Experimental Study on the Effect of Different Shear Reinforcement Shapes on Shear Failure Behavior and Internal Crack Pattern of RC Beams

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Abstract

Various types of shear reinforcement are used for example general closed stirrup and reinforcement bar with mechanical anchor. However, most standards and specifications take only the cross-sectional area of the vertical components of the reinforcement components into account when determining their effect, such as on shear crack development and shear strength. Consequently, the full effect of different shear reinforcement shapes on the shear failure behavior of reinforced concrete (RC) beams is not clear. In this study, differences in shear failure behavior of RC beams using three types of shear reinforcement (closed stirrups, U-shaped stirrups, and rod-shaped reinforcements with mechanical anchor) were investigated by carrying out loading experiments. The three-dimensional displacement distribution on the side faces of each beam and the internal crack patterns were obtained. It was clarified that there is a clear difference in internal crack pattern and spreading deformation behavior according to shear reinforcement shape, and this influences the shear strength of the RC beam.

1. Introduction

In designing RC structures, an important aim is to prevent collapse due to brittle shear failure. Many shear failure tests of RC beams have been carried out to clarify the effects of various parameters (such as size, amount of reinforcement and material strength) on shear failure strength (Leonhardt 1962; Kani 1967; Niwa et al. 1986; Vecchio et al. 1988; Walraven et al. 1994; Muttoni et al. 2008). Based on the results, the design codes provide shear capacity evaluation equation considering both concrete contribution and shear reinforcement contribution (fib 2013; ACI 2015; JSCE 2018). In each design equation, although the concrete contribution is evaluated by different equation empirically obtained, shear reinforcement contribution is evaluated by truss theory. However, there remain many unclear areas regarding failure behavior and shear force resistance mechanism. In order to discuss the shear force resistance mechanism of RC beams with and without stirrup, Nakamura et al. (2018) investigated numerically about the basic beam and arch actions. In the study, it was clarified that the shear force of RC beam with stirrup is resisted by a mechanism comprising beam action (mainly consisting of truss action) and concrete arch action, regardless of the shear span to depth ratio. The importance to evaluate shear resistance mechanism based on beam and arch action is recognized and several studies to discuss the action experimentally and numerically have been carried out (Kim et al. 1999; Nakamura et al. 2006; Yamada 2019; Gunawan et al. 2020). It should be remarked that although closed stirrup with hook ends was commonly used as shear reinforcement in past studies, recently the use of other type of shear reinforcement is increasing.

In recent years, the increase of the amount of shear reinforcement is often required to enhance shear capacity considering large earthquake action. Then, the arrangement of hook-anchored shear reinforcement is made difficult by the high density bar arrangement. As a solution to this problem, mechanical anchorage methods using rod-shaped reinforcement (Wright et al. 1997; Thompson et al. 2002) have come into use, and the anchors provided at the ends are placed on the main reinforcement or distribution reinforcement (Gayed et al. 2004). There are some cases where the shear reinforcement effect of mechanical anchorage bars has been experimentally verified, but the shear failure behavior is discussed mainly based on the crack patterns observed at the sides (Lubell et al. 2009; Ferreira et al. 2014; Lequesne et al. 2018).

Another situation is the seismic retrofitting of an existing RC structure to enhance shear capacity. In addition to general jacketing methods (Sichko et al. 2017), various reinforcement methods are used depending on site conditions. For example, a post-construction shear strengthening method has been developed for out-of-plane shear strengthening of underground structures where the rear side is set into the ground (Kawamura et al. 2013, 2020).

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As shown in Fig. 1, this is a method in which mortar is filled into holes drilled from one side of the RC member and rod-shaped reinforcement units (PHBs) with anchor plates at both ends are inserted. In the design of a strengthening plan using PHBs with small anchor plates, a method of reducing \( V_{cr} \) is adopted by applying the evaluation method of poorly anchored shear reinforcements proposed by Regan et al. (2004). Although the validity of this method has been verified by structural experiments at the member level, detail discussion of shear force resistance mechanism has not been investigated.

Sawabe et al. (2006) performed an analytical study using a three-dimensional finite element method for RC beams in which shear reinforcement fractured at the bend and failed to anchor. As a result, it was shown that where diagonal tensile failure is specified as the failure mode, if anchorage failure occurs near the support on the tensile side, there is a significant effect on the entire structure. Kumagai et al. (2017) carried out a comparative experiment in which closed stirrups and PHBs were arranged as the shear reinforcements for RC beams. They found that, when PHBs are installed, the maximum load capacity is reduced because the number of diagonal cracks that intersect the shear reinforcement decreases. These examples demonstrate that, in the practical application of technology developed to meet various needs of society, a variety of shapes and arrangements of shear reinforcement for RC members have been developed. In order to use these technologies effectively, it is important to study the structural performance from a new perspective, without being limited by conventional structural details. Yet the effect of these methods on shear failure behavior and its mechanism has not been clarified in detail. In addition, since the shear failure behavior of RC beam is strongly related to crack propagation to many directions, investigation of detail crack propagation is important. However, crack patterns have been generally confirmed by only side surface observation. Especially in the case when using the rod-shaped reinforcements such as PHB used in post-construction shear strengthening, it is necessary to study the detailed shear failure behavior because the arrangement is independent of the other reinforcement bars. It is possible that cracks may occur 3-dimensionally in beam, especially when there is no reinforcement arranged in the width direction such as straight rod shape reinforcement. It is expected that if 3-D crack pattern in beam is observed, the information gives new possibility to evaluate shear failure behavior.

