Experimental Study on Shear Resistance of Steel Beams and SC Column Joints Constructed by Simplified Method

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SUMMARY:
In this research, experimental study was carried out on shear resistance of beam-column joints of the new structure. The new structure was concrete encased steel (SC) structure that it removed the reinforcing bar from the SRC structure and used the welding wire mesh. The specimens were beam-column joints consisting of SC columns and steel beams. The column and beam-column joint used the welding wire mesh so that the cover concrete might not delaminate and the simplification of column main bar and shear reinforcement. Following considerations were obtained from the experimental results. There was no effect of the steel cross-sectional shape of column in ultimate shear strength of the beam-column joints, and they could be evaluated by the SRC standard equation of AIJ (Architectural Institute of Japan). However, there was a difference in the deformability of the beam-column joint.

Keywords: concrete encased steel structure, beam-column joints, ultimate shear strength, yield mode of steel

1. INTRODUCTION

Recently, construction number of Steel and Reinforced Concrete (SRC) Structures declines in Japan. Because, the structure design method of SRC is complicated and the processes of execution works are abounding for its construction. However, SRC structures are more excellent for ductility capacity than the RC structures, and the damages of the SRC structures ware slight in Hyogo-ken Nanbu Earthquake. Authors carried out the experimental studies in order to develop the new structure system using steel and concrete with execution method that is easier than the SRC structures and with earthquake resistant performance that is equivalent to the SRC structures, and the new structure which replaced the SRC structures was proposed. The new structure was concrete encased steel (SC) structure that it removed the reinforcing bar from the SRC structure and used the welding wire mesh. However, there was the unexpected destruction in the beam-column joint strongly designed further than the column.

Then, in this research, experimental study was carried out on shear resistance of beam-column joints of the new structure. The specimens were beam-column joints consisting of SC columns and steel beams. The column and beam-column joint used the welding wire mesh so that the cover concrete might not delaminate and the simplification of column main bar and shear reinforcement.

2. OUTLINE OF THE EXPERIMENT

2.1. Test Specimens and Materials Used

A total of four specimens ware tested. The dimensions and details of the specimens are shown **Figure 2.1.** and **Table 2.1.**.The specimen configuration represented beams and column segments between inflection points in a frame subjected to lateral loading. The contraction scale of the test specimens was about 1/2 of an SRC structure on the assumption of beam-column joints of a middle floor in a multi-storey multi-span. To make sure that the beam-column joint shear failure occurs prior to any other failure; the beam-column joint shear strength was designed smaller than the flexural and the shear strengths of the beam and column. However, only specimen SC/S-9j-W-27 became the column failure, when it was calculated at the real strength of the used material. Experimental variables were column cross-sectional shape and yield mode of the column steel. All specimens had columns with 1,600mm height and 300mm square section, and beams with 2,900mm length and wide flange shapes. All specimens contained wide flange shapes steel for the column and there is no column main reinforcement bars and shear reinforcement. Instead, the welding wire mesh was arranged in order to might not delaminate of the cover concrete. Though the cross section of the column steel was almost same for specimen SC/S-4j-W-27 and specimen SC/S-5j-W-27, the steel flange width was different. Specimen SC/S-8j-W-27 and specimen SC/S-9j-W-27 were also same. The differences between specimen SC/S-4j-W-27 and specimen SC/S-8j-W-27 and between specimen SC/S-5j-W-27 and specimen SC/S-9j-W-27 were the steel flange thickness of the column and steel web thickness of the beam-column joint. The failure mode of column steel was shear failure except specimen SC/S-8j-W-27. The failure mode of column steel was flexure for specimen SC/S-8j-W-27.

