- Technical Paper -

INVESTIGATION ON THE SHEAR OF REINFORCED CONCRETE HAUNCHED BEAMS WITH SHEAR REINFORCEMENT

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ABSTRACT

This paper presents the evaluation of shear carried by stirrups in reinforced concrete haunched beams (RCHBs) with stirrups. Three RCHBs with stirrups and one RCHB without stirrups were tested. The results demonstrated that bending positions of tensile rebars near the loading point highly influenced crack propagations and shear capacities in RCHBs with stirrups. It was due to different contributions of arch action and stirrups in the shear resistance. The calculated shear carried by stirrups with the angle of diagonal shear cracks showed good correspondence with the experimental results.

Keywords: RC haunched beam, crack pattern, angle of diagonal shear cracks, arch action

1. INTRODUCTION

In simply supported and continuous bridges, structural portal frames and mid-rise framed buildings, reinforced concrete haunched beams (RCHBs) with bent longitudinal bars are widely used in the shape of large haunches (Fig. 1). Such beams can reduce the structure's weight and contribute to an aesthetic design of the appearance. However, it is insufficient of the experimental data to predict the shear behavior of RCHBs. Moreover, rational and economical design method for RCHBs in the JSCE specifications for concrete [1] has not been completed. Engineers are using such beams based on the empirical and uneconomic design which is not safe and accurate. Therefore, it is necessary to explore the shear resistance mechanism of RCHBs to ensure the reasonable design.

In some previous researches, Tena-Colunga et al. [2] concluded that the shear capacity of RCHBs without shear reinforcement was affected mainly by the inclination of haunched portion and the effective depth at the mid span. Nevertheless, the authors (Hou et al. [3]) found through experiments that the bending positions of the tensile rebar affected the crack patterns and shear capacities of RCHBs without stirrups significantly. The different crack patterns played an important role in forming arch action to resist the shear force. However, since stirrups are always used in real construction and the presence of stirrups may affect the crack patterns in RCHBs, it is necessary to investigate the shear resistance mechanism of RCHBs when stirrups are provided.

The objective of this study is to investigate the shear carried by concrete and stirrups in RCHBs by clarifying the shear resistance mechanism. Continuing the authors' previous experiments [3], one RCHB without stirrups and three RCHBs with stirrups were tested. The influence of positions of the haunched portion from the loading point on the shear behavior of RCHBs with shear reinforcement was examined.

2. EXPERIMENTAL PROGRAMS

2.1 Materials

The longitudinal D25 tensile bars with yield strength of 411 N/mm^2 were used in all four specimens. The inclination of tensile steel bars, α was fixed to 11.3 degrees based on the dimension of a real structure with large haunches as well as considering the feasibility of the framework. Two round bars with a diameter of 6 mm and yield strength of 328 N/mm^2 were used as compression bars. In the one RCHB without stirrups, D6 stirrups with yield strength of 309 N/mm^2 were arranged at the spacing of 200 mm in the non-test shear span to ensure the failure of the test shear span. For the other three RCHBs with stirrups, D6 stirrups were arranged at the spacing of 120 mm in the test shear

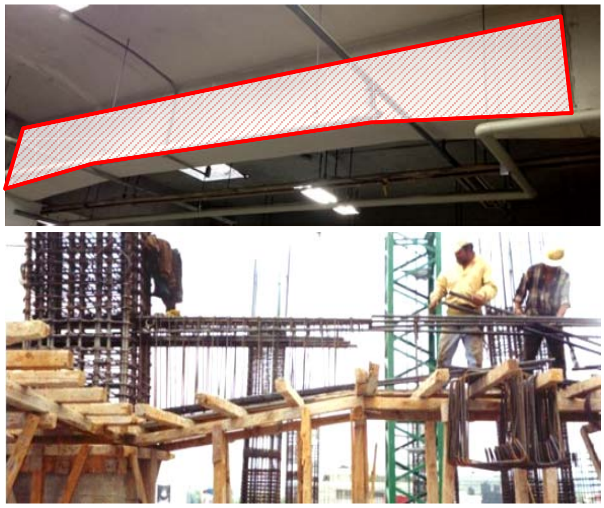

Fig. 1 RC buildings with haunched beams

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Table 1 Mix proportion of concrete

G_{max} (mm)	W/C	Unit weight (kg/m^3)				
		W	C	S	G	AE
20	0.60	178	297	847	946	0.446

G_{max}: maximum size of coarse aggregate; *W*: water; *C*: cement (density = 3.14 g/cm^3); *S*: fine aggregate; *G*: coarse aggregate; *AE*: air-entraining water-reducing agent.