In this study, loading tests of RC beam specimens with different shear reinforcement shapes are carried out. In particular, focusing on the shear failure behavior with rod-shaped reinforcements, it is compared with the case of closed stirrups and U-shaped stirrups. In the experiment, detailed measurements are taken of the three-dimensional displacement distribution of the beam side surface. From observations of crack patterns at many cut cross-sections, 3-D maps of internal cracking, including in the width direction, are created. The effect of the different shear reinforcement shapes on the shear failure behavior of RC beams is then discussed in detail, not just in terms of differences in maximum load bearing capacity, but from multiple perspectives including three-dimensional deformation behavior, internal crack pattern and the shear force resistance mechanism.

2. Experiment outline

2.1 Overview of specimens

A total of three RC beams with a shear span to depth ratio \( a / d = 2.86 \) were tested. Each is 200 mm wide \( \times \) 400 mm high \( \times \) 2,400 mm total length, as shown in Fig. 2. The tensile main reinforcement consists of \( 2 \times \) SD490/D29, and the compression main reinforcement is \( 2 \times \) SD345/D10. The tensile main reinforcement ratio \( p_t \) is 1.84%. In the test section of the shear span (left side of beam in Fig. 2), which is designed to ensure shear failure, the shear reinforcement is of a different type in each test beam and is spaced at 200 mm intervals in each case. The four shear reinforcement components in this section, aside from those at the loading point position and the support position, are designated S1 to S4 in order from the loading point side. In order to prevent shear failure in the other shear span (right side of beam in Fig. 2), closed stirrups are arranged at 100 mm intervals in common for all specimens.

The types of shear reinforcement used in the test section, which is the experimental parameter, are illustrated in Fig. 2 and detailed in Table 1, respectively. In Case-1, they are closed stirrups that surround all four tensile and compression main reinforcement rods. Anchorage is with acute-angled hooks around the compression main reinforcement. In Case-2, the shear reinforcement is U-shaped stirrups that surround the main tensile reinforcement rods. Anchorage is with semi-circular hooks at each compression main reinforcement. In Case-3, PHBs are used with a circular steel plate of thickness 9 mm and diameter 28 mm friction-welded to each end. This is a type of rod-shaped reinforcement used for post-construction shear strengthening. In this experiment, concrete was...
placed after the PHBs were arranged centrally in the width direction. In the height direction, the PHBs were arranged such that the upper and lower cover depth was the same as for the shear reinforcement in Case-1 and Case-2. The shear reinforcement arrangement, which does not interfere with the main reinforcements or distribution reinforcements, simulates the case when post-construction shear strengthening is applied. This is the main focus of this study.

The shear reinforcement consisted of SD295/D10 for Case-1 and Case-2, and SD345/D13 for Case-3. As shown in Table 1, the variation in the product of reinforcement ratio $p_w$ and yield strength $f_{wY}$ of the shear reinforcement among the three cases is about 3%, and this reinforcement design allows the difference in $p_w$ to be neglected.

**Table 1 Shear reinforcement in test section.**

| Reinforcement shape | Case-1 | Case-2 | Case-3 |
|---------------------|--------|--------|--------|
| Material            | SD295  | SD295  | SD345  |
| Diameter            | D10    | D10    | D13    |
| Reinforcement ratio $p_w$ | 0.36% | 0.36% | 0.32% |
| Yield strength $f_{wY}$ | 370 N/mm² | 370 N/mm² | 403 N/mm² |
| $p_w f_{wY}$        | 1.32 N/mm² | 1.32 N/mm² | 1.28 N/mm² |

**Table 2 Compressive strength of concrete.**

| Compressive strength $f'_c$ | Case-1 | Case-2 | Case-3 |
|-----------------------------|--------|--------|--------|
| 20.3 N/mm²                  | 21.5 N/mm² | 20.3 N/mm² |

2.2 Loading method

At the loading point, only rotational displacement is allowed while at the supports both rotational and horizontal displacement is allowed. A steel bearing plate with a width of 100 mm was used at both the loading and support points. Figure 3 shows the setup for the loading experiment. Static monotonic loading was carried out at the one loading point in the center using a hydraulic jack (maximum capacity 500 kN). In order to observe internal crack patterns somewhat beyond the point of maximum loading after the experiment, unloading continued to about 80% of the maximum load in the post peak region.

