SHEAR BEHAVIOR OF RC TAPERED BEAMS WITH STIRRUPS

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1. INTRODUCTION

In the current construction field, reinforced concrete members whose effective depth of the cross section varies uniformly along its axis (hereafter RC tapered beams) are frequently used in structural portal frames, cantilevers and bridge structures. Such beams are widely used due to economic and aesthetic reasons. Many studies on shear behavior of RC tapered beams without stirrups have been conducted. However, since stirrups are essential in actual construction to avoid the shear failure, the current problems are that, experimental studies and data on RC tapered beams with stirrups are rather insufficient, and the effects of stirrups are still unclear. Therefore, the objective of this study is to investigate the shear behavior of RC tapered beams with stirrups.

2. EXPERIMENTAL PROGRAMS

2.1 Test specimens and materials

Totally four RC tapered beams with the same dimension were tested. The shear span was 875 mm and the shear span to effective depth ratio was 3.5. The angle of the taper was 8.3°. The details of the specimens are shown in **Fig. 1** and **Table 1**. Each specimen was named after its stirrup ratio.

In each specimen, the water-cement ratio of concrete was 0.6. The design compressive strength of concrete was 30 N/mm^2. Two deformed high-strength steel bars (A_s=380.1 mm^2) with the yield strength of 1080 N/mm^2 were used as tensile bars. The yield strength of deformed high-strength steel bars used as compressive bars (A_s'=142.7 mm^2) was 358 N/mm^2 and D6 deformed steel bars for stirrups (A_w=63.3 mm^2) was 333 N/mm^2.

2.2 Loading method and measurements

All beams were tested under a four-point bending. During the loading tests, the applied load and the mid-span deflection were recorded. The strains of the stirrups were measured from upper, middle and lower spot of each stirrup (**Fig. 1**). The propagation and the final pattern of the cracks were recorded by taking pictures at every 10 kN during the loading and after failure.

3. EXPERIMENTAL RESULTS

3.1 Load-deflection curves

Figure 2 shows the load-deflection curves of all four specimens. The solid parts indicate the phase of loading and the dashed parts indicate unloading. Compared to the other three specimens, RW0, which was not strengthened with stirrups, failed suddenly at the occurrence of the diagonal crack. It can be seen that, as the stirrup ratio became larger, the shear capacity increased and the decrement of the stiffness after the occurrence of the critical diagonal crack became lesser.

3.2 Crack patterns

The crack patterns at just after the peak of all four specimens are shown in **Fig. 3**, where the red lines represent the critical diagonal cracks. No remarkable difference in quantity of cracks can be observed while the shapes of diagonal cracks varied among the four specimens. Obvious turnings can be seen in RW0, while the diagonal cracks were flatter in the cases of the other three specimens. According to Kostovos (1988), the change in direction of critical diagonal crack also indicates the change in direction of compressive strut. Therefore, it can be said that the existence of stirrups influenced the condition of the compressive strut in each specimen, which led to the difference in shear resistance mechanism. As in RW0, the clear shape of two abrupt changes in directions showed the compressive strut in arch. On the other hand, in the other three specimens, the turning angle in critical diagonal crack became less

Table 1 Experimental parameters

Specimens	r_w (%)	s (mm)	n
RW0	0		0
RW18	0.18	175	4
RW25	0.25	125	6
RW33	0.33	97	8

