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The use of T-headed bars in high-strength concrete members

J.M. Yang, K.H. Min, H.O. Shin, & Y.S. Yoon
Korea University, Seoul, Korea

ABSTRACT: There are several practical advantages to using T-headed bars, which have lager diameter heads, in concrete members including simpler installation, less congestion of reinforcement, more effective anchorage, improved seismic response, and enhanced shear resistance. Experimental tests using three kinds of high-strength concrete members having T-headed bars were performed. First, full-scale beam specimens constructed with high-strength concrete were tested to investigate the effect of T-headed bars as shear reinforcement. In the second test program, the benefits of T-headed bars in the disturbed regions of the dapped ended beams were investigated. Third, high-strength concrete corbels, in which headed bars were used as the main tension tie reinforcements, were constructed and tested. All test specimens reinforced with T-headed bars showed superior performance in terms of load carrying capacities, ductility, and crack width to those reinforced with conventional stirrups or main tension ties.

1 INTRODUCTION

In concrete members having disturbed regions such as corbels or dapped end beams, generally, stirrups and looped bars are used as the main tension tie reinforcement, or the bars are anchored welding them to transverse bars or bearing plates. This limits the number and strength of bars that can be used due to the lack of space for development length or insufficient anchorage of the main tension tie to develop its full tensile yield strength. Ghali, A. & Dilger, W. (1998) pointed out that conventional stirrups cannot develop the full yield strength at the leg near the hook and bend. The high compressive stress, developed on the concrete inside the hook, causes crushing of the concrete and slippage of the hook before the tensile stress in the leg reaches its yield strength.

T-Headed bars, as shown in Figure 1, were developed to overcome these problems (Berner, D. et al. 1999). Comprehensive research programs applying T-headed bars in slabs and footings, beams with thin webs, crossties in columns and walls, precast beams, deep beams, and pile caps have substantiated that T-headed bars conforming to ASTM A970-07 (2007) have many advantages include the following: simpler installation, less congestion of reinforcement, more effective anchorage, improved seismic response, and enhanced shear resistance (Ghali, A. & Youakim, S.A. 2005). In addition, T-headed bars enhance concrete compressive strength and ductility, anchorage by the heads is still provided even after the concrete cover spalls off, and improved anchorage by T-headed bars results in reduced crack widths and better confinement of the concrete (Mitchell, D. et al. 2005).

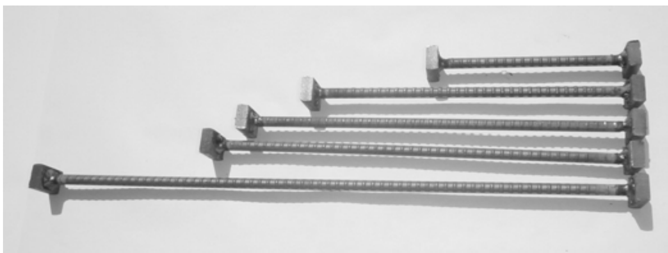
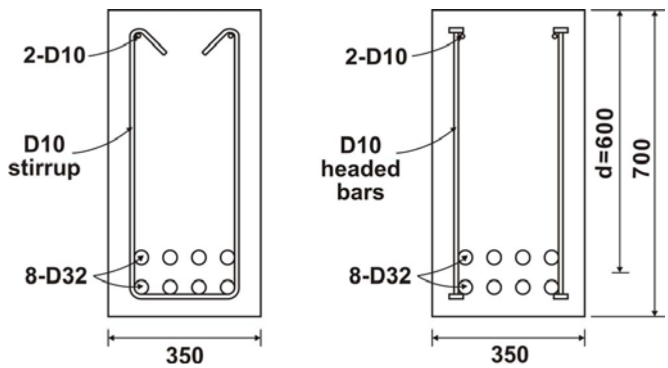


Figure 1. T-headed bars.



(a) Specimen SN (b) Specimen SNH

Figure 2. Section details of beam specimens (dimensions in mm).

This paper describes three research programs to study the beneficial effects of using T-headed bars in beams, dapped end beams, and corbels.