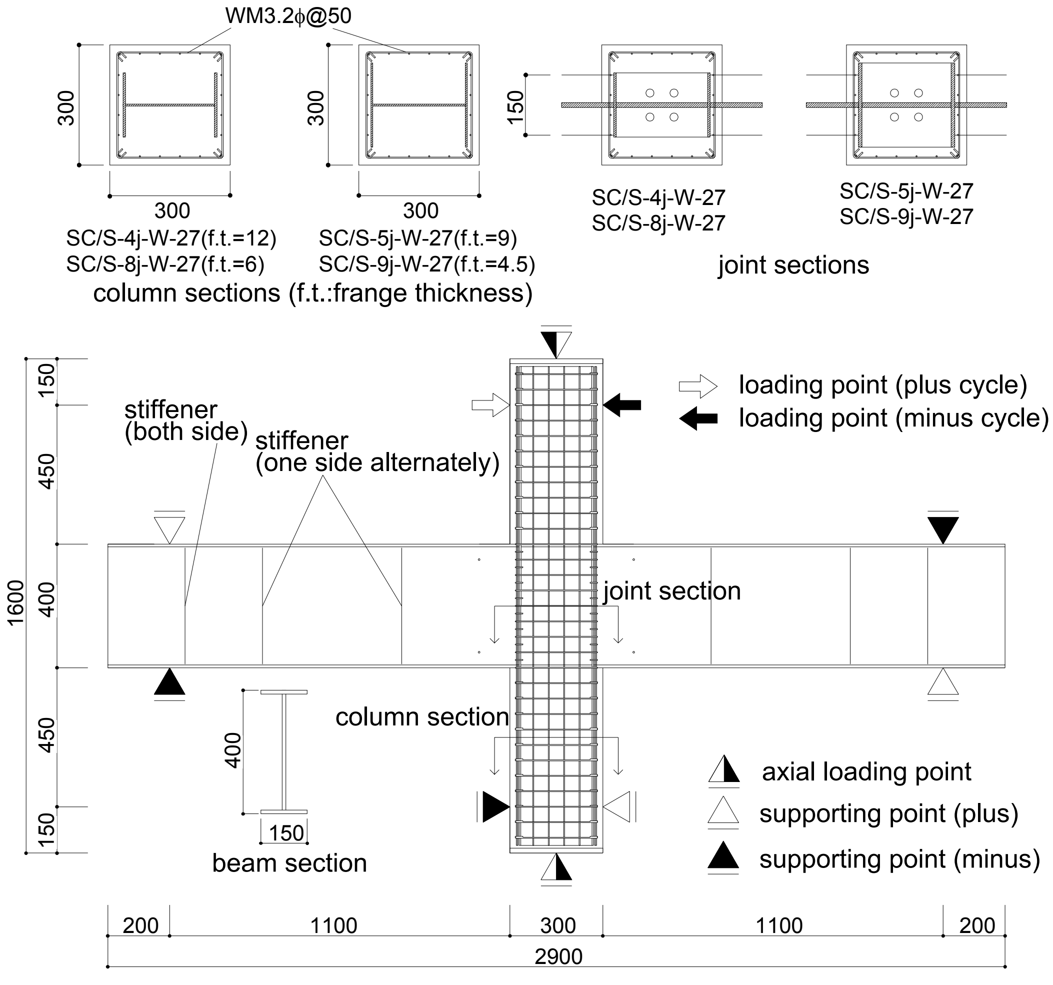


Figure 2.1. Outline of the specimens

Table 2.1. Detail of the specimens

Specimen	Column			Beam	Joint	
	p_w *2 (%)	Welded wire mesh	Steel*1	Steel*1	p_w *2 (%)	Steel web thickness (mm)
SC/S-4j-W-27	0.11	3.2ϕ@50	A	E	0.11	4.5
SC/S-5j-W-27			B	E		
SC/S-8j-W-27			C	F		9
SC/S-9j-W-27			D	F		

*2 *symbol;* p_w: shear rainforcement ratio

*1 steel configration
A:BH-240×160×4.5×12
B:BH-240×210×4.5×9
C:BH-240×160×4.5×6
D:BH-240×210×4.5×4.5
E:BH-400×150×12×12
F:BH-400×150×9×9

The design strength of the concrete was set at 27N/mm^2. The arrangements of the welded wire mesh were 3.2φ@50. Material properties are shown in **Table 2.2.**, **2.3.** and **2.4.**.