r_w: stirrup ratio; s: stirrup spacing; n: number of stirrups

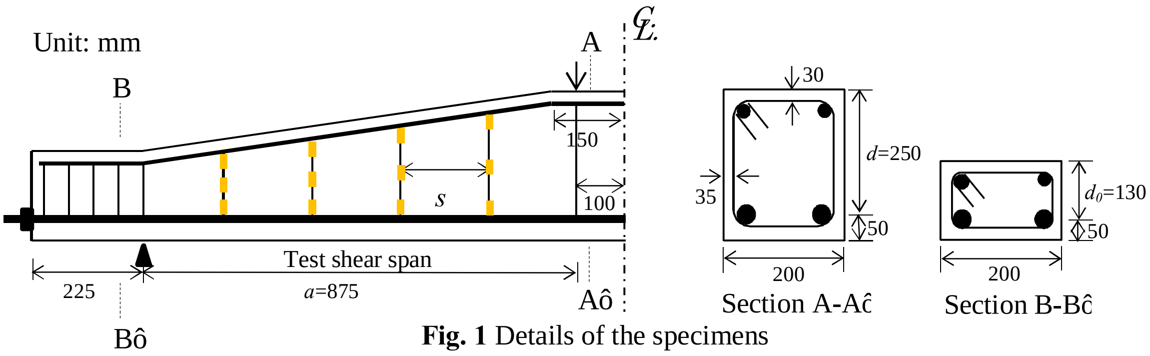

Fig. 1 Details of the specimens

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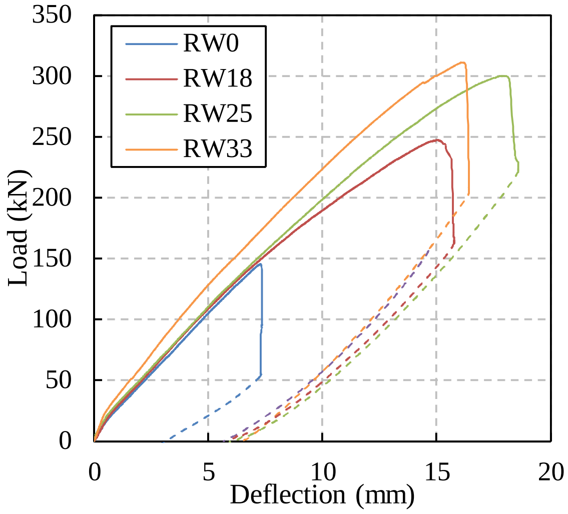
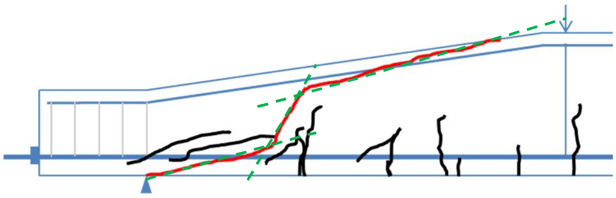
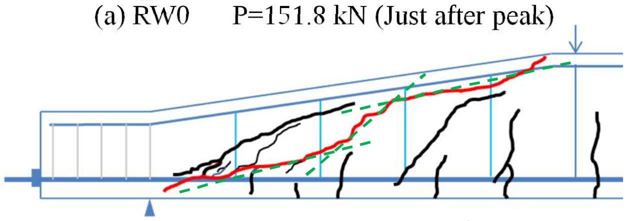


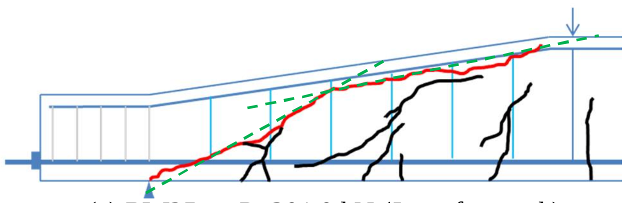
Fig. 2 Load-deflection curves



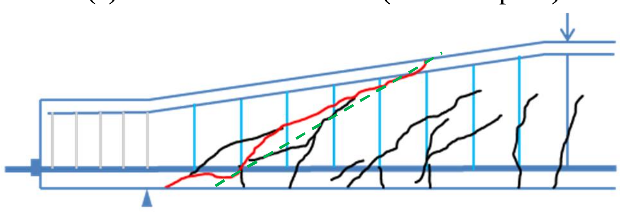
(a) RW0 P=151.8 kN (Just after peak)



(b) RW18 P=247.2 kN (Just after peak)



(c) RW25 P=301.0 kN (Just after peak)



(d) RW33 P=311.0 kN (Just after peak)

Fig. 3 Crack patterns

remarkable, implying the difference in the formation of the compressive strut due to the behavior of stirrups after the occurrence of the critical diagonal cracks.

3.3 Behavior and contribution of stirrups

All stirrups started to carry vertical load after the occurrence of flexural crack and the strain increased slowly. The increase suddenly became rapid at around 150 kN, which is extremely close to the failure load of RW0, 151.8 kN. This phenomenon applied to all stirrups regardless of the location. Consequently, the shear resistance mechanism before then could be considered the same as RW0. In addition, stirrups yielded mostly at the spots where critical diagonal cracks crossed, and earlier

Table 2 Evaluations of contribution of stirrups

Specimens	$V_{s\text{-}exp}$ (kN)	$V_{s\text{-}\varepsilon}$ (kN)	$V_{s\text{-}exp}$ /$V_{s\text{-}\varepsilon}$
RW18	47.7	42.2	1.13
RW25	74.6	61.0	1.22
RW33	79.6	55.2	1.44

$V_{s\text{-}exp}$: the difference in shear capacity with RW0; $V_{s\text{-}\varepsilon}$: shear resistance carried by stirrups calculated from strain

than other spots, slightly before the critical diagonal cracks crossed. No other necessary relations could be obtained between the cracks and the yielding of stirrups. Stirrups also yielded at some other spots due to the opening of minor cracks.

On the other hand, two perspectives to evaluate the contribution of stirrups were tabulated in **Table 2**. $V_{s\text{-}exp}$ shows the difference of shear capacity between each specimen with RW0, which is the evaluation of contribution of stirrups directly on the function. $V_{s\text{-}\varepsilon}$ is the experimental result of the stress in stirrups calculated from the strain. In order to confirm the selection of stirrups and strain gauges for calculation, a brief modeling of critical diagonal cracks was conducted in **Fig. 3**. Critical diagonal cracks were modelled as green straight dashed lines by connecting where the critical diagonal crack crossed the tensile reinforcement, compressive reinforcement, and turnings in directions. The closest strain gauges on stirrups crossed by the modelled lines were used for calculation. Comparing these two results, it can be seen that the difference became larger as the stirrup ratio increased. It can also be noticed that, the critical diagonal crack in RW33 crossed less stirrups than RW25 despite of its largest stirrup ratio. These indicated that, the contribution of stirrups was actually overestimated, thus the contribution of concrete was underestimated. The extent increased as the stirrup ratio increased.

4. CONCLUSIONS

Investigation on the effect of stirrups on RC tapered slender beams was conducted in this study and the following conclusions were drawn:

1) As the stirrup ratio increased, the shear capacity increased and the decrement in stiffness became lesser.

2) The critical diagonal cracks became flatter as the stirrup ratio became larger, implying the difference in the formation of compressive strut after the occurrence of the critical diagonal crack.

3) The results of stirrupsô contribution calculated from the shear capacity were all larger than that from the strain in the stirrups. The difference became larger with the increase in the stirrup ratio.

ACKNOWLEDGEMENTS

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