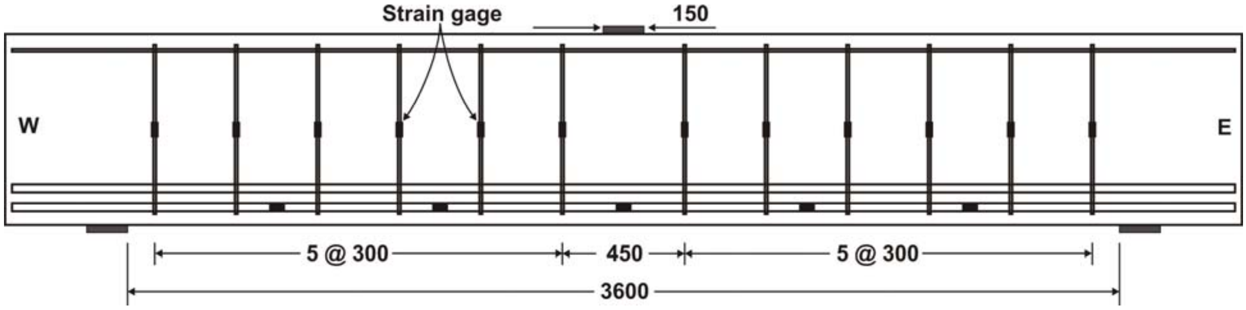


Figure 3. Reinforcement details and strain gage locations of beam specimens (dimensions in mm).

2 EXPERIMENTAL PROGRAM

2.1 *Beam specimens for shear test*

Two full-scale beam specimens constructed with high-strength concrete were tested. Figure 2 shows the details of the 350 mm wide x 700 mm deep specimens, and the effective depth of all specimens was 600 mm. Each specimen had different types of shear reinforcements of conventional U shape open stirrup and T-headed bar stirrup, respectively. Specimen SN was reinforced with normal-strength stirrups, which have 135° standard hooks, as shown in Figure 2a. Specimen SNH was reinforced with headed bars with a 31.0 mm circular head diameter and an 11.0 mm head thickness as the shear reinforcement. The headed bars were made of straight bars cut from the same stock used for fabricating the stirrups of Specimen SN and welded to circular heads at each end. Figure 2b shows the section details of Specimen SNH.

As shown in Figure 3, the overall length of all specimens was 4550 mm and the distance from the edge of the loading plates to the edge of the supports was 1725 mm, resulting in clear shear span-to-depth ratios (a/d) of 2.875. The flexural tension reinforcement for all specimens consisted of 8-D32 bars in two layers, giving a longitudinal reinforcement ratio of 3%. This amount of flexural reinforcement was chosen to insure that shear failure would occur before flexural failure. A spacing of 300 mm for shear reinforcements spacing was chosen for all specimens considering the spacing limits requirement ($d/2$) for shear reinforcement in the ACI 318-08 (2008).

All test specimens were tested using one point concentrated loading of a 2800 kN universal testing machine. A 150 x 25 mm and two 200 x 25 mm steel bearing plates were placed at the location of the loading and supports, respectively, to prevent local crushing of the concrete. The loading was applied monotonically in small increments, while the loads, deflections and strains were recorded at each increment. At each load stage, the crack pattern and crack widths were also recorded. The width of diagonal shear cracks was measured using a crack width comparator. The midspan deflection and support settlements were measured with linear voltage differential transformers (LVDTs). The strain rosettes using LVDTs and strain targets were also attached to the side-face of the beam to enable the determination of the principal strains. Electrical resistance strain gages were glued to the center of all stirrups and to the two longitudinal bars in the bottom layer.

2.2 *Dapped end beam specimens*

Two dapped end beam specimens were constructed and tested. As shown in Figure 4, the dapped end was 80 mm long with a section size of 200 x 180 mm, and the section size outside of the dapped end region was 200 x 300 mm. The effective depth was 250 mm and the shear span length was 850 mm, resulting in shear span-to-depth ratios (a/d) of 3.4, for all specimens. Specimens were designed according to the modified compression field theory to lead shear failure at both supports. All specimens had two layers of 2-D19 longitudinal bottom reinforcements and 2-D10 longitudinal top reinforcements, resulting in longitudinal reinforcement ratio (ρ) of 1.7%.