Table 2.2. Mechanical properties of concrete

Specimen	compressive stress σ_B (N/mm^2)	tensile stress σ_t (N/mm^2)	compressive strain ε_u (μ)	Young's modulus $E_{1/3}$ (kN/mm^2)	Young's modulus $E_{2/3}$ (kN/mm^2)
SC/S-4j-W-27	30.2	9.05	2480	26.0	22.0
SC/S-5j-W-27	30.8	12.08	2630	26.5	22.5
SC/S-8j-W-27	28.4	2.06	2780	25.5	21.5
SC/S-9j-W-27	29.2	2.16	2520	25.7	21.7

Table 2.3. Mechanical properties of welding wire mesh

Specimen	steel	yield stress σ_y (N/mm^2)	yield strain ε_y (N/mm^2)	Young's modulus E (kN/mm^2)
SC/S-4j-W-27 SC/S-5j-W-27	3.2f@50 (W.M.)	663	5170	210
SC/S-8j-W-27 SC/S-9j-W-27		614	5290	193

Table 2.4. Mechanical properties of steel plate

Specimen	steel plate	yield stress σ_y (N/mm^2)	yield strain ε_y (N/mm^2)	Young's modulus E (kN/mm^2)
SC/S-4j-W-27 SC/S-5j-W-27	PL4.5	360	1990	201
	PL9	281	2540	197
	PL12	291	3470	200
SC/S-8j-W-27 SC/S-9j-W-27	PL4.5	326	2860	187
	PL6	304	1680	169
	PL9	305	1660	169

2.2. Loading and Instrumentation

Loading arrangement is schematically shown in **Figure 2.2.**. The incremental forced displacement was given to the specimen at the top of the column cyclically during the application of column axial stress of $\sigma_B/6$. The incremental loading cycles were controlled by story drift angles, R_c, defined as the ratio of lateral displacements to the column height, δ/h. The lateral load sequence consisted of two cycles to each story deformation angle, R_c of 0.002, 0.005, 0.010, 0.017, 0.026, 0.037 and 0.05 radians. During the tests, the forces, displacements and reinforcement strains were measured.