2.3 Measurements and observations

The applied load was measured using a load cell installed at the loading point. In addition, vertical displacement was measured using displacement gauges at the loading point and the support positions.

Strains were measured with strain gauges at three vertical points on each of the S1, S2, and S3 shear reinforcements: upper, middle, and lower. Additionally, strain was measured at the mid-point of the upper and lower horizontals in Case-1 and the lower horizontal in Case-2. A waterproof tape was wrapped around the strain gauges of the reinforcement, but it was kept to a minimum so as not to affect the bond behavior with concrete. Furthermore, using strain gauges for concrete, the strain in the width direction of the specimen was measured on the top surface at the location of the S2 and S3 shear reinforcements.

The Digital Image Correlation (DIC) method (GOM 2020) was applied to one side face of the shear span in the test section in order to confirm crack propagation and principal strain distribution on the surface (Smrkic et al. 2018). A red spray was applied to this surface of the specimen in advance to generate a random pattern. Photographs were shot continuously from a fixed point using a digital single-lens reflex camera with 24.16 mil-
lion pixels and these were later subjected to image analysis processing.

On the other side face of the shear span in the test section, three-dimensional displacement including out-of-plane direction was measured using an optical motion capture (MC) system (OptiTrack 2020) that has been shown to be useful in structural experiments (Asai et al. 2020). Special markers that reflect infrared light were attached to a grid pattern of measurement points over a height of 80 mm and a width of 100 mm. Images were obtained with infrared cameras placed at three fixed locations for continuous measurement. A marker attached to the bearing plate at the support point was regarded as the reference point, and relative displacements with respect to this point were taken to be the displacements at each measurement point.

After the experiment was completed, the crack patterns on the side face measured by MC and on the top surface of the specimen were confirmed visually. Furthermore, resin mixed with fluorescent paint was injected into the cracks to strengthen them and, after curing, test sections were cut axially at 50 mm intervals. By irradiating this cut surface with black light, the position and width of the cracks could be easily confirmed. A three-dimensional internal crack map was created using these recorded crack positions and widths at each observed cut surface.

3. Experimental results

3.1 Load-displacement relationship and surface crack patterns

Figure 4 shows the relationships between load and vertical displacement. This is a relative displacement obtained by subtracting the vertical displacement at the supports from the measured value at the loading point. Figure 5 shows the crack patterns on the side and top surfaces after the experiment. The cracks shown by thick lines in the figure are diagonal cracks that are wider and more dominant with respect to shear failure than others. Figure 6 shows the principal strain distribution on the side face at maximum load as obtained from the DIC measurements. The surface shown in Fig. 6 is the opposite side to the sketched crack pattern in Fig. 5. The crack patterns in Fig. 5 and the principal strain distribution in Fig. 6 do not match completely because of differences between the post-unloading state and the state at maximum load and because different surfaces were measured.

In all cases, diagonal cracks occurred in the test section at a load of about 120 to 150 kN, and there was no difference in stiffness during the loading process.
Table 3 Experimental and calculated shear strength.

|                | Case-1 (Closed) | Case-2 (U-shaped) | Case-3 (Rod-shaped) |
|----------------|-----------------|-------------------|--------------------|
| **Calculated** |                 |                   |                    |
| $V_c$          | 75 kN           | 77 kN             | 75 kN              |
| $V_y$          | 80 kN           | 80 kN             | 78 kN              |
| $V_z$          | 155 kN          | 157 kN            | 153 kN             |
| **Experiment** |                 |                   |                    |
| $V_{c,exp}^*$  | 102 kN          | 83 kN             | 56 kN              |
| $V_{y,exp}^*$  | 69 kN           | 70 kN             | 58 kN              |
| $V_{max,exp}$  | 171 kN          | 153 kN            | 114 kN             |
| $V_{max,exp}/V_y$ | 1.11          | 0.97              | 0.73               |

$V_{c,exp}$ and $V_{y,exp}$ show the value at the time of maximum load.

In Case-1 with the closed stirrups, the load continued to increase even after the occurrence of diagonal cracks, and the maximum load reached 343 kN at the vertical displacement of 7.6 mm. After reaching this maximum load, the load gradually decreased and compression failure occurred near the loading point. The area of failure was on both edges of the top surface as shown in Fig. 5(a), corresponding to the outside corners of the curved parts of the closed stirrup.

In Case-2 with the U-shaped stirrups, the stiffness after diagonal crack occurrence was slightly lower than in Case-1 and the maximum load was 306 kN at a vertical displacement of 6.5 mm. That is, the maximum load is about 11% lower than in Case-1 with the closed stirrups. Both the diagonal cracks on the side surface and the cracks on the top surface were like Case-1.