Two specimens were reinforced with conventional steel bars and T-headed bars, respectively. Specimen D1 had D10 stirrups with standard 135° hooks as the shear reinforcement at supports forming disturbed regions, and the main horizontal tension tie in the dapped end was anchored with welding to a steel angle. Specimen D2, while, had D10 T-headed bars as the shear reinforcement near supports and as the main horizontal tension tie in order to ensure proper anchorage. It is noted that a standard 135° hook stirrup represented equivalent shear reinforcements with two T-headed bars. In Specimen D2, rectangular heads (30 x 24 mm width, 10 mm thickness) were welded to both ends of D10 bars, as shown in Figure 1.

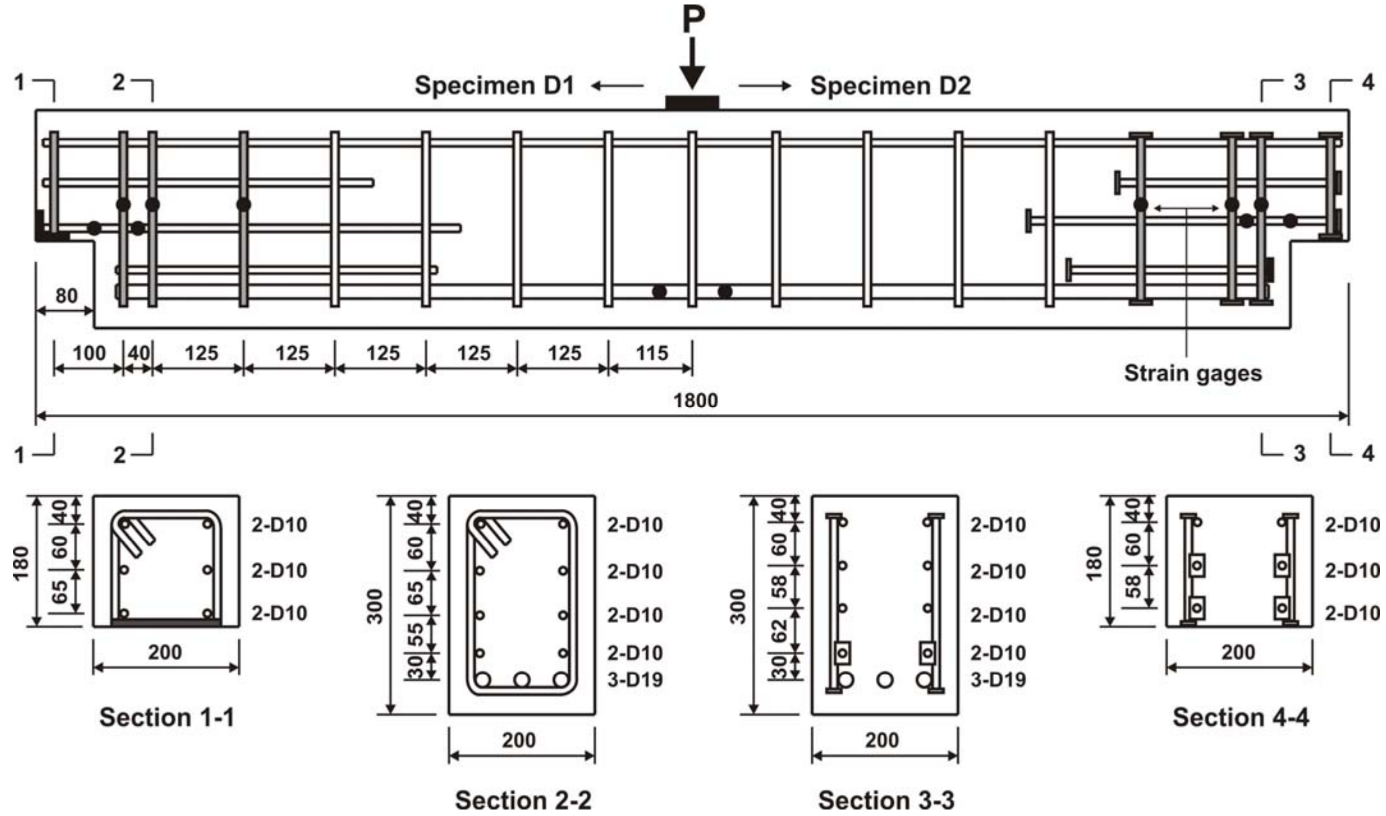


Figure 4. Reinforcement details and strain gage locations of dapped end beam specimens (dimensions in mm).

All specimens were subjected to static loading using a 2800 kN universal testing machine. Twenty-four electrical strain gages for each specimen were glued to the steels at the location of critical section for shear and flexural. Four strain gages were glued to midspan of bottom layer steel to measure the strain of longitudinal reinforcements. Twenty strain gages were glued to mid-height of shear reinforcements