BEHAVIOR OF DIAGONAL COMPRESSION FAILURE WITH DIFFERENT STIRRUP RATIO IN HIGH-STRENGTH CONCRETE BEAMS

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1. INTRODUCTION

With the availability of high-strength concrete and high-strength steel bar in these days, designers are able to derive advantages of the increase in span length of bridges and the reduction of the cross section of beams, allowing the use of I-section beams. Though diagonal compression failure may rarely occur in typical RC beams, there are still cases when such failure can occur in I-beams with a very thin web and dense shear reinforcements. However, there is insufficient research in the mechanism of diagonal compression failure, especially in beams with stirrup ratio (r_w) lower than 2%. In addition, the current JSCE standard specification[1)] for diagonal compressive capacity has been quite conservative and no longer appropriate for the application to high-strength reinforced concrete. Therefore, an investigation of the diagonal compressive capacity of the high-strength RC beams is needed. This study focused on the effect of stirrup ratio to the diagonal compressive capacity.

2. EXPERIMENTAL PROGRAM

(1) Specimen details

The summary of test variables and details of specimens are provided in **Figure 1** and **Table 1**. Three beams were tested by conducting a three-point bending test in a 2000kN capacity hydraulic testing machine. Yielding of longitudinal and shear reinforcements was prevented by using high-strength bars (f_y> 953 N/mm^2). In order to avoid the local failure, the web width was increased to the bottom flange width at the support. The experimental parameter was the ratio of stirrup with the same diameter of stirrups (10mm). The other three beams tested by Kobayashi[2)] are also presented to determine the influence of stirrup ratio. In order to exclude dependence of other parameters, each beam was designed to have same the shear span of 660 mm, *a/d* of 3, total length of 1800 mm and total height of 260 mm.

(2) Instrumentation and test procedures

In all specimens, applied load, displacements and the strains of concrete, longitudinal and shear reinforcements were measured. For tensile bars and stirrups, the strains were measured at mid span and at *d*/2 from top fiber in 6, 8 or 10 locations, consequently. Also, the flexural crack width was measured by using a 150 mm gage length π-gage attached at the bottom of each beam.

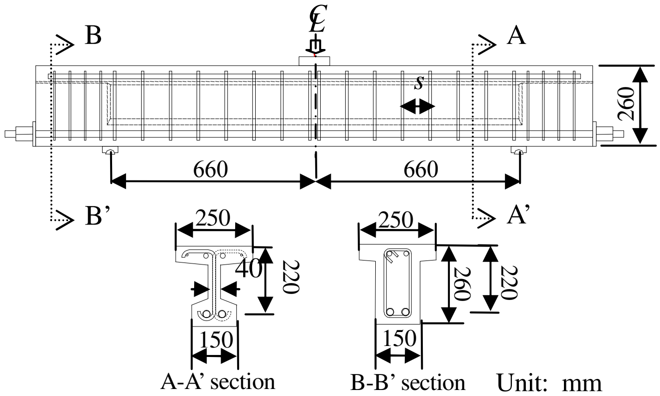

Figure 1 Dimensions and steel layout of beam specimens

Table 1 Details of test beams

Specimen	f'_c [N/mm^2]	b_w [mm]	d [mm]	p_w *1 [%]	r_w *2 [%]	ϕ *3 [mm]	s *4 [mm]
UH1.2	100	40	220	8.8	1.2	10	150
UH1.5					1.5		120
UH1.8					1.8		100
UH2[2)]					2.0		90
UH3[2)]					3.0		60
UH4[2)]					4.0		45

*1 longitudinal reinforcement ratio, *2 stirrup ratio, *3 nominal diameter of stirrup, *4 spacing of stirrup

Table 2 Summary of experimental results

Specimen	f'_c [N/mm^2]	f_t [N/mm^2]	V_{exp} *1 [kN]	v_{exp} *2 $/f'^{1/2}_c$	V_{yd} *3 [kN]	v_{yd} *4 $/f'^{1/2}_c$
UH1.2	105	4.54	102.7	1.14	116.5	1.32
UH1.5	101	3.65	108.0	1.22	138.1	1.57
UH1.8	107	3.57	134.3	1.47	161.0	1.83
UH2[2)]	102	6.57	137.0	1.54	174.1	1.98
UH3[2)]	98.2	6.49	144.9	1.66	246.2	2.80
UH4[2)]	99.1	6.91	167.6	1.91	318.3	3.62

*1 the capacity from experimental result, *2 shear stress from experiment (= $V_{exp}/b_w d$), *3 design shear capacity for diagonal tension failure[1)], *4 shear stress for diagonal tension failure (= $V_{yd}/b_w d$)

Keywords: diagonal compression failure, high-strength concrete, diagonal compressive capacity
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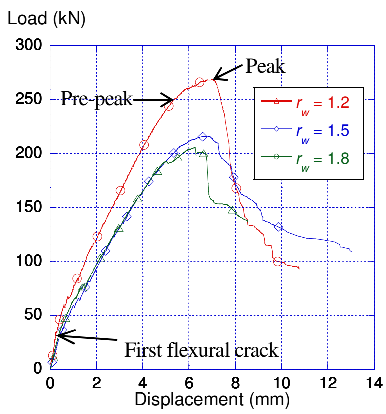

