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DUCTILITY EVALUATION METHOD IN COLUMN WITH WING WALLS

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Abstract

In reinforced concrete construction, a column with wing walls is a structural member that improves the stiffness and horizontal load capacity of the column. After the maximum strength has been reached, however, the strength drops sharply if the wing walls had severe damage due to compressive failure at wall edge, which results in poor ductility. Therefore, it is important to improve ductility by securing confined areas on the edges of the walls, as well as accurately evaluating the ductility.

At present, in the guideline of the Architectural Institute of Japan, the method to estimate the ultimate deformation angle of a column with wing walls considers only whether wall edge confinement exists or not; the number of confining bars in the wall edges is not quantitatively considered. It has been confirmed that, thus, the ductility of a column with wing walls with an insufficient confinement bars is overestimated. For that reason, we proposed a ductility evaluation method that considers conditions such as the length of the confined area and the intervals between the confinement bars in accordance with ACI (American Concrete Institute) standards, in order to quantitatively consider the number of confinement bars in the wall edges in the method to estimate the ultimate deformation angle of a column with wing walls. However, the number of test specimens evaluated by this method was limited, so we did not conduct sufficient accuracy verification.

In this study, therefore, we examined the accuracy of the method using 24 specimens of columns with wing walls that had been implemented in the past structural experimental test. The result shows that it underestimates the ductility of the specimens with a small confinement area. Accordingly, we propose a ductility evaluation method in which the number of confinement bars is appropriately considered by improving confinement condition items in the ACI standards, and discuss the validity of the method.

Keywords: Column with wing walls, Deformability, Ultimate deformation angle, Edge confinement, Reinforcement anchorage

1. Introduction

In reinforced concrete structures, columns with wing walls can be used as structural members as they have high stiffness and strength. However their strength drops rapidly after reaching the maximum strength, namely their ductility is low, it is extremely important to improve the ductility by ensuring that there are confined areas on the edges of the walls. Additionally, the ductility must be accurately evaluated. However, the conventional method for estimating the ultimate deformation angle of column members with wing walls [1] only considers whether edge wall confinement exists or not. The amount of bar confinement at the wall edges is not quantitatively taken into account. Reference [3] showed that ductility is overestimated in column specimens with wing walls containing an inadequate amount of bar confinement.

To quantitatively include the effect of the amount of bar confinement in the wall edges for calculation of the ultimate deformation angle of column members with wing walls [1], a study [3] proposed a ductility evaluation method. In this method, the amount of bar confinement in the wall edges is quantitatively assessed by applying the conditions satisfied by edge wall confinement in [2]. However, this method of estimating the ultimate deformation angle has only been applied to two test specimens of columns with wing walls [3]; hence, adequate accuracy verification has not been conducted.

In this study, the accuracy of a method for estimating ultimate deformation angles [3] was verified by applying it to test specimens of columns with wing walls that have previously been used in bending yield experiments [3-14]. Simultaneously, through investigation of the confinement conditions that enable appropriate evaluation of edge wall confinement effects in columns with wing walls, we propose a method to estimate the ultimate deformation angle, where the ductility of columns with wing walls can be calculated accurately to give estimates that are on the safe side.

2. Test specimens

2.1 Test specimens specifications

The specifications of the test specimens are shown in Table 1. Twenty-four test specimens from studies [3-14] were used, including columns with double-bar wing walls and edge confinement. The mechanical properties and loading schedules of the test specimens are available in the original references.

2.2 Evaluation of the damage resistance of members

The maximum strength under positive load, the deformation angle at the maximum strength, and the ultimate deformation angle of the test specimens are shown in Table 2. As shown in Fig.1, the deformation angle, according to the envelope, when the strength has deteriorated to 80% of its maximum is defined as the ultimate deformation angle. The experimental ultimate deformation angle of test specimens CWJ and CWA (from [12-14]) is denoted as > 4% in Table 2. This is because the experiments conducted in those studies stopped loading when the deformation angle reached 4%. The strength did not decrease to 80% of the maximum in specimens CWJ and CWA; hence, the ultimate deformation angle was not observed.

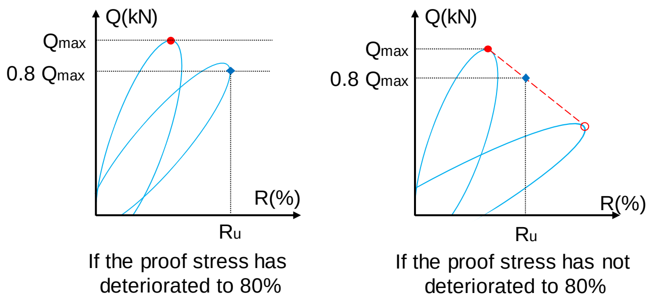

Fig.1－How to determine the Ultimate deformation angle

3. Evaluation of the ultimate deformation angle

3.1 Existing method of evaluating the ultimate deformation angle

The ultimate deformation angle was calculated based on [1] and its accuracy was verified for the specimen columns with wing walls given in Table 1. The method is shown in Eq. (1), the calculation results are shown in Table 3, and the accuracy distribution and standard deviation of the calculated ultimate deformation angles (R_u) are displayed in Fig.2.