to measure the strain of shear reinforcements in the disturbed region. The location of strain gages for all specimens is shown in Figure 4. The midspan deflection and support settlements were also measured with LVDTs.

2.3 *Corbel specimens*

Two double-sided high-strength concrete corbel specimens were constructed. All specimens were 300 mm in width, 350 mm in overall corbel depth, with a 300 x 300 mm column. Figure 5 shows the geometry and reinforcement layout of the specimens. The Specimens CW0 and CH0 used different anchorage method of the main tension tie. The main tension tie reinforcement of the CW0 consisted of four 15M bars, welded to 15M transverse bars in order to satisfy the anchorage provision of the ACI 318-08 (2008), while the main tension tie reinforcement of the CH0 consisted of four 15M friction-welded headed bars, with a 50.8 mm head diameter and a 12.7 mm head thickness. Two additional 10M hoops, at a spacing of 60 mm, were placed over a depth of two thirds of the height of the corbels in order to satisfy the crack control requirements of the ACI 318-08 (2008). All specimens were subjected to vertical loading only.

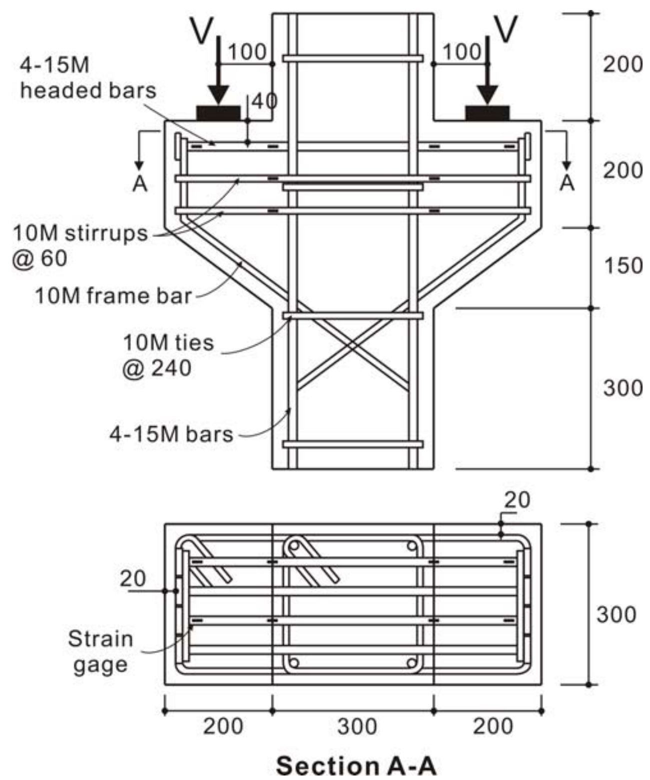


Figure 5. Reinforcement layout of corbel specimens (CH0) (dimensions in mm).

