International Journal of Engineering & Technology, 7 (4) (2018) 5783-5789

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i4.26838
Research paper

Failure patterns of dual headed bars in concrete loaded in tension and compression

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Abstract

Headed bars are used as an alternative to hooked bars and reduce steel congestion and fabrication difficulties in reinforced concrete joints. But, according to the ACI 318 code, classical headed bars cannot be used to develop bars when they are subjected to compression loading. The use of dual headed bars can provide a solution to anchorage problems for bars loaded in compression. This paper presents comparison of failure patterns for classical single headed bars and dual headed bars loaded in tension and compression. The results showed that dual headed bars exhibited significant higher anchorage capacity than classical single headed bars loaded in compression. No improvement, or even slightly lower anchorage strength was recorded when dual headed bars were loaded in tension. The failure pattern in compression loading is improved a lot by using dual heads in which end blowout mode of failure is prevented.

Keywords: *Headed Reinforcement; Development Length; Compression Loading; Failure Pattern; Anchorage; Bond.*

1. Introduction

In many reinforced concrete joints, anchorage through straight bar embedment cannot develop reinforcement due to limited available elements dimensions. Hooked bars are used in such locations to reduce the required development length, but hooks usually create reinforcement congestion and involve construction difficulties. Headed bars are generally used as an alternative to hooked bars. The anchorage capacity and failure patterns of classical headed reinforcing bars have studied by many researchers [3-9]. Most studies concluded that headed bars can develop reinforcement in tension as good as hooks and in many cases are superior to hooks. To study anchorage behavior and to distinguish between modes of failure of headed bars, many researchers used a useful distinction between shallow embedment and deep embedment of headed bars. Shallow embedment of bars was defined as the case in which the ratio of bar embedment to least lateral cover dimension is less than five. If the embedment ratio is more than five, the bar is considered as deeply embedded. The dominant failure pattern in shallow embedded bars is concrete breakout in a way similar to failure of anchor bolts in concrete. DeVries [3] and Bashandy [4] observed that the main failure pattern in deeply embedded headed bars is blowout of side concrete cover, particularly when the side cover is relatively small. Fig.1 shows difference in failure modes between shallow and deep embedded bars. When headed bars are loaded in compression, Papadopoulos et al. [9] observed an end blowout of concrete cover in specimens of deck of bridge when the concrete cover above the head is small and is not covered by the deck slab top reinforcement. Lee and Yu [10] used different anchorage methods to study the response of exterior beam-column Joints to cyclic loading. They found that using double mechanical devices attached on each beam reinforcing bar within the joint improved the cyclic behavior of exterior beam-column joints significantly. The improvement in cyclic behavior was due to preventing end blow out mode of failure on the back of the joint and preventing deterioration of bond along the reinforcing bar in the joint. However, their study did not include many parameters affecting the anchorage behavior and failure modes of bars with double mechanical attachments.

Shao et al. [6] tested 202 specimens representing exterior beam-column joints. They used classical single headed bars in the simulated beam-column joints. The purpose of their study was to assess the applicability of the existing ACI code provisions on the anchorage of headed bars with high-strength steel and concrete. They reported two types of failure modes in their study, concrete breakout and side-face blowout. They concluded that the provisions of the ACI 318-14 code do not account suitably for the effects of many parameters on anchorage of headed reinforcement. They proposed a new equation for the development length of headed bars to be included in the new edition of the ACI318-code. With support of the state of California department of transportation, Papadopoulos et al. [9] reported an experimental and numerical study on anchorage behavior of classical headed bars anchored in bridge slab-columns joint. Three full-scale bridge slab-column joint specimens were tested under lateral loading. They concluded that small embedment lengths ($8.7d_b$ and $9.8d_b$) in relatively thin slabs were sufficient to develop the columns moment but caused moderate to severe end blowout in the concrete cover of the slabs. They reported that punching cracking (concrete blowout) at head locations was the main failure mode rather than the breakout failure caused by tension on the bar. Therefore, they recommended placing the bar heads below the top layer of reinforcement in the deck slab in order to prevent end blowout at head locations, (Fig.1).