$$R_u = c \times 2t_w \times \varepsilon_{cu}/x_n \tag{1}$$

Here, R_u is the ultimate deformation angle (rad), $c = 6$ is an experimentally determined coefficient, t_w is the wall thickness (mm), ε_{cu} is the strain of concrete at the compression edge (0.006 and 0.003 with and without edge confinement, respectively), and x_n is the neutral axis position (mm). According to Table 3, the accuracy values obtained for test specimens CW3-DC, CWJ2, and CWJ2A, which have edge confinement ≤ 1.0, indicate that the ultimate deformation angles are overestimated. The reasons for the overestimation of the

Table 1－Specifications of the test specimens

	Reference [3]		Reference [4]			Reference [5-7]					Reference [8]		
Specimen	CW3-D	CW3-DC	SW	SWB	SWW	SW1	SW2	SW3	SW4	SW5	RC-42/63-N	RC-95/127-N	RC-95/127-□C
Clear hight(mm)	1700		1400			1400					750		
Inflection point hifht(mm)	2400		1400			2400	1800	2400	1800	2400	900		
Axial force ratio	0.1		0.2			800 (kN)					360 (kN)		
Column section；b×D(mm)	450×450		400×400			400×400		300×400			400×400		
Column main bars	16-D19		16-D16			12-D16		10-D16			12-D13		
Column hoop bars	4-D10@60		2-D6@50	4-D6@50	2-D6@50	2-D6@40					2-D6@50	2-D10@50	
Wing wall thickness(mm)	150		100			100		150			100		
Length of wing wall(mm)	450		400			400					300		
Vertical bars of wing wall	4-D6@125		4-D6@200	4-D6@100	4-D6@200	D6@150		D6@100			4-D6@90		
Vertical bars of wing wall edge	3-D10@40		4-D10@40			4-D13		6-D13@50			4-D10@50		
horizon rebar of wall	D6@125		D6@200	D6@100	D6@200	D6@150		D6@100			D6@50		
Confinement bars of wing wall edge	—	4-D6@125	—	2-D4@50	—	—		—		2-D6@40	—		2-D6@50
Concrete strength (N/mm²)	30.0	33.8	24.8	26.7	26.8	26.9	27.5	26.1	28.3	28.5	31.5	29.6	30.4

	Reference [9-11]							Reference [12-14]			
Specimen	L15A04	S15A04	S30A04	S15B04	S30B04	S15A04S	S30A05	CWJ	CWA	CWJ2	CWJ2A
Clear hight(mm)	1800	900						1600			
Inflection point hifht(mm)	2100	1050						2500			
Axial force ratio	0.15	0.15	0.3	0.15	0.3	0.15	0.3	162 (kN)			
Column section；b×D(mm)	600×600	300×300						250×250			
Column main bars	4-D25+8-D19	4-D13+8-D10						10-D16			
Column hoop bars	4-D13@100	4-D6@50						D6@50			
Wing wall thickness(mm)	240	120					150	125			
Length of wing wall(mm)	600	300					300	250			
Vertical bars of wing wall	2-D13@150	2-D6@75						D6@100	D10@100	D6@100	
Vertical bars of wing wall edge	4-D19	4-D10						—			
horizon rebar of wall	D13@100	D6@50						D6@100			
Confinement bars of wing wall edge	4-D13@100	4-D6@50		2-D6@50		4-D6@50		2-D10@50	3-D10@50	2-D10@50	
Concrete strength (N/mm²)	30.8	29.9	28.2	25.2	27.5	27.5	28.5	47.8	48.1	52.8	48.1

Table 2－ The maximum strength, the deformation angle at the maximum strength, and the ultimate deformation angle of the test specimens

	Reference [3]		Reference [4]			Reference [5-7]					Reference [8]		
Specimen	CW3-D	CW3-DC	SW	SWB	SWW	SW1	SW2	SW3	SW4	SW5	RC-42/63-N	RC-95/127-N	RC-95/127-□C
Maximum strength(kN)	476.1	504.0	459.0	464.0	487.5	293.0	421.0	409.0	535.0	427.0	390.0	388.0	400.0
Deformation angle at the maximum strength(%)	0.68	0.80	0.83	1.00	0.86	0.52	0.73	0.98	0.98	1.88	1.00	0.95	0.98
Ultimate deformation angle(%)	0.99	1.30	1.00	1.50	1.00	0.86	0.96	1.88	1.88	3.84	1.45	1.65	2.60

	Reference [9-11]							Reference [12-14]			
Specimen	L15A04	S15A04	S30A04	S15B04	S30B04	S15A04S	S30A05	CWJ	CWA	CWJ2	CWJ2A
Maximum strength(kN)	3211.0	417.0	475.0	399.0	482.0	390.0	533.0	187.6	186.2	170.2	197.2
Deformation angle at the maximum strength(%)	0.75	1.49	1.46	2.95	1.44	1.49	2.98	4.00	4.00	0.95	0.85
Ultimate deformation angle(%)	3.00	3.01	3.15	3.81	3.01	3.15	3.71	Over 4%	Over 4%	4.00	2.66

Table 3－ Calculation results of Eq. (1)