In Case-3 with the rod-shaped reinforcements, the load did not increase beyond approximately 220 kN which is after diagonal cracks occurred and remained almost constant as the vertical displacement increased. Ultimately, the maximum load was 227 kN at a vertical displacement of 6.4 mm. The maximum load was 34% less than that in Case-1 with the closed stirrups. In the crack patterns obtained after loading, three diagonal cracks were confirmed on the side surfaces of Case-1 and Case-2, whereas two were found in Case-3. Since a third diagonal crack was confirmed in the principal strain distribution on the opposite side at maximum load, this difference in number is due to closing as unloading took place. That is, in reality the diagonal crack patterns were almost same as in Case-1 and Case-2. However, in Case-3, cracks with the appearance of bond-splitting cracks occurred along the tensile main reinforcement near the support position, a result of the rod-shaped shear reinforcement not enclosing the main reinforcement. A new finding about crack propagation in Case-3 is that an axial crack occurred centrally (in the width direction) on the top surface at a location about 700 mm long from the loading point directly above the rod-shaped reinforcements. An axial crack on the top surface may play a significant role in the reduced maximum load.

Table 3 compares the shear strength $V_y$ calculated by Eq. (1) and the experimental result $V_{max,exp}$. Here, $V_y$ corresponds to the load at diagonal crack initiation, a value calculated using the formula proposed by Niwa et al. (1986) and given as Eq. (2), and $V_{max,exp}$ is the load borne by the shear reinforcement, as calculated by truss theory assuming that the angle of the diagonal crack is 45°, as shown in Eq. (3). Actual strengths based on material tests on the reinforcement and concrete are used in the calculation.

$$V_y = V_c + V_s$$

$$V_y = 0.2 \cdot (p_s \cdot f_y^{1.3} \cdot (d/1000)^{-1/4} \cdot 0.75 + 1.4/(a/d) \cdot b_w \cdot d)$$

$$V_{max,exp} = \frac{A_s \cdot f_{sy}}{s_s} \cdot z$$

where, $p_s$ is the tensile reinforcement ratio $(= A_s/(b_w \cdot d))$, $f_y$ is the compressive strength (N/mm$^2$) of concrete, $d$ is the effective depth (mm), $a$ is the shear span (mm), $b_w$ is the web width (mm), $A_s$ is the area (mm$^2$) of the tension reinforcement, $s_s$ is the spacing of shear reinforcement (mm), $V_{max,exp}$ is the total area (mm$^2$) of shear reinforcement placed in distance $s_s$, $f_{sy}$ is the yield strength (N/mm$^2$) of the shear reinforcement, and $z$ is the distance (mm) between the resultant compressive force and the centroid of the tension reinforcement $(= d/1.15)$. The experimental value of shear strength, $V_{max,exp}$, is calculated as half of the maximum load and in Case-1 is 1.11 times of $V_y$. In Case-2, the load is 0.97 times, very close to the calculated value. But in Case-3 it is 0.73 of the calculated value. The calculation method of $V_{max,exp}$ and $V_{y,exp}$ is explained in Section 4. The values are used for the discussion in Section 5.

### 3.2 Internal crack patterns

Figure 7 illustrates the three-dimensional internal crack pattern over the entire test section for each case. These crack patterns were created based on the observed cracks in each cross section at the cut surfaces. This 3-D internal crack map is probably first trial in the field of RC structures. Cross sections of the crack patterns in the cut plane near the S2 and S4 shear reinforcements are shown in Fig. 8. For Case-3, a cross-sectional photograph between S2 and S3 location when cracks filled with resin and irradiated with a black light is also shown to explain the characteristic vertical crack in the cross-section.

In Case-1 with the closed stirrups, there is a complex of cracks near the top of the cut surface near S2 because of crushing, and the occurrence of splitting crack patterns at the corner is confirmed. The diagonal crack near the tensile reinforcement is present across the entire width direction, while another diagonal crack at mid-height is confined within the stirrup verticals. This suggests a possibility that diagonal cracking may originate within the stirrups and propagate toward the sides, because the stirrups provide less restraint against diagonal cracking.
in the center of the beam due to the greater distance from the stirrup verticals.

Near S4, several diagonal cracks are seen across the width of the beam both above and below the tensile reinforcement; these are cracks propagating toward the support point. At the mid-point of the cross-section, there are vertical cracks spreading toward the bottom surface of the beam. Over the entire test section, internal cracks cross almost the entire width direction. The diagonal cracks, which are thought to be the dominant contributor to shear failure, are 1.5 to 3 mm wide, and they are relatively larger near the side faces of the beam.