McConnell and Wallace [11] constructed 18 beam-column knee joints using single headed bars and hooked bars. They tested the specimens under cyclic loading to study their behavior under seismic loading, and they recommend joint details for seismic design. Based on their work, they reported push-out mode of failure on the top corner of some knee joint specimens. This failure mode was a result of compressive forces on the head. They recommended

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providing sufficient concrete cover behind the head by terminating longitudinal beam bars inside the column core, and proposed using additional horizontal hoops to restrain the heads and control this mode of failure.

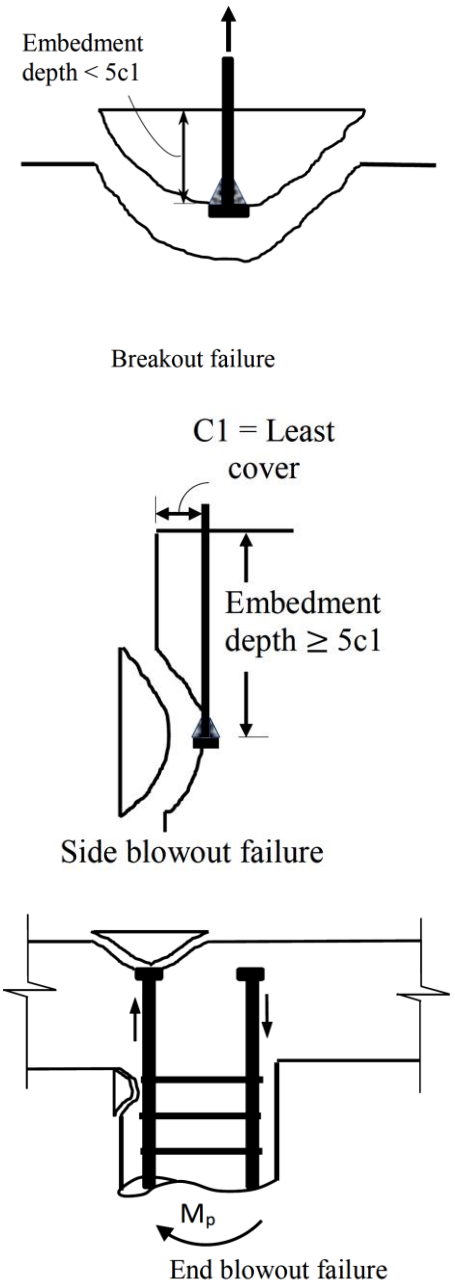


Fig. 1: Failure Modes of Classical Headed Reinforcement Exhibited by Past Research.

The use of dual headed bars provide a promising solution through improving bond performance in tension and compression loading of bars. In this research, to understand the bond behavior of dual headed bars, the failure mechanism for dual headed bars is studied in both compression and tension loading and compared with classical single headed bars.

2. Research significance

According to the ACI- 318 code, using hooked bars and classical headed bars are not effective in developing bars in compression. Hence, there is no currently other way to develop bars in compression than using straight embedment of bars. Therefore, reducing the development length of bars in compression is somewhat difficult with such limitations. But, there are situations that require developing bars in compression within a relatively short embedment of bars. Examples are in slab-column joints and in knee joints subjected to seismic loading where special detailing is required as discussed previously, otherwise an end blowout mode of failure is expected.

To improve beam-column joint performance and acquire a ductile plastic hinge in the joint, the tension and compression beam reinforcement must be developed within the available short distance in the column core. To be consistent with the ACI 318-14 code (R25.4.4.2), headed bars in beam-column joints should extend through the confined column core to the far face of the column, allowing for cover behind the head even if the consequent embedment length is more than the required development length. However, in seismic loads, such embedment of bars in the joint leaving a small concrete cover behind the head will not be effective in resisting end blowout forces when the bar forces are changed from tension to compression. Using dual headed bars can provide a solution to the problem of end blowout of concrete cover. No data available showing that dual headed bars can be used to develop reinforcement in compression loading. Their behavior in tension and compression loadings should be studied.