	Reference [3]		Reference [4]			Reference [5-7]					Reference [8]		
Specimen	CW3-D	CW3-DC	SW	SWB	SWW	SW1	SW2	SW3	SW4	SW5	RC-42/63-N	RC-95/127-N	RC-95/127-□C
Experimental ultimate deformation angle (%)	0.99	1.30	1.00	1.50	1.00	0.86	0.96	1.88	1.88	3.84	1.45	1.65	2.60
Calculated ultimate deformation angles ; Ru (%)	1.10	2.23	0.71	1.42	0.71	0.73	0.73	1.25	1.30	2.61	1.14	1.11	2.24
accuracy	0.90	0.58	1.42	1.06	1.41	1.18	1.32	1.50	1.44	1.47	1.28	1.48	1.16

	Reference [9-11]							Reference [12-14]			
Specimen	L15A04	S15A04	S30A04	S15B04	S30B04	S15A04S	S30A05	CWJ	CWA	CWJ2	CWJ2A
Experimental ultimate deformation angle (%)	3.00	3.01	3.15	3.81	3.01	3.15	3.71	Over 4%	Over 4%	4.00	2.66
Calculated ultimate deformation angles ; Ru (%)	2.81	2.77	2.32	2.68	2.33	2.77	2.85	4.31	4.57	4.52	4.04
accuracy	1.07	1.09	1.36	1.42	1.29	1.14	1.30	—	—	0.88	0.66

ultimate deformation angle, which causes them to be evaluated as on the danger side, are followings : 1) determination of the strain term ε_{cu} in Eq. (1) is based solely on the existence or nonexistence of edge confinement (0.006 and 0.003 with and without edge confinement, respectively) and 2) the strains ε_{cu} in test specimens CW3-DC, CWJ2, and CWJ2A, which had insufficient amounts of bar confinement at their wall edges, are overestimated.

3.2 Evaluation of ultimate deformation angle under American Concrete Institute (ACI) standard confinement conditions

The amount of bar confinement at the wall edges is not quantitatively considered in the ultimate deformation angle equation from Ref. [1] (Eq. (1) in Section 3.1). Therefore, based on [3], the amount of bar confinement in the walls is evaluated through a modification of the edge confinement conditions provided in the shear wall provisions of the ACI standards [2], which is used as the confinement conditions in Eq. (1). The confinement conditions in Ref. [2] are shown below.

・Confinement conditions in the ACI standards [2]:

(a) Length of confined area. The following two conditions are satisfied:

1) $x_n \ - 0.1 l_w$ or more

2) $x_n/2$ or more

(b) Intervals between confining bars. The following three conditions are satisfied:

1) $t_w/3$ or less

2) $6d_b$ or less

3) $101.6 + (355.6 - b_x)/3$ (mm) or less

(c) Ratios regarding confining bars. The following two conditions are satisfied:

1) $A_{sh1}/sb_{c1}, A_{sh2}/sb_{c2} \ \geq 0.3\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c}{f_{yt}}$

2) $A_{sh1}/sb_{c1}, A_{sh2}/sb_{c2} \ \geq 0.09\frac{f_c}{f_{yt}}$

Here, x_n is the neutral axis position (mm), l_w is the length of the entire column with wing walls (mm), t_w is the wall thickness (mm), d_b is the diameter of the bars at the wall edge (mm), b_x is the maximum distance between the cores of the vertical bars connecting the confining bars and tie bars (mm), A_{sh1} is the total cross-sectional area of the confining bars and tie bars in the in-plane direction (mm^2), A_{sh2} is the total cross-sectional area of the confining bars and tie bars in the out-of-plane direction (mm^2), s is the interval between the confining bars (mm), b_{c1} is the length of the confined area in the in-plane direction (mm), b_{c2} is the length of the confined area in the out-of-plane direction (mm), A_g is the area of the confined area including the covering depth ($l_{be} \times t_w$; mm^2), l_{be} is the distance from the compression edge to the confined area (mm), A_{ch} is the area of the confined area ($b_{c1} \times b_{c2}$; mm^2), f_c is the designed strength of the concrete (N/mm^2), and f_{yt} is the specified strength of the bars on the wall edge (N/mm^2).

The rationale behind the confinement conditions is as follows. Condition (c), regarding the ratios of confining bars, prevents the concrete strain at the compression edge from not reaching 0.006. This is the assumption under confinement when the ratios of bar confinement are small and the confinement is weak. Condition (a), regarding the length of the confined area, prevents buckling of the vertical bars of the wall outside the confined area when the confined area is small, which could happen even when condition (c) is satisfied in the confined area. Condition (b), regarding the intervals between confining bars, prevents local buckling between confining bars. This is possible when the interval between confining bars is large; even though conditions (a) and (c) are satisfied, the vertical bars of the wall located between confining bars that are effectively not confined become vulnerable points.

