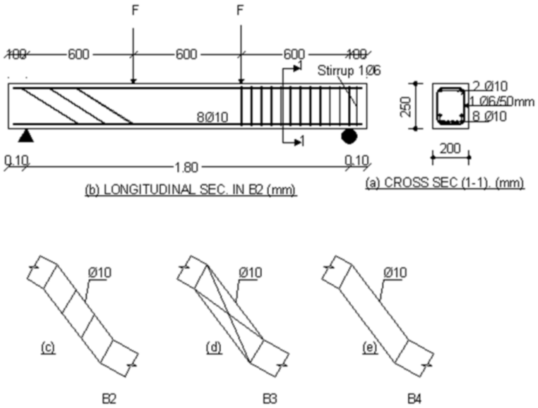

Figure 1: Steel reinforcement used in beam B2, B3, and B4.

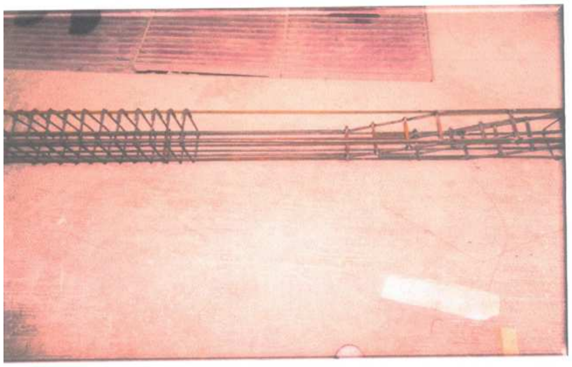

Figure 2: Steel cage reinforcement of Beam B2

Test Procedure

Prior to testing, the surface of the specimens was painted with white emulsion so that the detection of the cracks during the test was easier and their making become clearer. At age 28 days reinforced concrete beams were prepared for testing. The lines position of point load, support and the middle of beam span were marked to ease the installation of beam in testing frame. The test was carried out with the specimen placed horizontally in a simple loading arrangement. The beam was supported by solid round steel on their two edges as simply supported member. All the beams were designed to ensure the beams will only fail in shear rather than in flexure.

To ensure that shear cracks will occur near the support, two point loads were applied symmetrically to the beam with a_v less than 2.5d. In this testing, $a_v \approx 550$ mm, where a_v is shear span (the distance from the point of the applied load to the support), and d is the effective depth of a beam.

A loading jack was placed at the mid-span position above the beam. The load was applied by jacking the beam against the rig base member at a constant rate until the ultimate load capacity of the beam was reached. A universal column section was used to transfer the load to the beam at two point loads via transfer girder. A reasonable time interval was allowed in between 20.0 kN load increments for measuring deflections, marking cracks, measuring the shear reinforcement strain and recording the ultimate load. Each beam took about two hours to complete the test. Figure (2) shows the set-up of the test

Figure 2: Set-up of the test

Test Results

Four beams were prepared in this study for testing by applying two concentrated loads at 700 mm distance from the edges of the beams. Strain gages were used to measure the deformation. Loads were applied gradually while monitoring, flexural cracks, shear cracks, deflections and deformations.

The beam B1 was provided with the longitudinal reinforcement only. Three stirrups were used only to hold the main bars in place (one at the center of the beam and other two are placed at the either side of the beam). The load is applied gradually. When the applied load reached 80 kN, hair cracks became visible in the shear region at both sides of the beam. The main diagonal cracks appeared at the load of 100 kN in the shear region at approximately 30^o with the horizontal axis. The main diagonal crack increased in length and width with the increase of the applied load. The beam failed by shear at a load 135 kN and 10.35 mm maximum deflection at the center of beam.

The other beams B2, B3, and B4 were provided with sufficient longitudinal flexural steel reinforcement and two types of shear reinforcement (vertical stirrups at left side of Beam and improved welded bent-up bars at right side). The behavior of these beams under load was almost identical to the beam B1 except that the propagation of the main diagonal shear crack was at a slower rate. The angle of the main crack was also measure to be approximately 30^o for all of the beams. Beams B2, B3, and B4 failed by shear at a load of 225 kN, 220 kN, and 230 kN respectively. These beams failed by shear at the stirrups sides. Figure (3) shows the failure mode of beam B4 which considered to identical mode of failure for beams B2, and B3.

Figure 3: Beam B4 mode of failure at 230 kN applied load.

Deflection

The maximum deflection at the center of each tested was measured. The maximum deflection at the center of each beam was almost identical ranging between 10 mm to 11 mm. The average failure load of beams B2, B3, and B4 is 225 kN compared to 135 kN for of Beam B1.

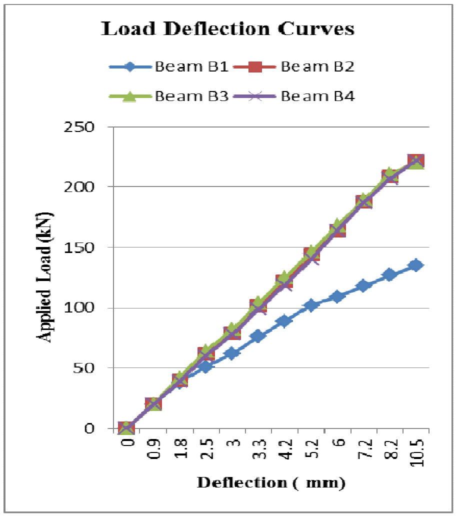

Figure 4: Load deflection relationship of all tested beams

Conclusion

This study presented a new type of shear reinforcement using rigid bent-up bars. These bent-up bars resisted shear in a plane rather than the tradition linear configuration. The experimental data shows that there is substantial improvement in shear performance of reinforced concrete beams. Also this study shows that the use of this type of rigid bent-up bars uses less steel by eliminating the use of traditional stirrups. The width and length of the cracks were observed to be less at the bent-up bars side compared to the traditional stirrups side.

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