The objective of this study is to understand the behavior and failure modes of dual headed bars loaded in compression as well as in tension.

3. Experimental work

Experimental work was done to study the anchorage performance and modes of failure of dual headed bars embedded in concrete and loaded in tension and compression forces. Thirty five specimens containing single or dual headed bars were cast and tested in pullout and compression loading. Eight specimens were tested in pullout, and concentrating on bond behavior of headed bars under compression forces, the balance of specimens were tested under compression loading.



(A)



(B)

Fig. 2: Dual Headed Bars (A) Circular Heads before Welding (B) Dual Headed Bars after Head Attachments.

4. Materials and methods

Reinforcing bars of diameters 16 and 22 mm were used in this research. Yield strength of bars was 570 MPa and ultimate strength was 710 MPa on average. Heads were attached to the reinforcing bars using 20 mm thick hollow circular plates by arc welding, the net bearing area of the heads were 3.8 times the area of the bar, (Fig. 2).

Concrete mix with different target compressive strengths were used. Mix proportions of the concrete are shown in Table 1. Type I Portland cement, gravel with a maximum size of 20 mm, and river sand of gradation F conforming to BS EN 882 with a fineness modulus of 2.2, were used for all mixes. To obtain a slump of 100mm, Naphthalene Sulphonate based superplasticizer type Rheobuild 561 was used in some mixes. Table 1 shows mix proportions for different target compressive strengths. Three standard 150 mm concrete cubes were cast for each batch to keep track of compressive strength for concrete.

Table 1: Mix Proportions for Concrete of Different Target Strengths

Material	25 MPa w/c = 0.51	35 MPa w/c = 0.44	45 MPa w/c = 0.38	55 MPa w/c = 0.34
Type I Cement kg/m^3	320	350	370	400
Water kg/m^3	163	154	140	136
River sand kg/m^3	790	780	730	720
River gravel kg/m^3	1060	1050	1090	1080
Super plasticizer kg/m^3	-	1.2	2.2	3.1

The specimens were designed to resemble stress distribution in the beam-column joint conditions, as a strut-and-tie model can form. The sides of the specimens were enlarged to provide adequate space for support of the reaction base plates and preventing stress concentrations at the edges of specimens, (Fig. 3). In the pullout test, a tensile force was applied to the bar using a 20 ton hollow hydraulic ram and the reactive forces were provided at the specimen sides. The load was read using the oil pressure gauge attached to the hydraulic ram. Double steel channels of section C100x50x10 were used to transfer forces to the base plates at the specimen edges.

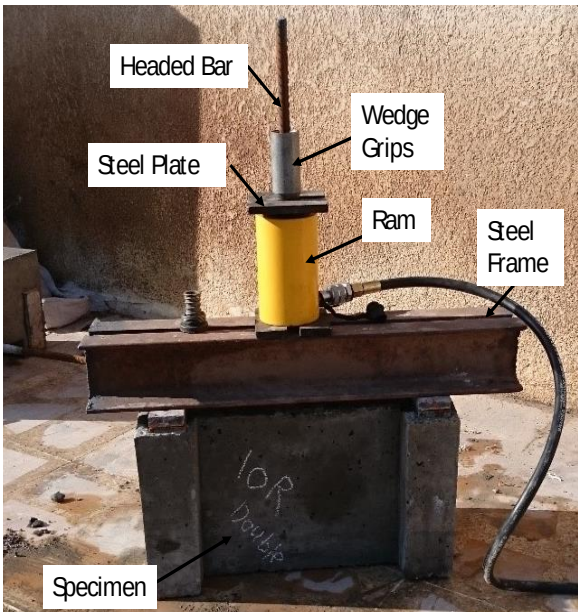


Fig. 3: Experimental Setup for Pullout Test.