In Case-2, with the U-shaped stirrups, the crack patterns are similar to those of Case-1. However, a notable difference arises in the upper region between the compression main reinforcement bars. Here, as seen in the cut surface near S2, in addition to the vertical cracks that occurred inside the semi-circular hooks, the crack propagate vertically near the top as if they wrap around the inside of the compression main reinforcement. This vertical crack is occurred along the hook, and propagates horizontally towards the sides above the compression main reinforcement bars. Since the U-shaped stirrups do not have an upper horizontal, there is a probable propagation path in this area. It can also be observed in the 3-D map of Fig. 7(b) that the vertical crack propagates between horizontal crack induced by compressive stress and diagonal crack. The lower part of the U-shaped stirrup is the same as that of the closed stirrup, and the crack pattern at the cut surface near S4 is similar to that of Case-1. The width of the diagonal cracks, which is considered to be the most dominant factor in shear failure, is the same as in Case-1.

In Case-3, with the rod-shaped PHB reinforcements, cracks are visible radiating downward from the top plate of the PHB in the cut surface near S2. There is a possibility that the diagonal cracks propagated like this to avoid the higher stiffness area formed by the presence of the rod-shaped reinforcements, or that these cracks were initiated by pressure from the anchorage plate. These cracks reach at the top surface immediately above the rod-shaped reinforcements and are the axial cracks observed on the top surface of the beam. The 3-D crack map in Fig. 7(c) shows clearly that this vertical crack extends for about 700 mm from the loading point in the area above the main diagonal crack. This type of vertical cracking is a new finding. An example of vertical crack in a cross-section between S2 and S3 can be confirmed by the photo under black light as shown in Fig. 8(c). The vertical crack from top surface to the position of diagonal crack is observed clearly at the center part. This is a characteristic crack caused by the arrangement of rod-shaped reinforcements in the post-construction shear strengthening. The smaller vertical crack observed in Case-2 may be the same type of crack. The diagonal cracks are almost horizontal across the entire width of the beam. The diagonal cracks that seemed to be most dominant in shear failure are 2.5 to 3 mm wide across the entire width of the beam, so they are larger than in the other cases. In the cut surface near S4, radiating cracks similar to those observed near the top of the beam are seen around the bottom of the PHB.

3.3 In-plane displacement of side face

Figure 9 shows the in-plane deformation on the side face of the test section as measured by MC. Displacements,
shown in vector notation, range from $\delta = 0$ to $\delta = 1.5$ mm of vertical displacement before the occurrence of diagonal cracking and from $\delta = 3$ to $\delta = 4.5$ mm after the occurrence of diagonal cracking.

In all cases, before the occurrence of diagonal cracks, there was a downward displacement slightly in the direction of the loading point, and displacement was greater near the loading point. This confirms the normal bending deformation behavior of the beam. In contrast, the in-plane deformation mode changed after the occurrence of diagonal cracks. Although the direction of displacement did not change significantly, there is a large difference in the amount of displacement at a boundary marked by the dominant diagonal crack. The change is particularly large in Case-3, with rod-shaped reinforce-
ments, so it is confirmed that the opening of diagonal cracks is relatively large. It is also confirmed that, in all cases, deformation under the diagonal crack proceeds as if the region were a rigid body. In this way, the in-plane deformation behavior when shear failure occurs can be clarified through displacement measurements obtained using MC.

### 3.4 Out-of-plane displacement on side surface

Figure 10 shows the out-of-plane displacement (displacement in the width direction of the beam) at the MC measurement points at the top, middle, and bottom of the side face marked by the broken green line in Fig. 9. For each reinforcement case, the figures show the top (H = 400 mm), middle (H = 240 mm), and bottom (H = 0 mm) MC measurement points from top to bottom, and the spreading direction is positive.

- **P = 100kN**
- **P = 200kN**
- **P = 343kN (Max)**
- **P = 227kN (Max)**

- **$\delta = 10$mm**
- **$\delta = 9$mm**
- **$\delta = 8$mm**

*Fig. 10 Out-of-plane displacement on the side face of the test section.*
ward displacement is defined as positive in this figure. In all cases, displacements at the middle and bottom of the beam are relatively small, but near the top there is a characteristic difference according to type of shear reinforcement.

In Case-1, with closed stirrups, displacement tends to be inward over the entire specimen occurred from the initial stage of loading, particularly upper part near the support end. There is a possibility that it is due to the effect of the entire RC beam specimen leaning backwards in view of the measurement surface. Focusing on local displacement due to loading, it can be confirmed that outward displacement in the out-of-plane direction occurs at the three measurement points closest to the loading point at the top of the beam when the load reaches maximum, in contrast with the other points. This area corresponds to the region where compression failure occurred, and in this region the displacement increased notably due to dilatancy behavior when vertical displacement reached 10 mm after maximum loading.

In Case-2, with U-shaped stirrups, the reason for the inward displacement of the upper part near the support is probably the same as in Case-1. Out-of-plane displacement is smaller overall than in Case-1, but after the maximum load, outward displacement at the upper measurement point closest to the loading point also increases significantly. This is also dilatancy behavior, but compression failure damage was small in this case, and this is reflected in reduced outward displacement than in Case-1.