Table 4－Results of applying confinement conditions in the ACI standards to specimens specimens

			Reference [3]			Reference [4]			Reference [5-6]			Reference [8]			Reference [9-11]		
Specimen			CW3-DC			SWB			SW5			RC-95/127-□C			L15A04		
			demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Length of confined area(mm)	①		348.4	330	ka= 0.95	387.3	100	ka= 0.26	293.6	225	ka= 0.77	230.8	51	ka= 0.22	434.8	470	ka= 1.08
	②		241.7			253.7			206.8			160.4			307.4		
Intervals between confining bars (mm)	①		75.0	125	kb= 0.48	66.7	50	kb= 1.2	66.7	50	kb= 1.2	50.0	50	kb= 1.0	100.0	100	kb= 1.0
	②		60.0			60.0			60.0			60.0			114.0		
	③		176.7			151.7			185.0			188.3			168.3		
Ratios regarding confining bars	in-plane direction	①	0.021	0.006	kc= 0.26	0.023	0.008	kc= 0.36	0.016	0.013	kc= 0.78	0.046	0.025	kc= 0.55	0.018	0.007	kc= 0.38
		②	0.008			0.007			0.007			0.008			0.007		
	out-of-plane direction	①	0.021	0.005	kc= 0.22	0.023	0.005	kc= 0.21	0.016	0.008	kc= 0.52	0.046	0.017	kc= 0.38	0.018	0.004	kc= 0.24
		②	0.008			0.007			0.007			0.008			0.007		
Reduction coefficient ;k1			0.00			0.21			0.52			0.22			0.24		

			Reference [9-11]														
Specimen			S15A04			S30A04			S15B04			S30B04			S15A04S		
			demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Length of confined area	①		222.4	235	ka= 1.06	282.3	235	ka= 0.83	232.4	79	ka= 0.34	281.3	79	ka= 0.28	222.4	235	ka= 1.06
	②		156.2			186.1			161.2			185.7			156.2		
Intervals between confining bars (mm)	①		50.0	50	kb= 1.0	50.0	50	kb= 1.0	50.0	50	kb= 1.0	50.0	50	kb= 1.0	50.0	50	kb= 1.0
	②		60.0			60.0			60.0			60.0			60.0		
	③		193.3			193.3			193.3			193.3			193.3		
Ratios regarding confining bars	in-plane direction	①	0.018	0.017	kc= 0.96	0.018	0.017	kc= 0.94	0.023	0.017	kc= 0.74	0.023	0.017	kc= 0.74	0.018	0.017	kc= 0.94
		②	0.007			0.007			0.007			0.007			0.007		
	out-of-plane direction	①	0.018	0.011	kc= 0.61	0.018	0.011	kc= 0.61	0.023	0.013	kc= 0.56	0.023	0.013	kc= 0.56	0.018	0.011	kc= 0.61
		②	0.007			0.007			0.007			0.007			0.007		
Reduction coefficient ;k1			0.61			0.61			0.34			0.28			0.61		

			Reference [9-11]			Reference [12-14]											
Specimen			S30A05			CWJ			CWA			CWJ2			CWJ2A		
			demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Length of confined area	①		254.8	269	ka= 1.06	134.8	130	ka= 0.96	122.0	210	ka= 0.72	129.4	130	ka= 1.0	148.4	130	ka= 0.88
	②		172.4			104.9			98.5			102.2			111.7		
Intervals between confining bars (mm)	①		50.0	50	kb= 1.0	41.7	50	kb= 0.72	41.7	50	kb= 0.83	41.7	100	kb= 0.36	41.7	100	kb= 0.36
	②		60.0			36.0			60.0			36.0			36.0		
	③		193.3			185.0			185.0			185.0			185.0		
Ratios regarding confining bars	in-plane direction	①	0.013	0.012	kc= 0.92	0.022	0.034	kc= 1.54	0.019	0.034	kc= 1.76	0.022	0.007	kc= 0.34	0.022	0.007	kc= 0.34
		②	0.007			0.009			0.009			0.009			0.009		
	out-of-plane direction	①	0.013	0.009	kc= 0.73	0.022	0.022	kc= 1.01	0.019	0.020	kc= 1.07	0.022	0.005	kc= 0.22	0.022	0.005	kc= 0.22
		②	0.007			0.009			0.009			0.009			0.009		
Reduction coefficient ;k1			0.73			0.72			0.72			0.00			0.00		

In Ref. [2], the condition "six times or less than the diameter of bars on wall edges", which is part of condition (b) (regarding the intervals between confining bars), was originally "six times or less than the minimum diameter of vertical bars". However, based on Ref. [3], we changed the latter condition back to the former, as we presumed that the buckling of the bars on the wall edges has a large impact on the ductility of columns with wing walls.

Using confinement conditions (a) to (c), the coefficients representing how well each quantity meets the respective conditions according to Ref. [3] (coefficients drop below 1.0 if the condition is not satisfied, and the coefficient is smaller if less satisfactory) are defined as k_a, k_b, and k_c, respectively. Assuming that the most unsatisfactory condition determines the ductility, $k_1 = \min(k_a, k_b, k_c)$ is defined according to the aforementioned rationale for setting the conditions. The ultimate deformation angle R_{u1} is calculated by reducing the strain ε_{cu} as shown below. Equation (2) shows how R_{u1} is calculated. Here, k_a and k_c are the actual values divided by the maximum value in the condition, because the confinement effect increases as the actual values increases with respect to the demand value. On the other hand, k_b is the minimum value in the condition divided by the actual value, because the confinement effect decreases as the actual values increases with respect to the demand value. However, when the interval between confining bars (condition (b)) becomes too large, there would be no confinement effect because of local buckling. Therefore, based on Ref. [3], $k_b = 0$ when $k_b \leqq 0.5$ was set, considering that the confinement effect would not be exerted when the actual values is more than double that of the demand value. In addition, the maximum value of k_1 was set to 1.0 because although a sufficient confinement effect is expected, the more than doubling in ductility from that attained without confinement when $k_1 \geqq 1.0$ has not been confirmed experimentally. $k_1 = 1.0$ is equivalent to the case of edge confinement in Eq. (1).