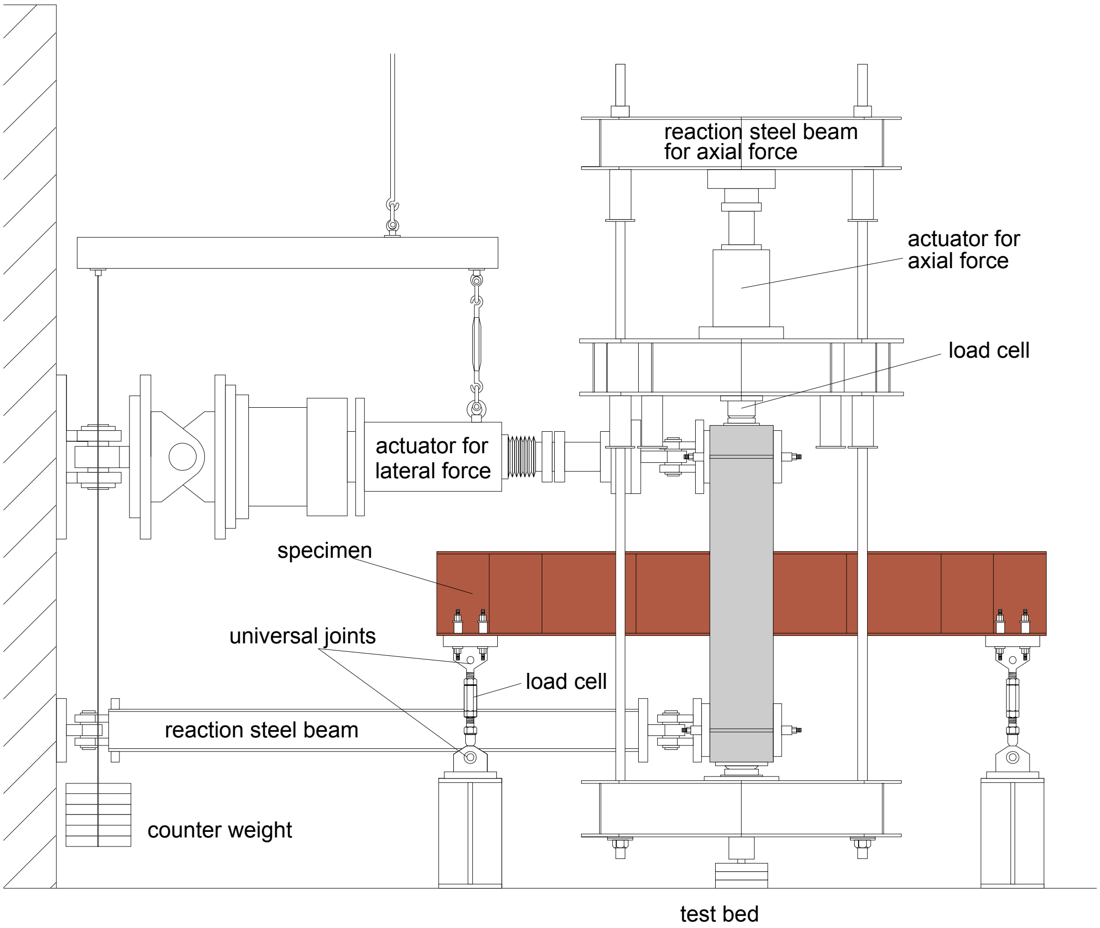


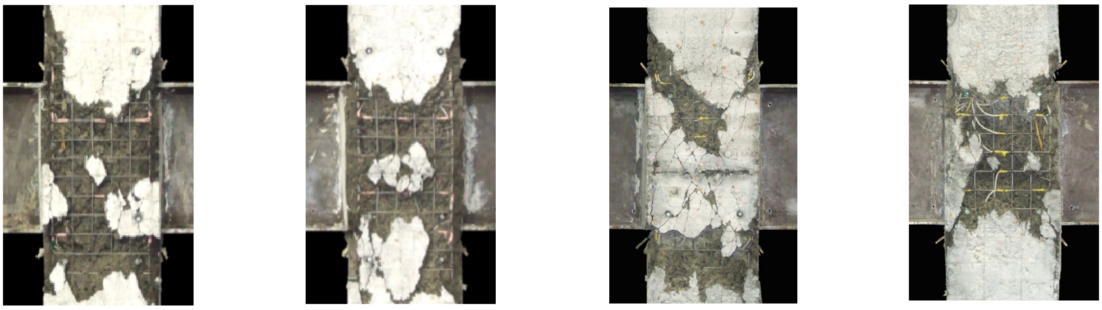
Figure 2.2. Outline of the loading equipment

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Circumstances of Failure

The circumstances of the failures for all specimens after testing are shown in **Photo 3.1.**. All specimens failed in beam-column joint shear. The general process of cracking was as follows. An initial flexural crack and a shear crack appeared in column and in beam-column joints during the second cycle loading (R_c=0.005 radian). After that, for specimen SC/S-4j-W-27 and specimen SC/S-5j-W-27, shear cracks markedly appeared in most parts of the joint by the fourth cycle loading (R_c=0.01 radian), and at the sixth cycle loading (R_c=0.017 radian), the steel web plate, the steel flange plate and the welded wire mesh of beam-column joint were yielded. However, for specimen SC/S-8j-W-27, the steel web plate and welded wire mesh of the beam-column joint were yielded at the second cycle loading (R_c=0.005 radian). After that, the steel flange plate of beam-column joint was yielded at the sixth cycle loading (R_c=0.017 radian). For specimen SC/S-9j-W-27, the steel web plate and welded wire mesh of beam-column joint were yielded at the fourth cycle loading (R_c=0.01 radian). The steel flange plate of the beam-column joint was yielded during the sixth cycle loading (R_c=0.017 radian).And the delaminating of the concrete in the center of joint and in the column end was remarkably observed under the eighth cycle loading (R_c=0.026 radian).