All test specimens were tested in an upside down position using a 11,400 kN universal testing machine. Only vertical loads were applied to the specimens with two 76 x 19 x 260 mm steel bearing plates centered at 100 mm from the face of the column on both sides (shear span to depth ratio, a/d was 0.33). The loading was applied monotonically in small increments, while the loads, deflections and strains were recorded at each increment. At each load stage, the crack pattern and crack widths were also recorded. Crack widths were measured using a crack width comparator at the level of the main tension tie reinforcement and along a horizontal line at the centroid of the crack control reinforcement. The vertical deflection and horizontal deformation of each loading point was measured with LVDTs. Electrical resistance strain gages were glued to the main tension ties in line with the column faces and at the ends of the main tension tie, as well as to the secondary crack control stirrups in line with the column faces, as shown in Figure 5.

3 MATERIAL PROPERTIES

Standard compressive cylinder tests using 100 mm diameter by 200 mm long cylinders were conducted to determine the mean values of the concrete compressive strength and the corresponding peak strain. Table 1 summarizes the material properties of the concrete. Table 2 provides the mechanical properties of the steel reinforcing bars used in the construction of all test specimens. These average values were determined by testing three random samples for each bar size of each specimen.

Table 1. Concrete properties.

Specimen	f'_c, MPa	ε'_c, %
SN, SNH	97.0	0.22
D1, D2	46.4	0.17
CW0, CH0	83.8	0.20

Table 2. Steel properties.

Specimen	Designation	Area, mm^2	f_y, MPa	ε_y, %	ε_{sh}, %	f_u, MPa
SN, SNH	D10	71	375	0.19	0.45	525
	D32	794	428	0.22	0.51	735
D1, D2	D10	71	452	0.23	0.54	564
	D19	287	413	0.21	0.50	699
CW0, CH0	10M	100	474	0.27	0.52	685
	15M	200	499	0.26	1.63	651

4 TEST RESULTS AND COMPARISON OF RESPONSES

4.1 *Beam specimens for shear test*

Figure 6 shows the shear versus midspan deflection relationships for two beam specimens. The formation of the primary shear crack was observed in the readings taken from the strain gages on the stirrups as well as sudden increase in midspan deflections in the shear-deflection curve of Figure 6.

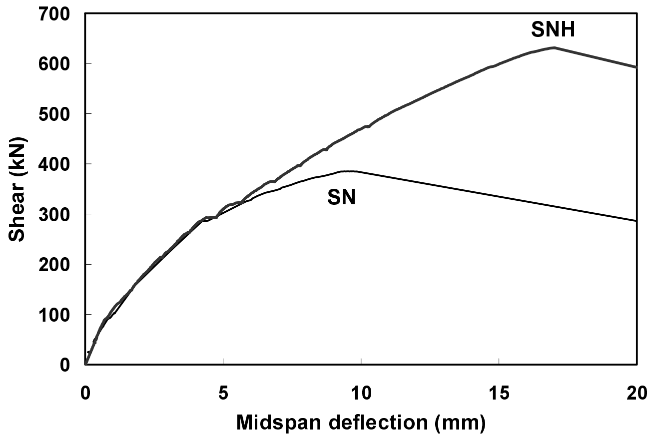
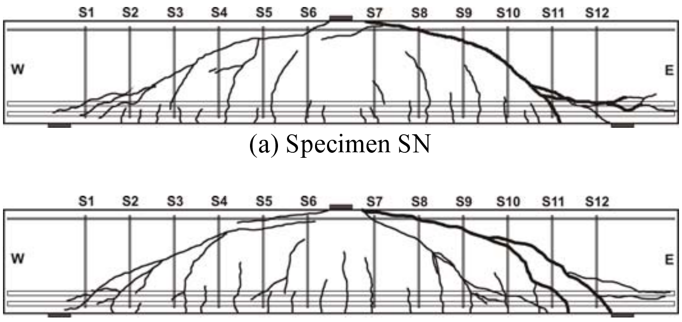


Figure 6. Shear versus midspan deflection relationships of beam specimens.