$$R_{u1} = c \times 2t_w \times \varepsilon_{cu1}/x_n \quad (2)$$

Here, R_{u1} is the ultimate deformation angle calculated using the reduction coefficient k_1, $c = 6$ is an experimentally determined coefficient, t_w is the wall thickness (mm), ε_{cu1} is the strain of concrete on the compression edge (0.003 without edge confinement and $0.003 \times (1 + k_1)$ with confinement), k_1 is the reduction coefficient of the strain ε_{cu} defined by $\min(k_a, k_b, k_c, 1)$, k_a is the proportionality coefficient for the confinement length, k_b is the proportionality coefficient for the confining bar interval and is zero when originally $k_b \leqq 0.5$, k_c is the proportionality coefficient for the confining bar ratio, and x_n is the neutral axis position (mm).

Table 4 shows the results obtained by applying the confinement conditions in the ACI standards to tests of the specimens columns with wing walls and edge confinement from Table 1. Table 5 shows the calculated results of ultimate deformation angle R_{u1} for all specimens in Table 1, and Fig.3 shows the accuracy distribution and standard deviation of R_{u1}. Based on Table 5 and Fig.3, the ultimate deformation angles for specimens CW3-DC, CWJ2, and CWJ2A, as calculated with Eq. (1), were evaluated to be on the danger side, but the values calculated with Eq. (2) were evaluated to be on the safe side. Table 4 indicates that for the test

Table 5－ Calculation results of Eq. (2)

	Reference [3]		Reference [4]			Reference [5-7]					Reference [8]		
Specimen	CW3-D	CW3-DC	SW	SWB	SWW	SW1	SW2	SW3	SW4	SW5	RC-42/63-N	RC-95/127-N	RC-95/127-□C
Experimental ultimate deformation angle (%)	0.99	1.30	1.00	1.50	1.00	0.86	0.96	1.88	1.88	3.84	1.45	1.65	2.60
Reduction coefficient ;k1	0	0	0	0.21	0	0	0	0	0	0.52	0	0	0.22
Calculated ultimate deformation angles ; Ru (%)	1.10	1.12	0.71	0.86	0.71	0.73	0.73	1.25	1.30	1.98	1.14	1.11	1.37
accuracy	0.90	1.16	1.42	1.75	1.41	1.18	1.32	1.50	1.44	1.94	1.28	1.48	1.90

	Reference [9-11]							Reference [12-14]			
Specimen	L15A04	S15A04	S30A04	S15B04	S30B04	S15A04S	S30A05	CWJ	CWA	CWJ2	CWJ2A
Experimental ultimate deformation angle (%)	3.00	3.01	3.15	3.81	3.01	3.15	3.71	Over 4%	Over 4%	4.00	2.66
Reduction coefficient ;k1	0.24	0.61	0.61	0.34	0.28	0.61	0.73	0.72	0.72	0	0
Calculated ultimate deformation angles ; Ru (%)	1.74	2.23	1.87	1.80	1.49	2.23	2.47	3.70	3.93	2.26	2.02
accuracy	1.72	1.35	1.69	2.12	2.02	1.42	1.50	―	―	1.77	1.32

specimens where the reduction coefficient k_1 was determined by either the length of the confined area (condition (a)) or the ratios of confining bars (condition (b)) from the confinement conditions provided in [2], the calculated ultimate deformation angles are substantially lower than the experimental values. Thus, these calculations underestimate the ultimate deformation angle. Possible reasons for the overestimation are: 1) the length of confined area (condition (a)) was set to prevent buckling of the vertical bars in the wall outside of the confined area, 2) buckling of wall edge bars significantly affects the ductility of the columns of wing walls and 3) this condition considers prevention of buckling of vertical bars other than those in the wall edges, which may be excessive. Specimens S15A04 and S15B04, which are found in [9-11], were compared next. Variable k_1 is determined by the length of the confined area in both specimens. Although the length of the confined area of S15B04 was only about 0.36 times that of S15A04, the ultimate deformation angle of S15B04 was approximately 1.27 times greater than that of S15A04. On the other hand, for specimens SWB and RC-95-127-□C from [4] and [8], respectively, the ultimate deformation angle calculated by applying the strain ε_{cu} = 0.006 in Eq. (1) gives high accuracy, even though the length of the confined area is extremely short (k_a = 0.26 and 0.22, respectively) compared to that calculated using condition (a) in [2]. Therefore, sufficient ductility can be attained solely by confinement of the wall edges, because the length of the confined area should not have a significant effect on the ductility. Condition (c), regarding the confining bar ratio, considers the ratio of the core concrete cross-section within the confined area to the wall cross-sectional area (A_{cg}/A_{ch}). Thus, it is necessary to ensure a certain confinement length. However, as adequate ductility is expected simply by confining the wall edges in columns with wing walls, just as with (a), this condition, which takes the size of the confined area into account, would be inappropriate.