In the compression tests of headed bars, same specimen shape and configurations were used. The specimen was put in a steel frame, and a compressive force was subjected on top of the bar and the reactive forces were provided by supports under the specimen. A load cell was put between the hydraulic jack and the steel frame to read the compression force on the bar, (Fig. 4). The portion of bar above the interior head was debonded by covering with PVC tubes in both tension and compression tests to eliminate effect of bond along this portion on test results. Specimen configuration and dimensions are shown in Fig. 5. Bar embedment length in pullout tests ℓ_{eht} is taken as the distance between bearing face of the exterior head and specimen top face (Fig. 5c).

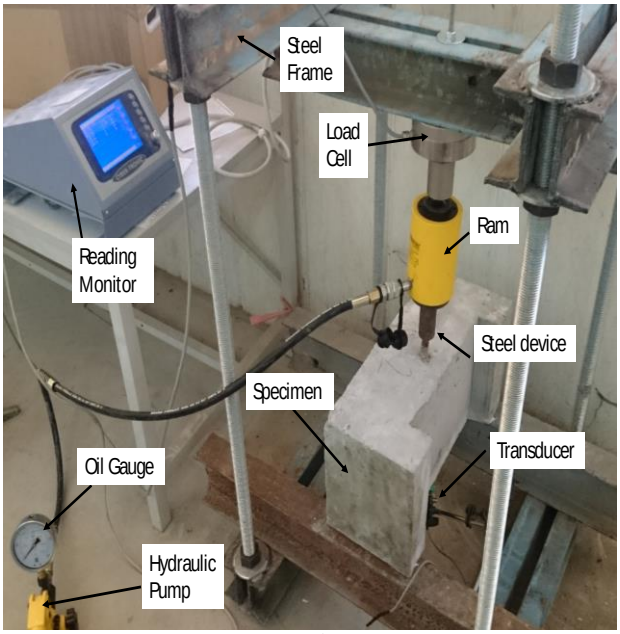
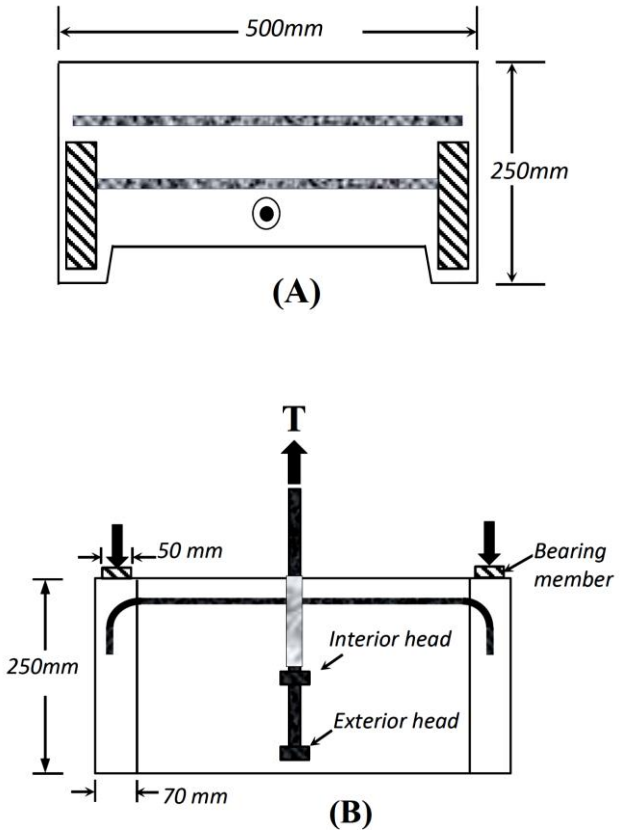


Fig. 4: Experimental Setup for Compression Loading.