In Case-3, with rod-shaped reinforcements, outward out-of-plane displacement at the top is seen from the loading point to near the S3 shear reinforcement position once loading reaches 200 kN and until the maximum load. Displacement is largest at the loading point end and decreases toward the support end. The region of out-of-plane displacement corresponds to the region in which axial cracks are seen on the top surface of the beam. This result clarifies that the axial crack propagated along the top surface from the loading point end to the support end before the maximum load. At a vertical displacement of 8 mm after maximum loading, this displacement in the width direction increased further in this region.

Figure 11 shows the change in out-of-plane displacement at point ‘a’ (shown in Fig. 9) close to the loading point where displacement was greatest, together with the load-displacement relationship. Although in Case-2 there is rather a lot of noise, the point of change in the displacement increase gradient is clear in each case.

It can be seen that the out-of-plane displacement begins to rise rapidly at a vertical displacement of about 7 mm in Case-1, slightly before peak load. In Case-2, this occurs at about 6 mm and in Case-3 with the rod-shaped reinforcements at about 4 mm. These change points match well with the timing at which the load increase leveled off. This confirms that an RC beam reaches the limit of its capacity to bear shear force when spreading displacement in the out-of-plane direction begins in the compressive stress region. It is also clarified that there are two mechanisms for out-of-plane displacement: dilatancy due to compression failure of the concrete and splitting behavior due to the development of a vertical crack along the axial direction. The latter mechanism has not previously been recognized in the shear failure of RC beams. In Case-3, with rod-shaped reinforcements, since the latter mechanism is dominant, special considerations are required when verifying shear failure response. Further, small vertical cracks between the compression main reinforcement were also observed in Case-2, as shown in Figs. 7(b) and 8(b). The out-of-plane displacement in Case-2 is considered to be mainly due to compressive failure. In addition, there is a possibility that vertical cracks that occurred in the same way as in Case-3 also have an influence.

3.5 Change in vertical/horizontal strain of shear reinforcement and strain in width direction

Figure 12 shows the vertical strain of shear reinforcements of S1 to S3 at the measurement point nearest the dominant diagonal crack together with the load-displacement relationship. These strain measurement points are indicated in Fig. 5.

In all cases, the strain begins to increase when vertical displacement reaches about 2 mm, which corresponds to the occurrence of diagonal cracking. Thereafter, at least one shear reinforcement yields in each case at near the maximum load. It is confirmed that the shear reinforcement verticals have similar tensile resistance to diagonal crack opening regardless of type of reinforcement. There is a possibility that the gradient of strain increasing with vertical crack opening vary with the distance between the strain measurement position and the diagonal crack position.

![Fig. 11 Change in out-of-plane displacement of the side face of beam near loading point.](image-url)
Figure 13 shows strain in the width direction at upper and lower shear reinforcement horizontals and at the concrete top surface, together with the load-displacement relationship. These strain measurement points are indicated in Fig. 2.

In Case-1, the strain in the upper horizontal of stirrups S2 and S3 (S2U and S3U) begins to increase when the vertical displacement reaches 3.5 mm after the occurrence of diagonal cracking. This increase in strain starts slightly after the rise in vertical strain. The strain is highest closer to the loading point (S2U) and at S2U the strain reaches the yield strain near the maximum load point, which is almost the same displacement at which the vertical strain reaches yield. The strain at the lower horizontal (S2L and S3L) begins to increase when the vertical displacement reaches about 1 mm, which is before the occurrence of diagonal cracking, and the S2L strain reaches the yield strain after the maximum load point. The strain of the concrete top surface in the width direction (C2U and C3U) gradually increases, but at S2 position (C2U) it decreases momentarily at a vertical displacement of about 3 mm. This can be understood as a stress release caused by propagation of the diagonal crack. The C2U strain increases again thereafter and reaches about 150 μ at the maximum load. Although a slight spreading deformation in the width direction occurs, it is supposed that initiation of axial cracking on the top surface, as seen in Case-3, is suppressed by the tensile resistance of the upper horizontal of the closed stirrup. Since the lower horizontal of stirrup S2L also yields, it is also supposed the existence of the effect of suppressing the deformation that spreads in the width direction as in the upper part.

In Case-2, the strain at the lower horizontal (S2L and S3L) begins to increase when the vertical displacement reaches 1 mm, which is before the occurrence of diagonal cracking, and the S2L strain reaches the yield strain after the maximum load, similarly to Case-1. The strain of the concrete top surface in the width direction (C2U and C3U) gradually increases, but at S2 position (C2U) it decreases momentarily at a vertical displacement of about 2 mm. There is a possibility that the difference in
distance between the top surface and diagonal cracks influence the strain variation, which is smaller than in Case-1. The C2U strain reaches about 110 μ at the maximum load. This behavior is similar to that of Case-1.