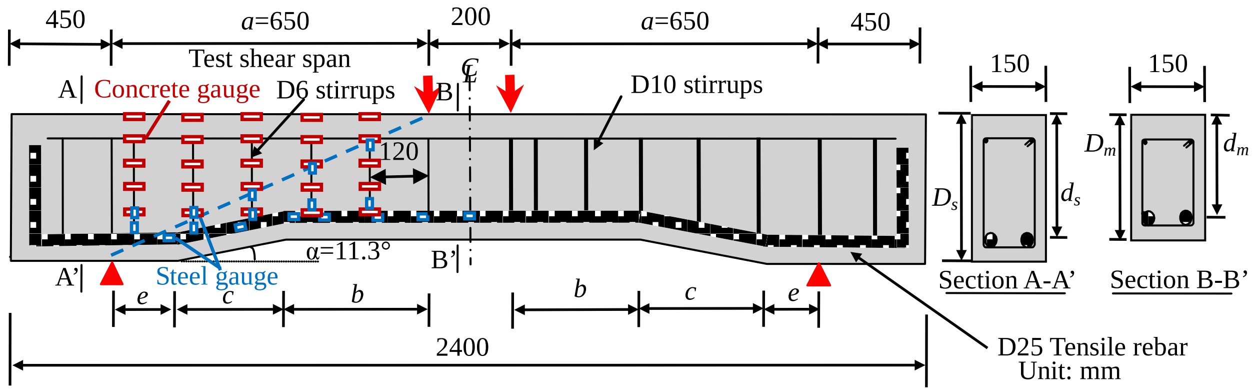


Fig. 2 The detail of specimen HS-300

Table 2 Specimens' details and material properties

Specimen	f_c' (N/mm^2)	a (mm)	b (mm)	c (mm)	e (mm)	D_s (mm)	d_s (mm)	D_m (mm)	d_m (mm)	a/d_s	a/d_m	ρ_{sv}
H-0	33.0	650	0	250	400	300	250	250	200	2.6	3.25	0.314%
HS-0	33.5		0		400							
HS-100	28.0		100		300							
HS-300	34.4		300		100							

f_c': compressive strength of concrete; *a*: shear span; *b*: distance between loading point and beginning of haunched portion; *c*: length of haunched portion; *e*: distance between support and end of haunched portion; D_s: beam depth at support; d_s: effective depth at support; D_m: beam depth at mid span; d_m: effective depth at mid span; S in the specimen name means with stirrups in the test shear span; ρ_{sv}: stirrup ratio.

span while D10 stirrups with yield strength of 363 N/mm^2 were arranged at the spacing of 120 mm in the non-test shear span to ensure the failure of the test shear span.

To obtain the concrete strength of 30 N/mm^2, high-early strength Portland cement, fine aggregates, coarse aggregates, and air-entraining water-reducing agent were mixed in proportion as shown in Table 1.

2.2 Test Specimens

The details of tested beams are illustrated in Fig. 2 and Table 2, including the dimension and reinforcing bars arrangement in RCHBs. With a 650 mm shear span (*a*) and varying effective depth from 250 mm (d_s) to 200 mm (d_m) along the member axis, the shear span to effective depth ratio also varied from 2.6 to 3.25. All the specimens were designed to fail in the left shear span by providing less or no stirrups (for the beam H-0) in the test shear span as shown in Fig. 2. The experimental parameters of these beams were the positions of the haunched portions from the loading point, which were also used to name the specimens. For example, in the beam HS-100, "HS" means a haunched beam with stirrups and "100" represents the distance between the haunched portion and loading point (*b*). By comparing with the RCHBs of same dimensions without stirrups in this study and the authors' previous study [3], the effect of stirrups on shear behaviors and shear contributions are clarified.

2.3 Loading Test and Instrumentation

A four-point bending test with simply-supported condition was provided to all specimens as illustrated in Fig. 2. Steel plates of 50 mm width were placed on the pin-hinge supports, while teflon sheets and grease were inserted between the specimen and supports in order to prevent the horizontal friction. At the loading points, steel plates with 65 mm width and 150 mm length were also placed. Figure 2 shows the detailed loading setup with the locations of loading points and supports.