Since the purpose of this work is to study anchorage behavior and modes of failure for dual headed bars, embedment length was chosen such that failure is governed by concrete failure rather than by yielding or fracture of bar. Two No. 12 mm longitudinal bars were put on top of the specimens to provide for flexural demand.



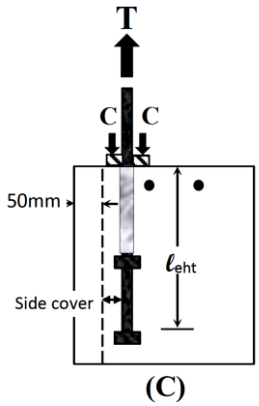


Fig. 5: Test Specimen Definition in Pullout Loading with Forces Acting on it (A) Top View (B) Front View (C) Side View.

Since interior head is the principal head in determining the strength capacity in compression loading of the bar, bar embedment length in compression loading ℓ_{ehc} is defined as the distance between the bearing face of the interior head and the specimen lower face (Fig. 6c). Two No. 12 mm longitudinal bars were put on bottom of the specimen to provide for flexural demand.

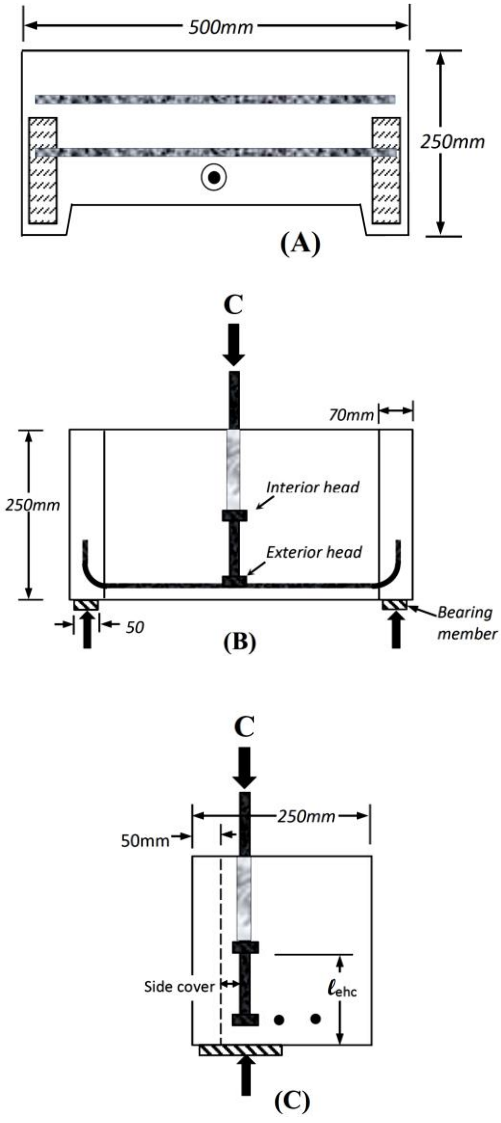


Fig. 6: Test Specimen Definition in Compression Loading with Forces Acting on It (A) Top View (B) Front View (C) Side View

5. Results and discussion

In pullout tests, dual headed bars generally showed slightly lower anchorage strength than classical single headed bars. The pullout capacity at failure for a specimen with single headed bar was 84.4 kN while for specimens had dual headed bars with a distance between heads varying between $4d_b$ and $7d_b$, the average pullout capacity was 80.14 kN, which is about 5% less than the single-headed bar capacity. All specimens had 30 mm side cover and 25 MPa concrete capacity. The decrease in anchorage capacity for dual headed bars in tension can be understood by examining the cracking pattern and modes of failure for both types of headed bars. In the specimens with dual headed bars a premature bearing failure at the location of interior head was noticed due to the formation of a crushed concrete wedge pushed by the interior head mainly in specimens with small side cover. This local failure at the location of interior head decreased embedment length of the lower head which is a key factor affecting the anchorage capacity of headed bar. This behavior is in agreement with the test results obtained by Wright and McCabe [12]. They reported that PVC sheathing of the straight part of headed bar decreased the occurrence of surface cracking before the final anchorage failure and increased its anchorage capacity. Wright and McCabe attributed this behavior to the elimination of splitting forces caused by slip of the deformed bar and, therefore, the head capability was improved. However, the loss in anchorage strength of dual headed bars in tension was insignificant in comparison to the improvement attained in anchorage strength in compression loading, as will be presented later. Figures 7 and 8 show cracks propagation in single and dual headed bar specimens, respectively.