The conditions regarding the (a) length of confined area and (c) ratio of confining bars in Eq. (2) are intended for bearing walls, and adequate accuracy cannot be expected for columns with wing walls. Therefore, the confinement conditions were changed to be suitable for columns with wing walls, as follows: condition (a) (length of the confined area) was disregarded because the impact of the confined area length on ductility is insignificant based on the aforementioned reasons; condition (c) (confining bar ratio) was changed to the horizontal bar ratio for columns with wing walls, as defined in [3] based on [1], instead of using the ACI standard. Study [3] states that, when categorizing the type of member in columns with wing walls (as in [1]), category FC can be regarded as FB, and FB as FA, when the confinement is demonstrated to have a horizontal bar ratio of ≥ 0.6% or higher over ≥ two-thirds of the area between the compressed edge and neutral axis position. A more accurate ductility assessment is possible by considering the horizontal bar ratio not only in the in-plane direction but also in the out-of-plane direction. Equations (3) and (4) illustrate the horizontal bar ratio calculation in the in-plane and out-of-plane directions in [3], and Fig.4 shows the details of the symbols

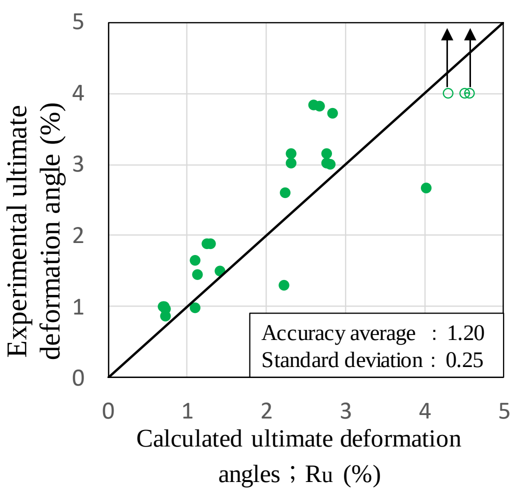

Fig.2－Accuracy distribution and standard deviation of the calculated ultimate deformation angles (R_u)

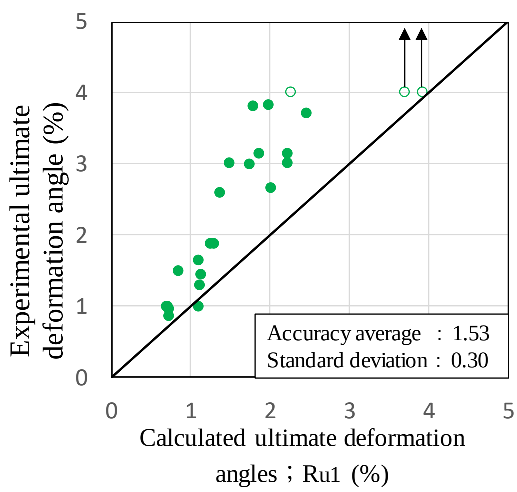

Fig.3－Accuracy distribution and standard deviation of the calculated ultimate deformation angles (R_{u1})

used.

(d) Ratios regarding horizontal bars, where the horizontal bar ratio is more than 0.6% in both the in-plane and out-of-plane directions.

Horizontal bar ratio in the in-plane direction: $p_{sh1} = a_{t1}/st$ (3)

Horizontal bar ratio in the out-of-plane direction: $p_{sh2} = a_{t2}/sL$ (4)

Here, p_{sh1} is the horizontal bar ratio in the in-plane direction, a_{t1} is the total cross-sectional area of horizontal bars in the in-plane direction within the confined area at the edge of wing walls (mm^2), s is the interval between horizontal bars (mm), t is the wall thickness (mm), p_{sh2} is the horizontal bar ratio in the out-of-plane direction within two-thirds of the distance between the compressed edge and neutral axis positions, a_{t2} is the total cross-sectional area of horizontal bars in the out-of-plane direction within the confined area at the edge of the wing walls (mm^2), and L is two-thirds of the length from the compressed edge to the neutral axis position (mm).

The coefficient k_d compares how close the horizontal bar ratios in the in-plane and out-of-plane directions are to 0.6%, according to condition (d) (for horizontal bar ratios) described in [3]. A new reduction coefficient is defined as $k_2 = \min(k_b,\ k_d)$, and the ultimate deformation angle R_{u2} is calculated as shown in Eq. (5).