During the loading tests, the mid-span deflection was measured using four displacement transducers at the mid span and supporting points. Since the main cracks occurred along the tensile rebar in the authors' previous experiments, two strain gauges were attached for each stirrup. One was near the bottom, closed to the tensile rebar, and the other one was along the line from the support to the loading point (Fig. 2). The concrete

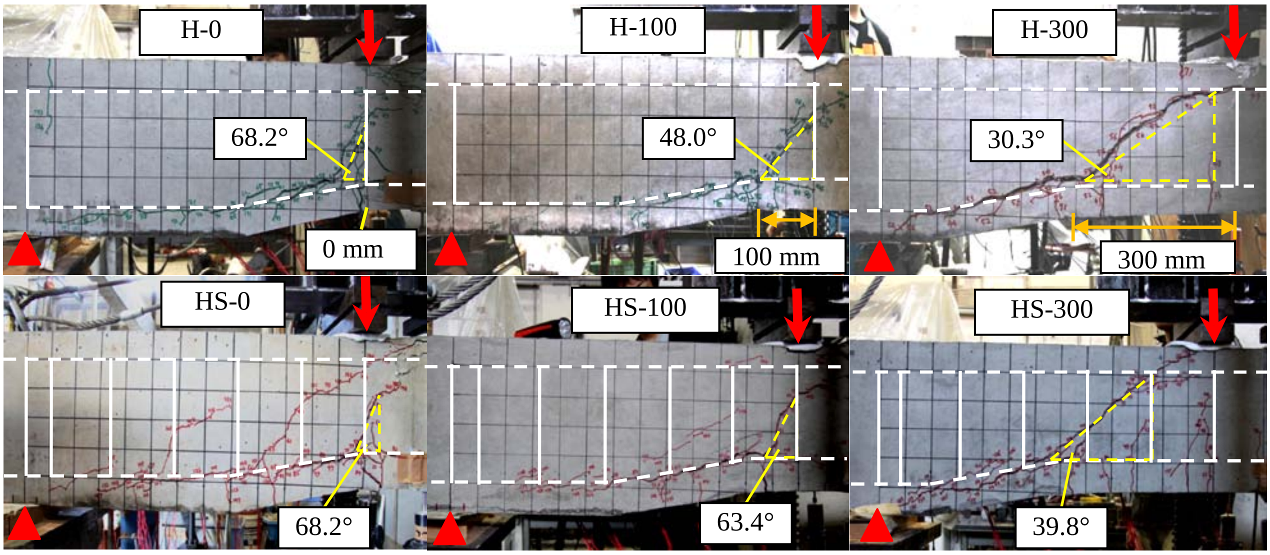


Fig. 3 Cracks at peak load

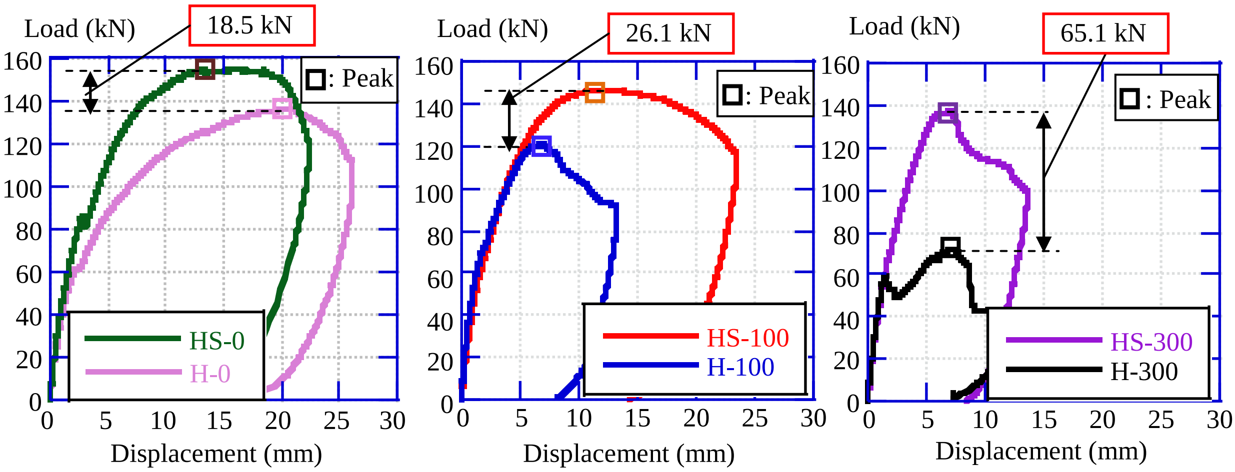


Fig. 4 Load-displacement curves

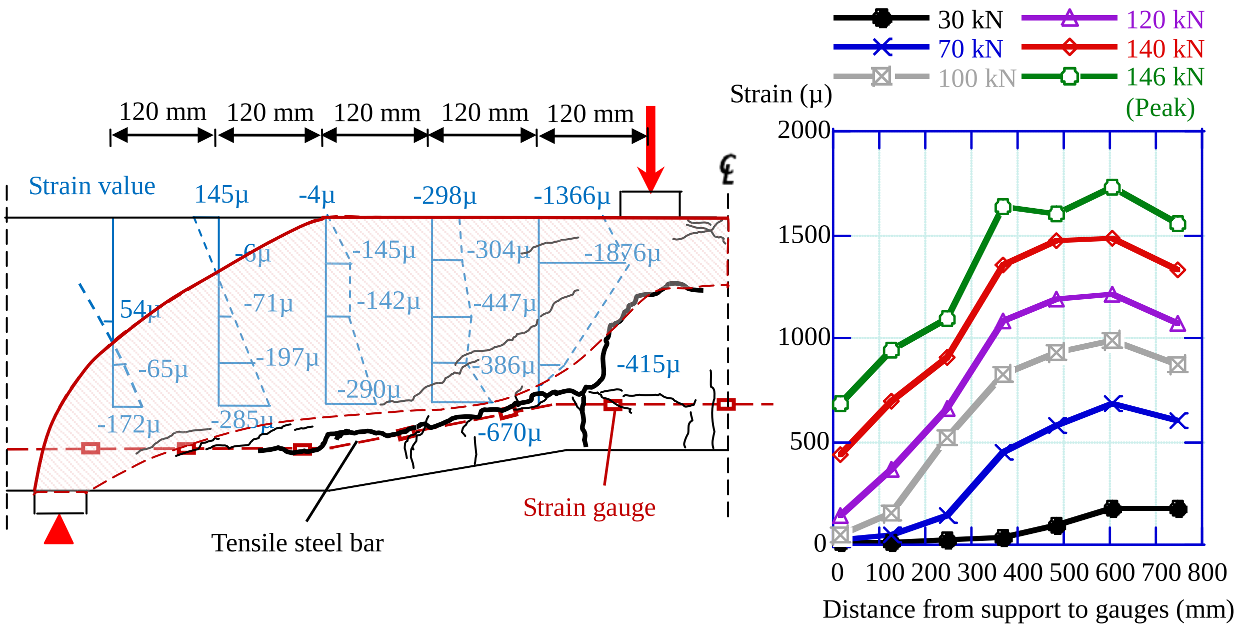
strain at the five sections of stirrups was measured by attaching strain gauges on the surface of concrete with spacing of 50 mm (Fig. 2). The strain in tensile steel bars at near the sections of stirrups was also measured (Fig. 2). In addition, the crack propagation on the surface of test-span during the loading test was captured by taking pictures.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Crack Patterns

Figure 3 shows the crack patterns in the specimens at the peak load. The beam H-100 with concrete compressive strength of 33.6 N/mm^2 and the beam H-300 with concrete compressive strength of 36.7 N/mm^2 are RCHBs without stirrups from the authors' previous experiments [3], while the other four specimens are from this study. Except for the presence of stirrups, the dimensions and steel bar arrangements between RCHBs without stirrups and RCHBs with stirrups were same. The white dash lines at the bottom represent the positions of tensile longitudinal bars while the white solid lines represent the positions of stirrups in the specimens. For the new RCHB without stirrups H-0, after the flexure cracks, the main crack started from the bending position of the tensile rebar near the loading point and it proceeded along inclined rebar and towards the loading point as well. Such kind of crack pattern is same as the conclusion in the previous research [3], which can be also found in the beam H-100 and H-300. Therefore, the conclusion is verified in the beam H-0.