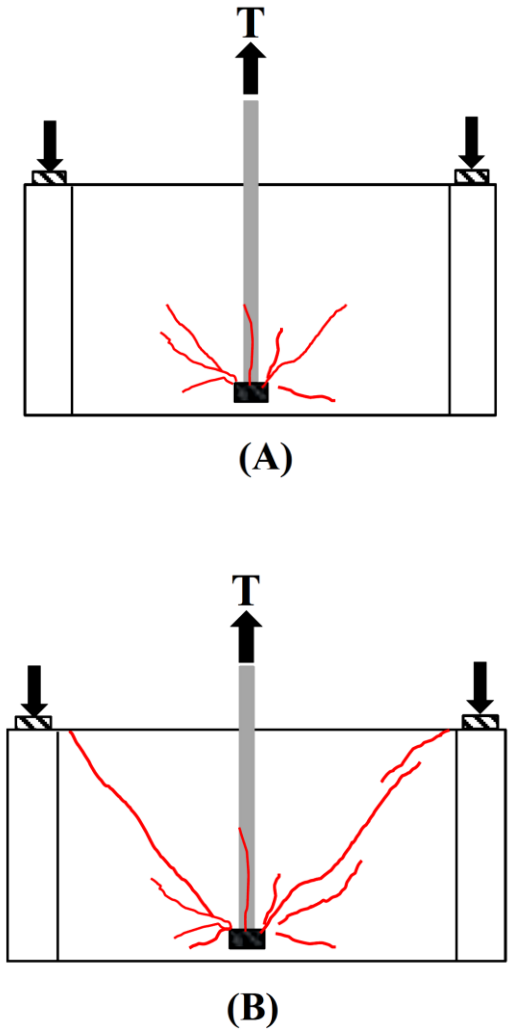


Fig. 7: Cracks Propagation in Single Headed Bar Specimens in Pullout Tests (A) Initial Crack (B) Cracking at Failure.

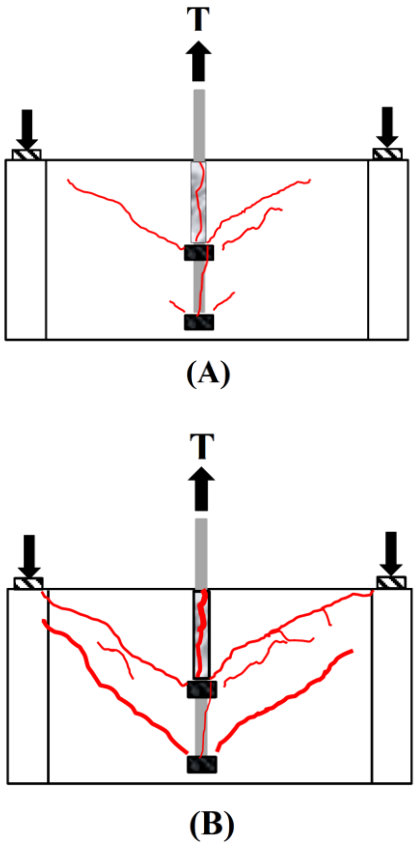


Fig. 8: Cracks Propagation in Dual Headed Bar Specimens in Pullout Tests (A) Initial Cracks (B) Cracking at Failure.

Fig. 9 shows failure patterns of single and dual headed bar specimens loaded in tension.



(A)



(B)

Fig. 9: Failure of Headed Reinforcement in Pullout Tests (A) Single Headed Bar (B) Dual Headed Bar.