Table 6—Results of applying confinement conditions (b) and (d) to test specimens

		Reference [3]			Reference [4]			Reference [5-6]			Reference [8]			Reference [9-11]		
Specimen		CW3-DC			SWB			SW5			RC-95/127-□C			L15A04		
		demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Intervals between confining bars (mm)	①	75.0	125	kb=0.48	66.7	50	kb=1.2	66.7	50	kb=1.2	50.0	50	kb=1.0	100.0	100	kb=1.0
	②	60.0			60.0			60.0			60.0			114.0		
	③	176.7			151.7			185.0			188.3			168.3		
horizontal bar ratio (%)	in-plane direction	0.60	0.34	kd=0.57	0.60	0.63	kd=1.05	0.60	0.85	kd=1.42	0.60	1.27	kd=2.12	0.60	2.34	kd=3.90
	out-of-plane direction	0.60	0.39	kd=0.65	0.60	0.75	kd=1.25	0.60	0.80	kd=1.33	0.60	0.89	kd=1.48	0.60	2.10	kd=3.50
Reduction coefficient ;k2		0.00			1.00			1.00			1.00			1.00		

		Reference [9-11]														
Specimen		S15A04			S30A04			S15B04			S30B04			S15A04S		
		demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Intervals between confining bars (mm)	①	50.0	50	kb=1.0	50.0	50	kb=1.0	50.0	50	kb=1.0	50.0	50	kb=1.0	50.0	50	kb=1.0
	②	60.0			60.0			60.0			60.0			60.0		
	③	193.3			193.3			193.3			193.3			193.3		
horizontal bar ratio (%)	in-plane direction	0.60	2.11	kd=3.52	0.60	2.11	kd=3.52	0.60	2.11	kd=3.52	0.60	2.11	kd=3.52	0.60	2.11	kd=3.52
	out-of-plane direction	0.60	0.91	kd=1.52	0.60	1.02	kd=1.70	0.60	0.88	kd=1.47	0.60	0.77	kd=1.28	0.60	1.22	kd=2.03
Reduction coefficient ;k2		1.00			1.00			1.00			1.00			1.00		

		Reference [9-11]			Reference [12-14]											
Specimen		S30A05			CWJ			CWA			CWJ2			CWJ2A		
		demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k	demand value	actual value	k
Intervals between confining bars (mm)	①	50.0	50	kb=1.0	41.7	50	kb=0.72	41.7	50	kb=0.83	41.7	100	kb=0.36	41.7	100	kb=0.36
	②	60.0			36.0			60.0			36.0			36.0		
	③	193.3			185.0			185.0			185.0			185.0		
horizontal bar ratio (%)	in-plane direction	0.60	1.69	kd=2.82	0.60	2.79	kd=4.65	0.60	2.79	kd=4.65	0.60	1.01	kd=1.68	0.60	1.01	kd=1.68
	out-of-plane direction	0.60	1.00	kd=1.67	0.60	2.27	kd=3.78	0.60	2.27	kd=3.78	0.60	0.70	kd=1.17	0.60	0.66	kd=1.10
Reduction coefficient ;k2		1.00			0.72			0.83			0.00			0.00		

$$R_{u2} = c \times 2t_w \times \varepsilon_{cu2}/x_n \quad (5)$$

Here, R_{u2} is the ultimate deformation angle value calculated using the reduction coefficient k_2, $c = 6$ is an experimentally determined coefficient, t_w is the wall thickness (mm), ε_{cu2} is the strain of the concrete at the compression edge (0.003 without edge confinement and $0.003 \times (1 + k_2)$ with edge confinement), k_2 is the reduction coefficient of the strain ε_{cu} defined by $\min(k_b, k_d, 1)$, k_b is the proportionality coefficient that satisfies condition (b) (intervals between confining bars) and $k_b = 0$ when $k_b \leqq 0.5$, k_d is the proportionality coefficient for condition (d) (horizontal bar ratios) described in [3], and x_n is the neutral axis position (mm).

Table 6 shows the results of applying confinement conditions (b) (interval between confinement bars as in the ACI standards) and (d) (horizontal bar ratio provided in [3]), to the edge-confined specimens columns with wing walls in Table 1. Table 7 shows the ultimate deformation angles R_{u2} calculated for the specimens columns with wing walls in Table 1, and Fig.5 shows their accuracy distribution and standard deviation. Table 7 and Fig.5 demonstrate that R_{u2}, as obtained by considering confinement conditions (b) and (d), calculates the ultimate deformation angles of the specimens with edge confinement relatively accurately. The ultimate deformation angles were evaluated to be on the safe side, and the standard deviation was low. However, the ultimate deformation angle was underestimated in specimen CWJ2 from [12-14]. The experimental values of the ultimate deformation angle were ≥ 4.0% for CWJ and CWA; however, 4.0% is at the maximum strength and, thus, there is no decrease in strength and very high ductility. Therefore, the calculated ultimate

Table 7 — Calculation results of Eq. (5)

	Reference [3]		Reference [4]			Reference [5-7]					Reference [8]		
Specimen	CW3-D	CW3-DC	SW	SWB	SWW	SW1	SW2	SW3	SW4	SW5	RC-42/63-N	RC-95/127-N	RC-95/127-□C
Experimental ultimate deformation angle (%)	0.99	1.30	1.00	1.50	1.00	0.86	0.96	1.88	1.88	3.84	1.45	1.65	2.60
Reduction coefficient ;k1	0	0	0	1.0	0	0	0	0	0	1.0	0	0	1.0
Calculated ultimate deformation angles ; Ru (%)	1.10	1.12	0.71	1.42	0.71	0.73	0.73	1.25	1.30	2.61	1.14	1.11	2.24
accuracy	0.90	1.16	1.42	1.06	1.41	1.18	1.32	1.50	1.44	1.47	1.28	1.48	1.16