Figure 2 Load-displacement curve

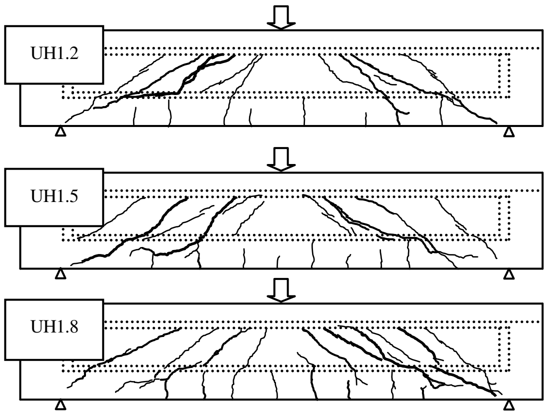

Figure 3 Crack patterns at peak load

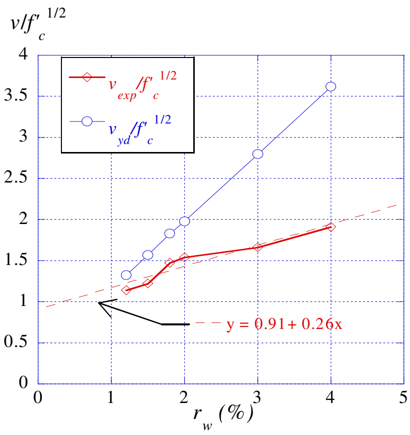

Figure 4 effect of r_w to $v/f'_c{}^{1/2}$

3. EXPERIMENT RESULTS

(1) Load-displacement relationship and crack patterns

Load-displacement relationship is illustrated in **Figure 2**. All of three specimen show similar behavior, except for the peak load. It can be divided into four stages by three dividing points, i.e. first flexural crack point, pre-peak point and peak point. Examples of the points of UH1.8 are demonstrated. Firstly, specimens behaved in elastic manner until the first flexural crack occurred in the bottom flange near mid-span, which was reflected in the graph as a rate of inclination decreased. In the second stage, diagonal cracks appeared in a sequence from mid-span to support. As the increase in the applied load, the load-displacement curve remained to advance linearly with a drop in applied load when each diagonal crack occurred at mid-depth of the web and propagated to the whole web. Third stage began after the pre-peak point; the displacement increased with a relatively small increase in applied load. A more inclined crack appeared in the direction from the support to the loading point and concrete at the web began to crush. **Figure 3** shows crack patterns at the peak load. Data from the strain gage attached in stirrups reveals no yielding strain in all stirrups. The forth stage started after the peak load. The applied load suddenly decreased with a slightly increase in displacement. In this region, cracks in the line between the support and the loading point became wider. Also, cracks propagated at the top flange.

(2) Dependence of stirrup ratio to diagonal compressive capacity

The experimental results are summarized in **Table 2**. The dependence of f'_c to diagonal compressive capacity is considered by $f'_c{}^{1/2}$ in predicting equations of JSCE[1]. The application of $v/f'_c{}^{1/2}$ in order to neglect the effect of f'_c in the case of using concrete of f'_c greater than 100 N/mm^2 has been confirmed[2]. The relationships between r_w and $v/f'_c{}^{1/2}$ are demonstrated in **Figure 4**. To predict the criteria between these two failure modes, the design shear capacity for the diagonal tension failure ($V_{yd} = V_{cd}+V_{sd}$[1]) to $f'_c{}^{1/2}$ is plotted in the figure. With the decrease in r_w, the diagonal compressive capacity decreases and the amount of wide diagonal cracks at the peak load also decreases (from **Figure 3**). The cause seemed to be that the diagonal stress concentrated in more specific parts, resulting in the reduction of the diagonal compressive capacity. Furthermore, it can be seen that a linear relationship agrees well with the test results. From this relationship, it implies that when r_w is reduced to approximately 1% by expanding stirrup spacing, the failure mode may change to the diagonal tension failure.

4. CONCLUSIONS

(1) By considering the crushing of concrete at the web combined with crack patterns and no yielding of stirrups, it indicated that all specimens failed in the diagonal compression failure.

(2) The experimental results reveal that with the decrease in the stirrup ratio, diagonal compressive capacity gradually decreased with a linear relationship and diagonal cracks were widely distributed.

REFERENCES

1) Japan Society of Civil Engineers (JSCE): *Standard Specification for Concrete Structures [Design Performance]*, 2007

2) Kobayashi, C., Watanabe, K. and Niwa, J.: "Experimental Study on Diagonal Compression Failure of RC Beams Using High-Strength Concrete", *Proceedings of 8th International Symposium on Utilization of High-Strength and High-Performance Concrete*, Vol. 2, pp.1031-1036, 2008