Two modes of failure were observed in pullout tests, side-face blowout failure, and shear related failure. In specimens failed by side-blowout, a longitudinal crack first initiated at face of the specimen then propagated radially from the head location towards the support. At failure, the side concrete cover spalled at head locations. In some specimens the side cover spalled completely, and a crushed concrete zone could be noticed above the head location. Sometimes, this failure mode was so sudden and explosive to the extent that the side cover was blown out, so exposed the head, as shown in Fig. 10. This failure mode is exhibited particularly by specimens of small concrete cover.



Fig. 10: Explosive Side-Face Blowout.

Specimens failed in shear related mode was not accompanied with side spalling of concrete cover. The cause of failure was the increase of width of the diagonal cracks and failure characterized by separation of concrete along the struts. This type of failure has occurred suddenly in some specimens and with a pronounced thud, (Fig. 11).



Fig. 11: Sudden Shear Related Mode of Failure.

In specimens tested in compression, the cracking patterns followed almost a similar pattern of those tested in pullout, but in a reverse direction, as can be seen in Figures 11 and 12. Results in compression tests showed a remarkable increase in anchorage strength achieved by using dual headed bars in comparison with classical single headed bars. The anchorage strength of a specimen with single headed bar in compression loading was 16.4 kN, while it ranged between 50.8 and 75.2 kN for specimens had a distance between heads of $4d_b$ and $7d_b$ respectively. All specimens had a side cover for bars of 30 mm and compressive strength of 25 MPa. The increase in anchorage strength is more than 300% in comparison with specimens that had same test parameters but with single headed bars. This improvement in anchorage strength can be explained by comparing the cracking patterns and failure modes in specimens of both types of headed bars. In specimens that had dual heads, the failure was controlled by the interior head, which pushed a larger volume of concrete cone in comparison with specimens that had single heads, where the failure was controlled by thickness of concrete cover below the head, (Fig. 12). The anchorage strength was further improved by increasing the spacing between heads, which increases the embedment depth of the bar.



(A)



(B)

Fig. 12: Failure of Headed Reinforcement in Compression Tests (A) Single Headed Bar (B) Dual Headed Bar.

Figures 13 and 14 shows cracking patterns and crack propagations in specimens of both types of headed bars.

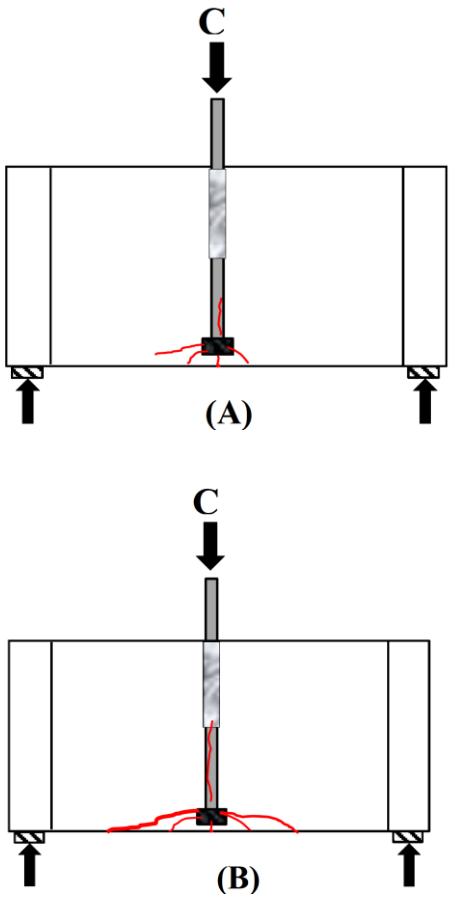


Fig. 13: Crack Patterns in Compression Tests of Single Headed Bars (A) Initial Cracks (B) Cracking at Failure.