In Specimen SN, in which conventional stirrups were used as the shear reinforcement, the primary shear crack occurred at a shear of 286.2 kN. After formation of the primary shear crack, the deflection and stirrup strain rapidly increased, and the ultimate failure occurred at a shear of 385.2 kN with crushing and separating of the top concrete cover, bucking of the compressive steels, and brittle shear-splitting cracks in the end region of the beam. Specimen SNH displayed similar shear of the primary shear cracking as that of Specimen SN, while Specimen SNH displayed 64% higher ultimate shear than Specimen SN. Unlike Specimen SN, which failed ultimately with a small additional shear of 99.0 kN after formation of the primary shear crack, SNH showed ultimate failure with large additional shear of 338.4 kN after formation of primary shear crack. In addition, SNH showed a smooth increase of midspan deflection without a rapid decrease of stiffness appearing in the shear-deflection relationship of the SN.

Low shear resistance provided by shear reinforcement of Specimen SN could be due to an insufficient amount of shear reinforcement and anchorage loss of hook in the U shape stirrup. Because the shear cracking of high-strength concrete appears at high shear, if the beam section does not contain an increased minimum amount of transverse reinforcement considering the high strength of concrete, the shear strength after the shear cracking will be difficult to be reserved by stirrups.

An anchorage loss of hooks in stirrups could result in Specimen SN becoming weak and brittle. The conventional stirrups cannot develop the full yield strength of the leg adjacent to the hook (Ghali, A. & Dilger, W. 1998). The high compressive stress, developed on the concrete inside the hook, causes crushing of the concrete and slippage of the hook before the tensile stress in the leg reaches its yield



(a) Specimen SN

(b) Specimen SNH

Figure 7. Crack patterns of beam specimens at failure.

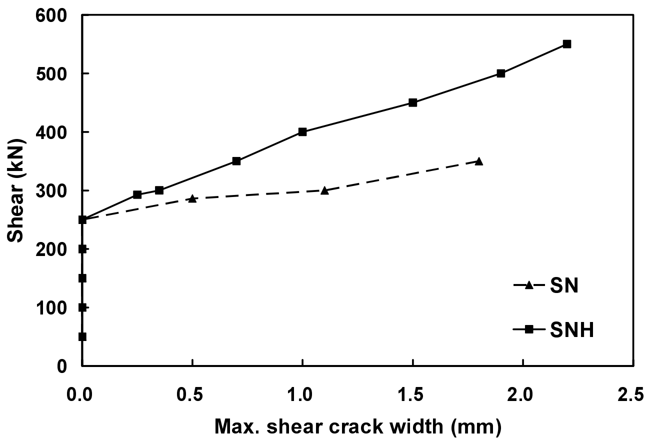


Figure 8. Shear versus maximum shear crack width relationships of beam specimens.

strength. Especially in the high-strength concrete beams, the combination of higher compressive stress and higher shear after formation of the primary shear crack could lead to a sudden increase of hook slippage near the shear crack propagated deeply into the compression zone. It was noted that the T-headed bars in SNH provided excellent end anchorage, thereby redistributing the stress between shear reinforcements, and reserving the shear strength after formation of the primary shear cracking, although the shear reinforcement amount of SNH was less than the minimum shear reinforcement requirement.

Figure 7 describes the crack patterns at ultimate failure for all specimens. All specimens showed typical shear cracking patterns, which started with the formation of a number of small flexural cracks and expanded to a diagonal shear crack. All specimens displayed the same angle of the primary shear crack as well as smoother shear crack surfaces, which is a feature of high-strength concrete. Due to the high strength of the concrete matrix, cracks pass through instead of around the aggregates, thereby reducing the aggregate interlock and the shear carried by concrete. This reduced aggregate interlock induces higher dowel forces in the longitudinal reinforcing bars, and results in brittle shear-splitting cracks in the end regions of beams (Yoon, Y.S. et al. 1996). Specimen SN showed conspicuous shear-splitting cracks, and this is another evidence of brittle shear failure at relatively low shear.