In Case-3, the strain of the concrete top surface in the width direction (C2U and C3U) gradually increases at first, and then falls into compression when the vertical displacement reaches about 2.5 mm. The behavior is similar to that of Case-1. After the load increase levels off, the tensile strain of the concrete suddenly increases rapidly, first above S2 (C2U) and then above S3 (C3U). This result leads to the same finding as in Section 3.4 based on the MC measurements: that the axial crack propagates along the top surface of the beam from the loading point end toward the support end. It is also concluded that this vertical crack propagation as well as that of the axial crack on the top surface is due to the PHB shear reinforcement’s lack of a horizontal to suppress deformation in the width direction.

4. Changes in shear force resistance mechanism

Based on the measurements of shear reinforcement vertical strain, the contributions of the concrete and the shear reinforcement to resisting shear force are calculated. The shear force \( V_{c,\text{exp}} \) borne by the shear reinforcement is calculated using truss theory for each of the S1 to S3 shear reinforcements, using Eqs. (4) and (5). These three bars are shear reinforcements with strain measured in the experiment. The values at the measurement point nearest the dominant diagonal crack shown in Fig. 5 were used in the calculations, and the average value of three reinforcements is taken.

\[
V_{c,\text{exp}} = \frac{A_v}{s} \cdot \sigma_v = \frac{\mu}{s} \cdot \varepsilon_v = \frac{\mu}{s} \cdot E_v \cdot \varepsilon_v
\]

(4)

where, \( \sigma_v \) is the stress of the shear reinforcement, \( E_v \) is Young’s modulus (200 kN/mm²), and \( \varepsilon_v \) is the strain of the shear reinforcement, assuming \( E_v \cdot \varepsilon_v \geq f_{vy} \), \( \sigma_v = f_{vy} \).

The total shear force \( V_{c,\text{exp}} \) is half of the applied load, and the value obtained by subtracting \( V_{c,\text{exp}} \) from \( V_{c,\text{exp}} \) is the shear force \( V_{s,\text{exp}} \) borne by the concrete. Figure 14 shows changes in the shear force resistance components calculated by this method. The values of \( V_{c,\text{exp}} \) and \( V_{s,\text{exp}} \) at maximum load are shown in Table 3 as experimental values.

In all cases, the shear force is borne by the concrete until the occurrence of diagonal cracking at a vertical displacement of about 2 mm. Thereafter, \( V_{c,\text{exp}} \) begins to increase. The shear force at the occurrence of diagonal cracking is almost the same as the value \( V_c \) calculated using Eq. (2).

The component of shear force borne by the concrete, \( V_{c,\text{exp}} \), increases after diagonal cracking in Case-1 with closed stirrups and Case-2 with U-shaped stirrups, but at maximum load it is 19% lower in Case-2 than in Case-1. This is assumed to be because compression of the concrete is not confined by a shear reinforcement upper horizontal, so deformation in the width direction is not suppressed as it is with the closed stirrup. In Case-3 with rod-shaped shear reinforcements, \( V_{c,\text{exp}} \) decreases after the occurrence of diagonal cracking and at maximum load is only 46% of that in Case-1. It is assumed that, with no confinement of concrete deformation in the width direction because there are no upper and lower horizontal and with a vertical crack propagating toward the top surface from the dominant diagonal crack, the arch action contributed by concrete stress is reduced by the effect of splitting behavior of concrete on compression stress flow along diagonal crack.

The component of shear force borne by the stirrups, \( V_{s,\text{exp}} \), is almost the same in Case-1 and Case-2 at maximum load, but in Case-3 it is 16% lower. It is assumed that cracks developing around the reinforcement ends or the vertical crack have a deleterious influence on the function of the reinforcement as a tensile material.

Based on these results, it is clarified that when U-shaped stirrups are used, the shear force borne by the concrete, which is mainly a result of arch action, is lower than when closed stirrups are used. Moreover, when rod-shaped reinforcements are used, the shear force borne by both concrete and the shear reinforcement decreases. Similar results have been reported by Kumagai et al. (2017). In this study, the effect of different shapes

![Fig. 14 Changes in shear force contribution.](image-url)
of shear reinforcement have been investigated in terms of reinforcement strain at the experimental measurement positions while changes in the shear force resistance mechanism, or the relative contribution of $V_{\text{cr}}$ and $V_{\text{exp}}$, are by indirect calculation using the test results. A more detailed analysis of the shear force resistance mechanism is possible by numerical analysis (Nakamura et al. 2018) for direct evaluation of the stress distribution in the cross section and the continuous strain distribution of the reinforcement. The authors hope to consider this in the future.

5. Discussion of relationships between shear reinforcement shape and shear failure behavior

The experimental results demonstrated that the shear failure behavior and maximum load capacity of RC beams differ significantly depending on the shape of shear reinforcement, even when the total amount of shear reinforcement is almost the same. Shear failure behavior of RC beams often show variable phenomenon such as crack patterns and shear capacity. Careful evaluation is necessary because there is one specimen in each case in the experiment. Since there is a possibility that the shear reinforcement shapes affect the maximum load based on the results of various measurements, this point is discussed below.