After maximum strength, for specimen SC/S-4j-W-27 and specimen SC/S-5j-W-27, the delaminating of the concrete in the center of joint and in the column end was remarkably observed. And, the widening of the bond slitting crack of the column steel flange was also remarkable in specimen SC/S-5j-W-27. In addition, the flaking of the concrete in the joint of specimen SC/S-5j-W-27 was less than that of specimen SC/S-4j-W-27, because, the concrete volume which the steel surrounds in the beam-column joint was big. There were the circumstances of failure which varied in the crack observation plane on specimen SC/S-8j-W-27. It seemed to be because the stress transmission to the beam-column joint differed in south face and north side by that specimen caused by tensile yield of the column flange out-of-plane deformation and that the steel flange of the beam-column joint in south face buckled. For specimen SC/S-9j-W-27, the cover concrete exfoliated with the collapse of the concrete at the column end, and the welding wire mesh was exposed. The damage of the concrete of the beam-column joint of specimen SC/S-9j-W-27 was more intense than that of specimen SC/S-8j-W-27. Therefore, for specimen SC/S-9j-W-27, the proof stress sharing of steel and welding wire mesh increased. After all, specimen SC/S-8j-W-27 became the flexural failure of the column, though the beam-column joint shear failure was assumed in the design, and specimen SC/S-9j-W-27 became the shear failure of the beam-column joint, though the column shear failure was assumed in the design. From the joint crack situation at R_c=0.005 and 0.010 radian, the joint crack number of SC/S-9j-W-27 (the yield mode of column steel was the shear) was more abounding than that of SC/S-8j-W-27 (the yield mode of column steel was the bending). And, in welding wire mesh strain distribution of the beam-column joint center, specimen SC/S-9j-W-27 was higher than specimen SC/S-8j-W-27. Therefore, the difference of the yield mode of the column steel seemed to affect the damage of the beam-column joint at R_c=0.01 radian, and in the structural design, it seems to be possible to reduce the damage of the beam-column joints by choosing that the yield mode of the column steel is bending.



SC/S-4j-W-27 SC/S-5j-W-27 SC/S-8j-W-27 SC/S-9j-W-27

Photo 3.1. Circumstances of failure

3.2. Load vs. Displacement Relationship

Skeleton curves of all specimens, which were obtained from the interaction curves of the column shear force 'Q_C' and story deformation angle 'R_c', is shown for comparison in **Figure 3.1.**. And, the interaction curve of the column shear force 'Q_C' and story deformation angle 'R_c' of all specimen are shown in **Figure 3.2.**.

All specimens also showed the fusiform hysteresis of good energy absorption. And the difference hardly could be observed in all specimens in the shape of the interaction curves.

The effect of the shape of the column steel section can be observed by comparing SC/S-4j-W-27 and SC/S-5j-W-27. Both specimen showed the behavior which was almost similar up to maximum strength,

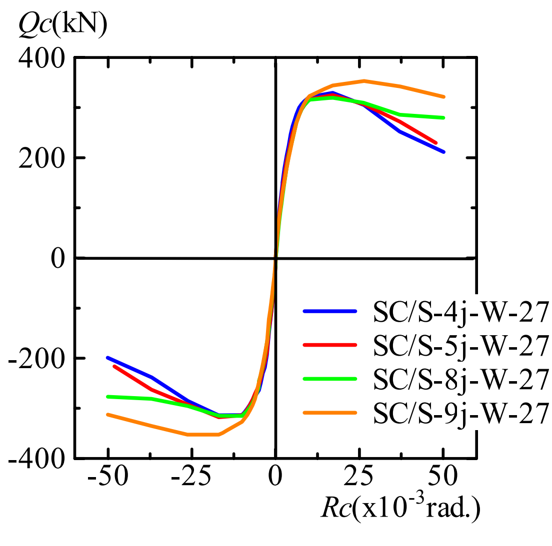
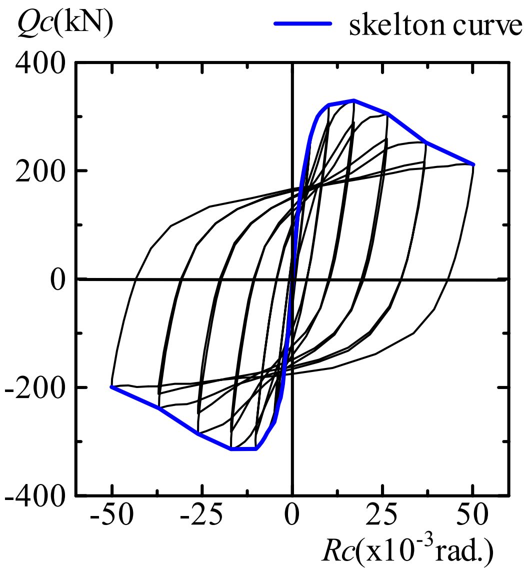
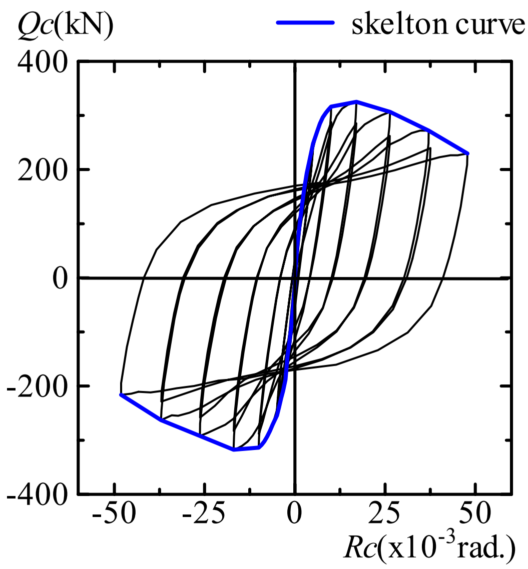