Figure 8 shows the shear versus maximum shear crack width for all of the specimens which were tested. The maximum shear crack width of Specimen SN increased rapidly after the formation of primary shear cracking, while Specimen SNH showed relatively slow increase in maximum shear crack width.

4.2 *Dapped end beam specimens*

Figure 9 compare the applied load versus midspan deflection responses of the dapped end beam specimens D1 and D2, and Figure 10 shows the crack patterns at ultimate failure. In Specimen D1, which was reinforced with conventional tension ties and stirrups, the first shear cracking appeared at a load of 38.6 kN at the re-entrant corner near supports and extended from the corner or the support toward the outermost closed stirrup as shown in Figure 10. The first yielding of closed stirrups was occurred at a load of 129.8 kN, and the peak load of D1 was 155.0 kN. The failure mode was very brittle because the tie stirrups and main tension ties anchored incompletely.

In Specimen D2, which was reinforced with headed bars, the first shear cracking at the dapped end region, the first yielding of closed stirrups, and the ultimate failure were appeared at a load of 39.5 kN, 145.0 kN, and 169.3 kN, respectively. T-headed stirrups used in Specimen D2 provided excellent anchorage for the inclined compressive strut; hence, the failure mode was more ductile than Specimen D1. The load carrying capacity and stiffness of Specimen D2 were higher than those of Specimen D1. This represents an increase in capacity of 9% due to the use of T-headed bars. In addition, the headed bar stirrups and the tension tie headed bars contributed to developing strain hardening of

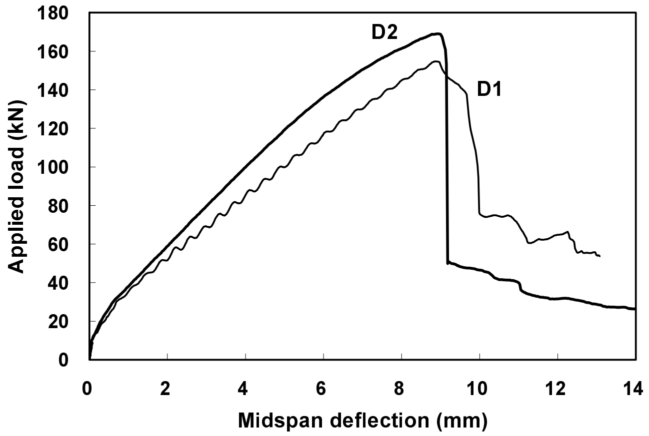


Figure 9. Shear versus midspan deflection relationships of dapped ended beam specimens.

Figure 10. Crack patterns of dapped ended beam specimens.

reinforcing steels and delaying buckling of the flexural compression steel.

4.3 *Corbel specimens*

Figure 11 shows the total shear load versus center deflection for all corbel specimens. Specimen CH0, of which the main tension tie reinforcements were anchored using headed bars, showed a higher peak shear load than Specimen CW0, of which the main tension tie reinforcements were anchored by structural welding to a transverse bar. The ultimate load carrying capacities of Specimen CH0 was 7% higher than that of Specimen CW0.

As shown in Figure 11, Specimen CH0 showed a higher stiffness than Specimen CW0. For the load-deflection responses, the slope of the straight line extending from the point of first cracking to the point of first yield of the main tension tie represents the post cracking stiffness. The stiffness of Specimens CH0 was 12% higher than that of Specimen CW0. In addition, the ductility of the corbel specimens, which was quantified as the ratio of the deflection at the peak load to the deflection at first yielding of the main tension tie, was 9% increased with the use of headed bars. This indicates that the use of headed bars for anchorage of the main tension reinforcement could be more effective in terms of ductility.

Figure 12 shows the crack patterns at peak load for the specimens. The first cracks appeared in all corbel specimens at the corbel-column interfaces, then propagated and reached the level of the center of the secondary crack control reinforcement. In addition, other secondary cracks, which later became the primary or major cracks, occurred near the inner edge of the bearing plate and propagated to the junction of the column and the sloping face of the corbel. All specimens failed by the beam-shear failure mode, which was initiated by a flexural type crack, whereby failure is caused by diagonal shear type cracks. All specimens showed crushing failure of the concrete at the bottom of the sloping face of the corbel after extensive yielding of the main tension ties and the secondary crack control reinforcements.