In case of the three RCHBs with stirrups, the main crack patterns show similarity with that of RCHBs without stirrups, especially for the beams with same dimensions (for example H-0 and HS-0). As the authors explained in the previous research [3], the reason of such crack patterns is supposed to be that, the bending shape of tensile rebars caused the stress concentration near the bending positions, while the tensile force tended to straighten the bent rebars and push over the concrete cover. Due to the existence of stirrups, more shear cracks and flexural cracks were observed, while the crack width became smaller. Finally, the load increase after diagonal cracks until the concrete crushing near the loading point was observed



(a) Distribution of strain in the concrete just before peak load

(b) Distribution of strain along tensile rebar

Fig. 5 Arch action in the beam HS-100

in all six beams that the failure mode was supposed to be the shear compression failure.

3.2 Load-displacement Curves

Figure 4 shows load-displacement curves for all these six beams. The shear capacity of the beam HS-0 was the largest (77.4 kN) among the three RCHBs with stirrups while the shear capacity of the beam H-0 was the largest (68.1 kN) among the three RCHBs without stirrups. For the beam HS-100 and HS-300, the shear capacities were smaller by 5.3% and 11.5% respectively than that of the beam HS-0. For the beam H-100 and H-300, the shear capacities were smaller by 11.5% and 47.1% respectively than that of the beam H-0. At the same time, by comparing the peak loads of the three RCHBs with stirrups and the peak loads of the three RCHBs without stirrups, it is showing that the increased load due to the stirrups in each group decreased from 65.1 kN in the beam HS-300 to 18.5 kN in the beam HS-0. It also indicates the load gaps between the three RCHBs with stirrups became smaller than the load gaps between the three RCHBs without stirrups. The reason behind such performances will be discussed in the following sections.

3.3 The Existence of Arch Action

As introduced in the section 2.3, in order to clarify the arch action in RCHBs, the strain distributions of five concrete sections and the tensile rebar were obtained by attaching strain gauges on the concrete surface and steel bar surface. This method was also used in the previous research [3] and got a good result in showing the arch action in RCHBs without stirrups. In this study, the existence of arch action in the beam H-0 and the other three RCHBs with stirrups was also verified by using this method. Figure 5 shows the evidence of arch action in the beam HS-100 as one example. Figure 5(a) shows the strain distribution of the five concrete sections just before the peak load. The positive value of the strain means tension, while the negative value means compression in the concrete. Through such strain distributions, the upper boundary of the inclined compression zone shown as the shadow part could be obtained as the red solid line. As the lower boundary was not measured, it was drawn subjectively as the red dash line based on current strain distributions as well as the position of tensile rebars. To determine the lower boundaries by using numerical analyses is one of the future tasks. Figure 5(b) shows the strain distribution along the tensile rebar at several load levels. The horizontal axis is showing the distance from the support to strain gauges which could also be found in Fig. 5(a). From the tendency of strain distributions, the bonding loss as the increase in the load level could be observed clearly. When the load was small, the strain tendency started from zero at the support and developed proportionally to the bending moment. It means the good bond existing in the beam. When the load was near the peak, the strain tendency started from around 700μ, while the strains in the haunched portion were almost flat. It means the partial loss of bonding. Both of the inclined compression zone and the bonding loss along the tensile rebar indicate the occurrence of arch action in RCHBs with stirrups [4].

3.4 Contribution of Concrete in Shear Resistance

Combining the experimental data in this study and the data from the previous experiments [3], Figure 6 shows the inclined compression zones in all six beams as the red shadow parts. The method of drawing the figures was same as the section 3.3. Agreeing with the conclusion in the previous research, since the