Figure 3.1. Skelton curves

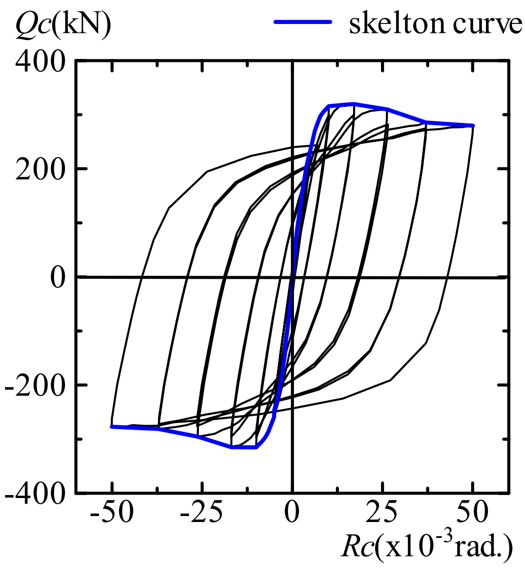
and it became the maximum strength at R_c=0.017radian, and the strength gently lowered afterwards. The strength decrease after the maximum strength of specimen SC/S-4j-W-27 was bigger than that of specimen SC/S-5j-W-27. As this reason, the proof stress share of the concrete seemed to decrease on specimen SC/S-4j-W-27 in which the concrete volume surrounded by the steel in the beam-column joint was small, since the flaking of the concrete after the maximum strength was remarkable. From the above fact, the steel cross-sectional shape seems to affect the strength reduction after the maximum strength. In the comparison of specimen SC/S-8j-W-27 and specimen SC/S-9j-W-27, specimen SC/S-8j-W-27 came to the maximum strength at R_c=0.017radian, while specimen SC/S-9j-W-27 came to the maximum strength at R_c=0.026radian. As the factor which became the maximum strength, yield of horizontal welding wire mesh reinforcement of the column end position, vertical welding wire mesh reinforcement of the beam-column joint, the steel flange of beam-column joint and the steel web were considered specimen SC/S-8j-W-27, and the yield of vertical welding wire mesh reinforcement, steel flange, steel web in the beam-column joint were considered specimen SC/S-9j-W-27.