	Reference [9-11]							Reference [12-14]			
Specimen	L15A04	S15A04	S30A04	S15B04	S30B04	S15A04S	S30A05	CWJ	CWA	CWJ2	CWJ2A
Experimental ultimate deformation angle (%)	3.00	3.01	3.15	3.81	3.01	3.15	3.71	4%以上	4%以上	4.00	2.66
Reduction coefficient ;k1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.72	0.72	0	0
Calculated ultimate deformation angles ; Ru (%)	2.81	2.77	2.32	2.68	2.33	2.77	2.85	3.70	3.93	2.26	2.02
accuracy	1.07	1.09	1.36	1.42	1.29	1.14	1.30	—	—	1.77	1.32

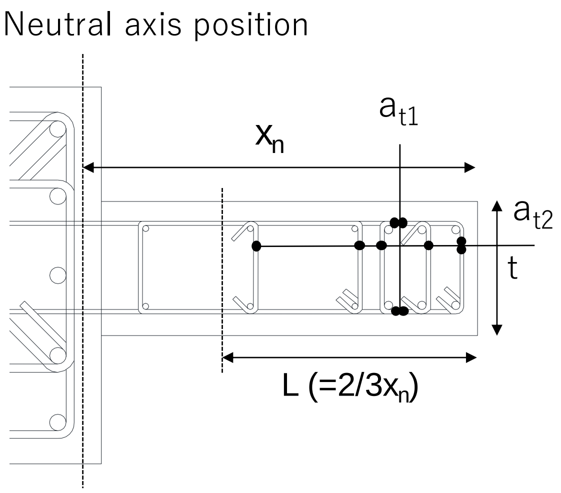

Fig.4 — Details of the symbols

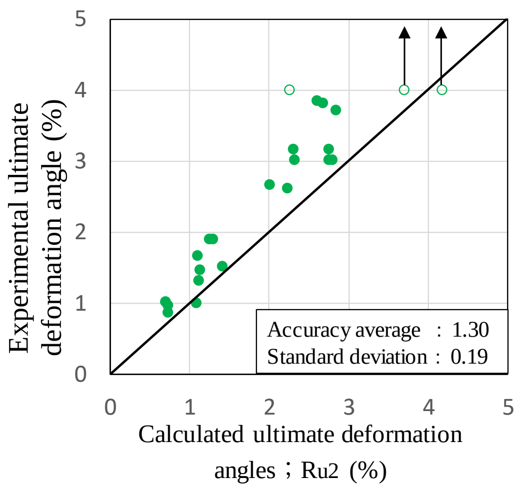

Fig.5 — Accuracy distribution and standard deviation of the calculated ultimate deformation angles (R_{u2})

deformation angle R_{u2} would be an underestimate.

The reason for the underestimation is that specimens CWJ, CWA, and CWJ2 all have vertical bars that are not fixed to the slab. When comparing CWJ2 and CWJ2A in [12-14], where the parameter is whether the vertical bars are fixed or not, the experimentally observed ultimate deformation angle for CWJ2 (in which the vertical bars are not fixed), is about 1.5 times greater than that for CWJ2A (with fixed vertical bar stabilization). According to [14], ductility improves when the vertical bars are not fixed to the slab because yield and buckling of the vertical bars in the wall are suppressed and, as a consequence, crushing of the wall bottom is also suppressed. Therefore, an improvement in ductility when vertical bars are not fixed to the slab must be considered when the abovementioned method is used to calculate the ultimate deformation angle in such specimens.

4. Conclusions

This study proposed a ductility assessment method that considers the amount of bar confinement at the wall edges in column members with wing walls in reinforced concrete structures with a bending yield mode. Ductility assessment was conducted on 24 specimens columns with wing walls from [3-14], including those with edge confinement bars considered in past structural experiments. The main findings of this study are as follows.

(1) The conventional method of ductility assessment for columns with wing walls, according to the standards of the Architectural Institute of Japan, considers whether there are confinement bars at the edge. However, since this method does not quantitatively consider the amount of bar confinement in the edge section, ductility may be overestimated in specimens columns with wing walls containing insufficient amounts of bar confinement at the wall edges, as shown in Table 3 and Fig.2.

(2) To quantitatively consider the amount of bar confinement at the wall edges in conventional ductility assessment, the ultimate deformation angle was calculated by considering the confinement conditions (a) (length of the confined area), (b) (interval between confinement bars), and (c) (confinement bar ratio), which are found in the ACI standards regarding shear walls. However, as bar buckling in wall edges strongly affects the ductility of columns with wing walls, the length of the confined area and confinement bar ratio conditions were found to be excessive. Hence, the ductility of test specimens with adequate edge confinement was underestimated.

(3) To appropriately consider the amount of bar confinement at the wall edges in conventional ductility assessment, the interval between confinement bars (part of the ACI standards) and the horizontal bar ratios in the in-plane and out-of-plane directions (according to the standards of the Architectural Institute of Japan) were applied as confinement conditions. Calculations of the ultimate deformation angle showed that the ductility of specimens columns with wing walls and a bending yield mode can be accurately calculated, and that these calculations are on the safe side.

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