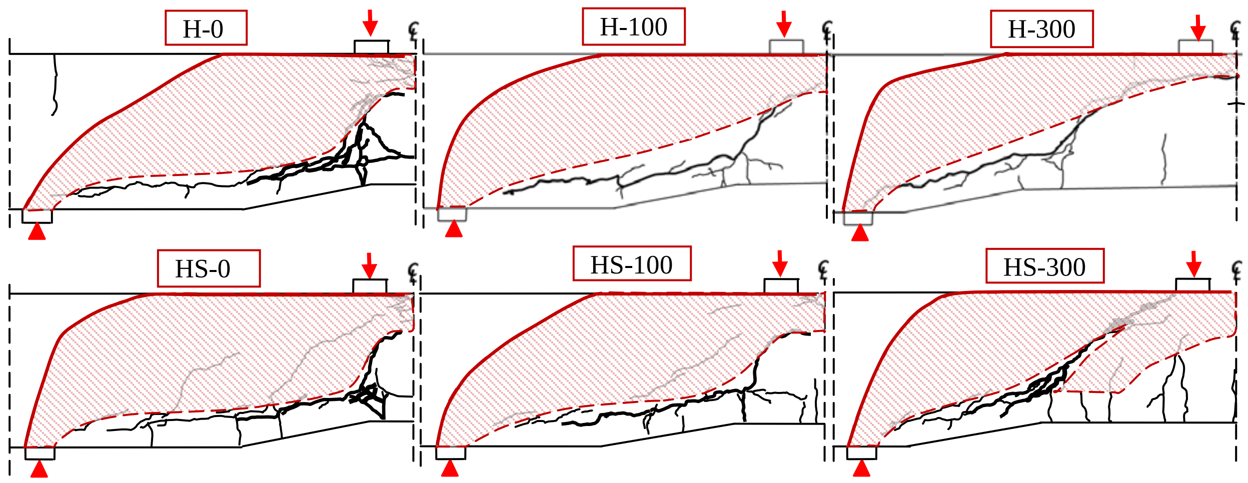


Fig. 6 Compression zones in six beams

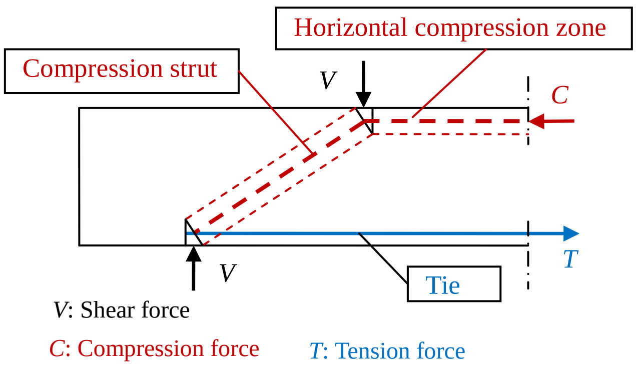


Fig. 7 Strut-and-tie model

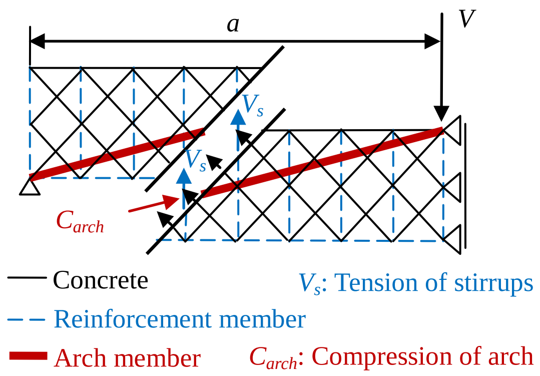


Fig. 8 Lattice model of RC beams with stirrups

bending position of the tensile rebar in the beam H-0 was close to the loading point, the generation of main cracks shifted close to the loading point, making the concrete area above the main cracks very large. According to the strut-and-tie model [5] in Fig. 7, the large concrete area, especially the area near the loading point where concrete crushing occurred, makes cross sectional area of the compression strut and horizontal compression zone larger, resulting in a stronger arch action to resist more shear force. There is a high possibility of concrete crushing in both compression strut and horizontal compression zone in a strut-and-tie model, which depends on the cross sectional area respectively. The failure due to concrete crushing near the loading point was considered as shear compression failure in this study.

In the other three RCHBs with stirrups, the arch action also developed to resist the shear force together with the contribution of stirrups. The lattice model [6] of RC beams with stirrups in Fig. 8 explains the possibility of combining arch member and stirrups in the total shear resistance. As the main diagonal cracks, inclined compression zones and failure models in the beams with same dimensions (for example H-0 and HS-0) were almost same, the contributions of concrete for shear in the beams with same dimensions are supposed to be same.