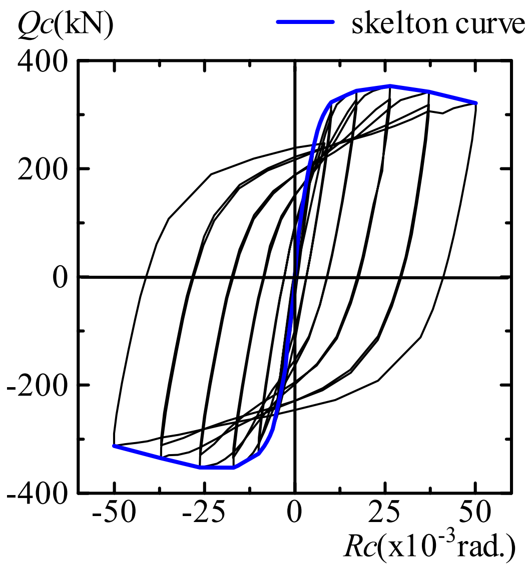
[Specimen SC/S-4j-W-27]



[Specimen SC/S-5j-W-27]



[Specimen SC/S-8j-W-27]



[Specimen SC/S-9j-W-27]

Figure 3.2. Relationships of column shear force 'Q_C' - story deformation angle 'R_c'

3.3. Ultimate Shear Strength of the Beam-Column joints

The calculated values of the ultimate strength of the beam-column joints for all specimens were calculated by the AIJ-SRC Standard equations (AIJ 2001) and reference (AIJ 2011) equations. The experimental and the calculated values are shown in **Table 3.1.**, and used equations are shown in **Table 3.2.**. The calculate values of ultimate strength of column in **Table 3.1.** (cal.3 and cal.4) were revised values which multiplied the coefficient in order to convert the values by **Table 3.2.** into median values.

Table 3.1. Experimental and calculated values on ultimate strength

specimen	experimental values of maximum strength	calculate values of ultimate strength							
		beam-column joint				column			
		AIJ-SRC standard (AIJ 2001)		reference (AIJ 2011)		shear		flexure	
	exp. (kN)	cal.1 (kN)	exp./cal.1	cal.2 (kN)	exp./cal.2	cal.3 (kN)	exp./cal.3	cal.4 (kN)	exp./cal.4
SC/S-4j-W27	330	281	1.17	330	1.00	433	0.76	572	0.58
SC/S-5j-W27	325	287	1.13	332	0.98	409	0.79	564	0.58
SC/S-8j-W27	319	402	0.79	320	1.00	416	0.77	406	0.79
SC/S-9j-W27	353	407	0.87	410	0.86	397	0.89	428	0.82

Table 3.2. Equations of calculation of shear strengths

Ultimate shear strength of joint

$$_{cal.J}Q_{su} = Q_{ju} / \left\{ \frac{(l - {}_{mC}d) \cdot h}{{}_{sB}d} - 1 \right\}$$

$$Q_{ju} = {}_j M_u / {}_{sB} d$$

AIJ-SRC Standard (AIJ 2001): cal.1

$$_j M_u = \underbrace{{}_cV_e \left({}_jF_s \cdot {}_j\delta + {}_wp \cdot {}_{rw}\sigma_y \right)}_{R/C} + \underbrace{\frac{1.2\,{}_sV \cdot {}_s\sigma_y}{\sqrt{3}}}_{Steel}$$

Reference (AIJ 2011) equation: cal.2

$$_j M_u = {}_i M_s + \min\left({}_o M_{ar}, {}_o M_T \right)$$

Ultimate shear strength of column: cal.3

$$_C Q_{su} = \underbrace{{}_s Q_U}_{steel} + \underbrace{{}_r Q_U}_{RC}$$

$$_s Q_U = \min({}_s Q_{sU}, {}_s Q_{bU})$$

$$_s Q_{sU} = {}_c t_w \cdot 2\left({}_C D_s - 2\,{}_c t_f \right) {}_{Cw}\sigma_y / \sqrt{3}$$

$$_s Q_{bU} = \Sigma({}_s M_U / h_e) = 2\,{}_s M_U / h_e$$

$$_r Q_u = \min({}_r Q_{sU1}, {}_r Q_{sU2}, {}_r Q_{bU})$$

$$_r Q_{sU1} = 7/8 \cdot {}_c b \cdot {}_c d (0.5 F_s \cdot {}_r \alpha + 0.5 p_w \cdot {}_{rw}\sigma_y)$$

$$_r Q_{sU2} = 7/8 \cdot {}_c b \cdot {}_c d (F_s \cdot b' / {}_c b + p_w \cdot {}_{rw}\sigma_y)$$

$$_r Q_{bU} = \Sigma({}_r M_u / h_e) = 2 \cdot {}_r M_U / h_e$$

Ultimate flexural strength: cal.4

$$_C Q_{Mu} = 2\,{}_C M_U / h_e$$

$$_C M_U = \underbrace{{}_s M_U}_{steel} + \underbrace{{}_r M_U}_{RC}$$

Symbols;