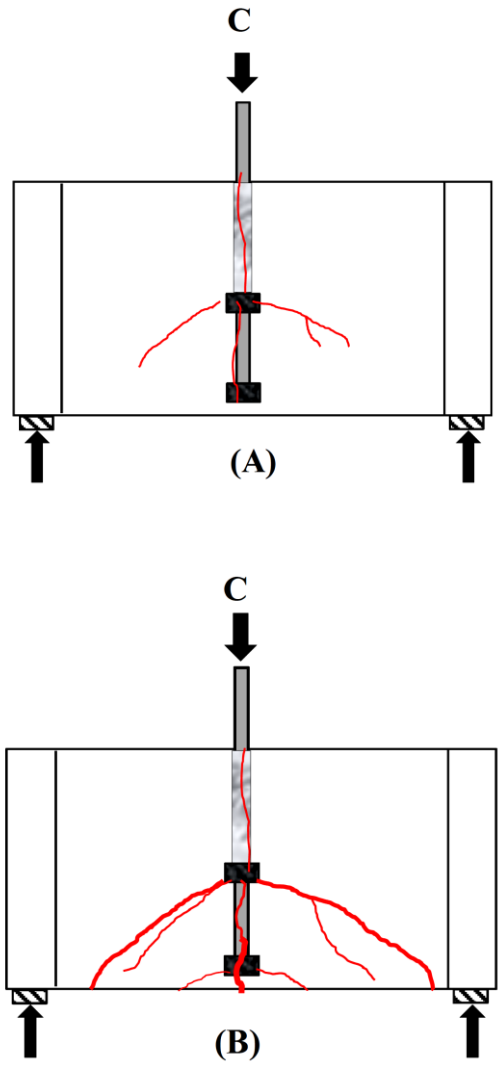


Fig. 14: Crack Patterns in Compression Tests of Dual Headed Bars (A) Initial Cracks (B) Cracking at Failure.

For single headed bars loaded in compression, end blowout mode of failure was observed in a manner similar to that reported by McConnell and Wallace [11] and Papadopoulos et al. [9]. In this mode of failure a concrete wedge below the head was blown out at relatively low load level.

In compression loading of dual headed bars, as in pullout tests, two modes of failure were observed, side-face blowout failure and shear related failure. Most of the dual headed specimens in compression tests exhibited side-face blowout failure. This failure mode occurred when the concrete wedge formed under the interior head and pushed the side concrete cover in a manner similar to that occurred in specimens tested in tension. In this mode of failure, often the damage was characterized by separation of the cracked concrete cover as shown in Fig.15.



Fig. 15: Side-Face Blowout Mode of Failure in Compression Test.

Shear related mode of failure occurred when the concrete behind the head was pushed and separated from the specimen as shown in Fig.16. This mode of failure happened in specimens which had relativity high side cover. The concrete side cover affected the anchorage capacity of dual headed bars under compression loading in a manner similar to that reported by DeVries [4] and Bashandy [3] for specimens tested in tension loading. Increasing the side cover not only influenced the mode of failure, but also increased the anchorage capacity in compression loading due to increasing confinement level of the concrete surrounding the head.



Fig. 16: Shear Related Mode of Failure in Compression Test.

6. Conclusions

Based on the results of this work, the following conclusions can be drawn:

1) Dual headed bars can be used to develop reinforcement in compression through increasing embedment length and improving mode of failure. No improvement is obtained for such dual headed bars loaded in tension.
2) Two modes of failure were observed on the tests of single and dual headed bars loaded in tension, side face blowout and shear related failure.
3) End blowout mode of failure was observed in single headed bars. For dual headed bars, two modes of failure were observed, side-face blowout and shear related failure.
4) The anchorage strength of dual headed bars loaded in compression increases as the spacing between the heads is increased.
5) The concrete side cover influenced the anchorage capacity and mode of failure of dual headed bars under compression loading in a manner similar to that reported by other studies for single headed bars in tension loading. Increasing the side cover improved the anchorage capacity of dual headed bars in compression loading.

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