3.5 Contribution of Stirrups in Shear Resistance

Considering the force acting at the diagonal crack in a RC beam with stirrups subjected to point loads, it can be seen that the shear force is resisted by the shear carried by concrete V_c (including the contribution of arch action) and the shear carried by stirrups V_s. Consequently, the shear capacity V of RC beams is simplified as the Eq. (1):

$$V = V_c + V_s \qquad (1)$$

Therefore, as V_c in the beams with same dimensions was assumed to be same in the last section, the shear carried by stirrups V_s can be calculated by subtracting the shear capacity of the RCHB without stirrups from the RCHB with stirrups in same dimensions (see $V_{s\text{-}exp}$ in Table 3). At the same time, Eq. (2) introduced from the truss theory with variable angle of diagonal crack was chosen to calculate the shear carried by stirrups V_s:

$$V_s = A_w\, f_{wy}\, (z \cot\theta / s) \qquad (2)$$

Where, A_w is the cross sectional area of stirrups in the range of s, f_{wy} is the yield strength of stirrup, z is the internal lever arm (=jd) with j = 7/8, θ is the angle of the diagonal crack to axis of a beam, and s is spacing of stirrups.

The main diagonal cracks in the beam HS-0 and HS-100 did not pass any stirrups, while the main diagonal cracks in the beam HS-300 passed two stirrups

Table 3 Summary of the calculation and experimental results

Specimen	V (kN)	V_{s-exp} (kN)	Diagonal cracks' angle (degree)	V_{s-cal} (kN)	V_{s-exp} / V_{s-cal}
HS-0	77.4	77.4-68.1=9.3	68.2	10.2	0.912
H-0	68.1	-	68.2	-	-
HS-100	73.3	73.3-60.3=13.0	63.4	12.8	1.016
H-100	60.3	-	48.0	-	-
HS-300	68.5	68.5-36.0=32.5	39.8	32.3	1.006
H-300	36.0	-	30.3	-	-

V: shear capacity; V_{s-exp}: shear carried by stirrups observed in the experiments; V_{s-cal}: shear carried by stirrups calculated by Eq. (2).

(Fig. 3). However, the two stirrups near the loading point in the beam HS-0 and HS-100 were also yielded due to debonding cracks before the peak load. That is why the yield strength of stirrup f_{wy} was used in Eq. (2). However, how to estimate the contribution became a difficult problem.

In this paper, the shear capacities of HS-0 and HS-100 did not increase so much comparied with HS-300 while the numbers of yielded stirrups were same. It indicates that the stirrups passed by debonding cracks did not contribute on shear significantly. In addition, by measuring the average angle of main diagonal cracks within the height of stirrups in the shear span, the values of angles were obtained (Fig. 3). When the diagonal cracks passed the tensile rebars and the compressive rebars, just connect the cross points to measure the angle. When the diagonal cracks extended out of the shear span before reaching the compressive rebars (HS-0 and HS-100), just measure the average angle in the shear span. In case of HS-0, since the crack in the shear span was too short and the crack was straight, the triangle was made outside of the shear span to make the measurement easier and more accurate. The result shows that the smaller angle was, the more increase of shear capacity was. The angle of diagonal cracks dominated the increased shear capacity rather than the yielded stirrups passed by debonding cracks. Such experimental results match with the assumption of Eq. (2) that the smaller angles of diagonal cracks are, the more contribution on shear the stirrups make. Therefore, the stirrups passed by debonding cracks were considered to perform as the stirrups passed by diagonal cracks partially in RCHBs. And the possibility of this assumption was checked in this study.

Using the angles and the Eq. (2) above, the value of V_s was calculated (see V_{s-cal} in Table 3). The mean value of the experimental value to calculated value of the shear carried by stirrups was 0.978 with the coefficient of variation (*C.V.*) of 5.8%. Therefore, it can be considered that the proposed method can evaluate the shear carried by stirrups in RCHBs. However, due to the limitation of number of specimens in the present study, the applicability of the proposed method should be evaluated by conducting more experiments with various ratios of stirrups or FEM analysis in the future.

4. CONCLUSIONS

(1) Similar to the crack patterns in RCHBs without stirrups, the main diagonal cracks in RCHBs with stirrups start from the bending position of the tensile rebar near the loading point. Then the main cracks proceed along the inclined tensile rebar and towards the loading point.

(2) When the bending position of the tensile rebar near the loading point is very close to the loading point, the above crack pattern still exists in RCHBs, causing a stronger arch action to resist more shear force.

(3) Due to the presence of stirrups, more shear cracks and flexural cracks were observed. But the arch action still developed in the shear span as debonding cracks and inclined compression zone occurred in RCHBs with stirrups.

(4) As the angles of diagonal cracks are related to the bending position of the tensile rebar, the number of stirrups that main diagonal cracks pass is also different. Thus, the shear carried by stirrups varies according to the diagonal crack's angle as well as the bending position of the tensile rebar.

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