Q_{ju} : ultimate shear strength of joint(N)
${}_jM_u$: ultimate flexural moment of joint(N・mm)
${}_{sB}d$: distance between steel flanges center of gravity (mm)
${}_{mC}d$: distance between main bars center of gravity (mm)
${}_cV_e$: volume of R/C of joint(mm^3)
${}_j\delta$: coefficient of shape of joint
${}_sV$: volume of steel of joint(mm^3)
${}_iM_s$: moment of inside element of joint (N・mm)
${}_oM_{ar}$: moment of outside element of joint by arch model (N・mm)
${}_oM_T$: moment of outside element of joint by truss model (N・mm)
${}_{rw}\sigma_y$: yield stress of shear reinforcement (N/mm^2)

${}_sQ_{sU}$: shear strength of steel (N)
${}_sQ_{bU}$: flexural strength of steel (N)
${}_rQ_{sU1}$: shear strength (N)
${}_rQ_{sU2}$: bond splitting strength (N)
${}_rQ_{bU}$: flexural strength of R/C (N)
F_s : shear strength of concrete (N/mm^2)
b' : effective width by steel flange (mm)
${}_cr_U$: reduction coefficient
$*\,{}_cr_U = 0.85 - 2.5\,{}_sp_c$

In comparison with experimental values and calculated values by AIJ-SRC standard (AIJ 2001), for specimen SC/S-4j-W-27 and specimen SC/S-5j-W-27, the ultimate shear strength of beam-column joint of experimental values had overestimated the calculated values about 13%-17%. Therefore, it seemed that the calculated values estimated the experimental values accurately. However, for specimen SC/S-8j-W-27 and specimen SC/S-9j-W-27, the experimental value had underestimated each calculated values. In specimen SC/S-8j-W-27, the maximum strength seemed to be shear failure of beam-column joint along the estimation in the design. In specimen SC/S-9j-W-27, it seemed to be shear failure of beam-column joint in spite of the shear failure of the column in the design, since the joint web plate yielded and the widening of the shear cracks were remarkably observed before maximum strength. For specimen SC/S-8j-W-27, the reason why the experimental value was lower than calculated value seemed to be a collapse of concrete at the column end and the widening of which the shear cracks of the joint ware remarkable. For specimen SC/S-9j-W-27, the reason why the experimental value was lower than calculated value seemed to be also the widening of which the shear cracks of the joint ware remarkable. Therefore, it is necessary to propose the calculation equations with the good accuracy in proportion to the failure type in future.

The differences between equation cal.1 and equation cal.2 are whether or not it considers the steel flange of the joint yield, and whether or not it considers the stress transfer mechanism of beam-column joint. So, in comparison with experimental values and calculated values cal.2, the experimental value agreed with calculated value on specimen SC/S-8j-W-27 in which the steel flange of the joint yielded. Then, it was a good evaluation in all specimens except specimen SC/S-9j-W-27. Examination will be necessary in future, because the reason why the shear strength of the joint of specimen SC/S-9j-W-27 cannot evaluate by the both equations was not proven.

4. CONCLUSIONS

The following observations were obtained from the lateral load reversal tests performed on beam-column joint specimens.

1) The difference of the yield mode of the column steel affected the number of joint crack and strain of the horizontal welding wire mesh at the story deformation angle R_c = 0.01radian. Therefore, it seemed to be possible to hold the damage of the joint by making the yield mode of the column steel in the design with the flexure.

2) It was better the accuracy in the evaluation of the ultimate shear strength of beam-column joint of equation by reference (AIJ 2011) than equation by AIJ-SRC standard (AIJ 2001).

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