In Figure 13, a comparison of crack widths is shown for the specimens. At the design service load level, which was assumed to be 600 kN (about 60% of the nominal design strength using the actual yield

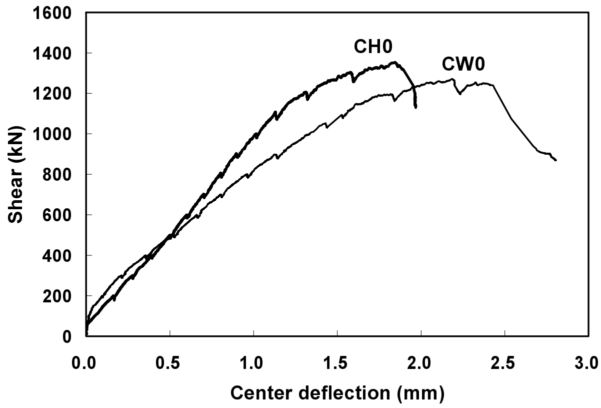


Figure 11. Shear versus center deflection relationships of corbel specimens.

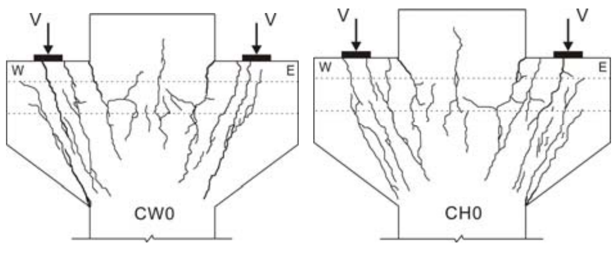


Figure 12. Crack patterns of corbel specimens at peak load.

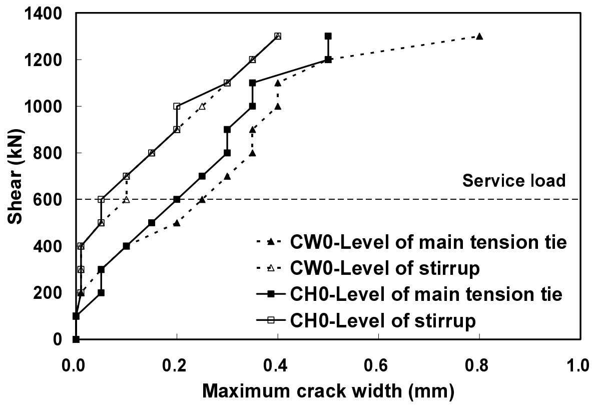


Figure 13. Shear versus maximum shear crack width relationships of corbel specimens.

strength of the reinforcement), the maximum crack widths were 0.25 mm for Specimen CW0, while 0.20 mm for Specimen CH0 at the level of the main tension tie. This indicates that the use of headed bars as a main tension tie has reduced the crack widths in the corbel specimens.

5 CONCLUSIONS

The conclusions drawn from these three kinds of experimental research program are:

(1) T-headed bars used as the shear reinforcement in shear tests of high-strength concrete beams provided excellent end anchorage, therefore the beam that had headed bars as the shear reinforcement showed significant reserve of shear strength and good redistribution of shear between stirrups after shear cracking.

(2) The dapped end beam reinforced with T-headed bars showed superior performances in terms of load carrying capacities, stiffness, and ductility. This is because T-headed bars ensured the anchorage of the main tension tie and stirrups.

(3) The corbel specimen that had T-headed bars as main tie reinforcement showed more improved load carrying capacity, stiffness, ductility, and crack control than the companion corbel specimen that had the main tie reinforcement welded to a transverse bar.

(4) T-headed bars can be used extensively in slabs, beams, crossties in column, beam-column joint, and so on. In addition, T-headed bars can be effective in reducing the brittleness of high-strength concrete members.

ACKNOWLEDGEMENTS

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