The great differences in experimental internal crack patterns and displacement behavior in the out-of-plane direction (width direction) in the compression area are attributed to shear reinforcement type. These variations lead to different values of shear force borne by the concrete. It appears that the presence or absence of horizontals in the shear reinforcement design is significant. These horizontals have the ability to resist displacement of the concrete in the width direction. The case with U-shaped stirrups (Case-2) have caused more damage in the compression zone, such as vertical cracks that wrap around the semicircular hooks, and shear force borne by the concrete is smaller than in the case with closed stirrups (Case-1). There is a possibility that this has led to the difference in shear capacity.

Also of importance is the position of the shear reinforcement verticals. A comparison between the U-shaped stirrups (Case-2) and the rod-shaped reinforcements (Case-3) shows that the initiation point and propagation behavior of diagonal cracks in the cross section are different in the two cases. In the case with rod-shaped reinforcements (Case-3), local stresses in the compression zone due to the pressure from the anchorage plate could have an influence on the crack patterns. This resulted in cracks that propagated to the top surface and then no further load increase. On the other hand, cracks are less likely to propagate toward the top surface when the shear reinforcement verticals are arranged near the side faces of the beam than when they are arranged in the center. The lower horizontals have also affected the results by preventing deformation in the width direction, since the lower horizontals of U-shaped stirrups was also in tension. There is a possibility that these factors are the reason for the difference in maximum load between Case-2 and Case-3 in this experiment.

The above factors have resulted in differences in the shear forces borne by the concrete between cases. As a result, the shear capacity of the shear reinforcement in the case of U-shaped stirrups (Case-2) was slightly lower in the case of closed-stirrups (Case-1), but the shear capacity in the case of rod-shaped reinforcements (Case-3) showed quite lower value than Case-1. Although the shear reinforcement vertical resists diagonal crack opening in the same way in Case-3, the crack patterns in the cross-section differed in that they intersect with the shear reinforcement.

6. Conclusions

In this study, RC beam specimens are subjected to loading tests to investigate the effect of different shear reinforcement shapes on shear failure behavior. The main conclusions reached from the experimental results are given below. It should be noted that this study was carried out using RC beams of small width in relation to cross-sectional height. As a result, the effect of deformation in the width direction is likely to be readily apparent. Confirmation is needed as to whether the shear failure behavior would be different in the case of relatively wide beam members and wall members with large width constraints. In addition, this study was carried out under the condition of $a/d = 2.86$. If the shear failure mode differs depending on the difference in $a/d$, a further study is necessary.

1. 3-D maps of internal cracking and cross-sectional cracking patterns were created for RC beams that failed in shear based on the cracks observed in many cross-sections cut from the beams. This map gives useful information that helps to understand internal crack patterns and the effect of the cracking on shear behavior.

2. Internal crack patterns in the concrete cross-section differed greatly depending on the shear reinforcement shape. A new finding is that, where rod-shaped reinforcements with mechanical anchor were used, cracks formed around top and bottom ends of the bars and these cracks propagated to the top surface in the form of a vertical crack. This led to axial cracks propagating from the loading point end to the support end.

3. In cases where the shear reinforcement consisted of U-shaped stirrups or rod-shaped reinforcements with mechanical anchor, the maximum load was clearly reduced compared to the case with closed stirrups. This reduction in maximum load was greater in the case of rod-shaped reinforcements.

4. The shear force borne by the tested RC beams was lower when displacement of the concrete occurred in
the out-of-plane direction in the compressive stress region. Moreover, it was clarified that there are two mechanisms for out-of-plane displacement: dilatancy due to compression failure of the concrete and splitting behavior due to the development of a vertical crack in the axial direction. The latter mechanism was observed in the beam with rod-shaped reinforcements.

(5) It was shown that positioning the shear reinforcement vertically near the side faces of the beam suppresses deformation in the width direction, demonstrating that the position of the shear reinforcement is also important. It was confirmed also that the lower horizontal of the shear reinforcement effectively prevents deformation in the width direction.

(6) It was clarified that, when U-shaped stirrups are used, the shear force component borne by the concrete, and which mainly derives from arch action, is lower than when closed stirrups are used. In the case of rod-shaped reinforcements, the shear force borne by both concrete and the shear reinforcement is lower.

(7) The reduction in shear force borne by the concrete was more notable in the case of a single rod-shaped shear reinforcement than when U-shaped stirrups were used. It is supposed that since concrete deformation in the width direction was not confined at all in the case of the rod-shaped reinforcements, due to lack of upper and lower horizontals, vertical cracks were able to propagate toward the top surface from the dominant diagonal crack. Thus, the splitting behavior significantly reduces the arch action of the concrete and hence the stress that it can bear as compressive stress flows along the diagonal crack.

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