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AN EXPERIMENTAL STUDY ON HYSTERETIC BEHAVIOR OF CONCRETE FILLED TUBULAR MEMBERS UNDER REPEATED AXIAL LOADING

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SUMMARY

When tubular members are used as compression members in steel structures, they are superior in buckling strength to shaped steel member. However, in post-buckling stage, the compressive resistance of tubular member decreases radically, because the section is easy to change into a shallow ellipse. Furthermore, crack is easy to occur under repeated axial loading. These weak points may be improved by filling the tube with concrete. The paper clarifies the fundamental properties of strength and behavior of concrete-filled tubular members under repeated axial loading. And the behavior of K-braced frames, which bracings are the concrete-filled tubular members, are also discussed.

1. INTRODUCTION

A tubular member under axial compression is superior in buckling strength to a shaped steel member. However, in post-buckling stage, the compressive resistance decreases radically, because the section of the tubular member is easy to change into a shallow ellipse. Furthermore, if the tubular member is subjected to the repeated axial load such as the bracing member of a building frame under earthquake or wind, the cracks easily occur on the sharply bent portions of the member. However, these week points of the hollow tubular member are expected to be improved by filling the tube with concrete, since the infill concrete restrains the deformation of the section. The researches on the behavior of the concrete-filled tubular members under repeated axial loading can be scarcely found out, except for the study by Goel (Ref.1) who has reported the experimental result of a concrete-filled rectangular tubular bracing. The paper will experimentally clarify the fundamental behaviors of the concrete-filled tubular members under repeated axial loading.

A braced frame which bracings are hollow tubular members or shaped steel members shows unstable behavior due to buckling phenomena of the bracings, except for special design such as an eccentric bracing system. On the other hand, a braced frame, in which the concrete-filled tubular members are used as bracings of K-braced system, can be expected the stable behavior without buckling of the bracings. The reason is that the buckling strength of the compression bracing becomes larger than the yield strength of the tension bracing due to the effect of infill concrete, if the pair of compression and tension bracings have the same sections and their effective lengths are limited. The behaviors of the K-braced frames are also discussed by theoretical consideration.

2. TEST PROGRAM

Figure 1 shows a model of specimen. The specimen is simply supported at both ends, and subjected to axial load N. δ designates the corresponding axial deformation, and ℓ the member's length. The experimental parameters are (1) slenderness ratio of a tube λ, (2) concrete-filled or hollow tube, and (3) axial loading program : (A) repetition with large amplitude of axial deformation or (B) repetition with the gradually increased amplitude. These parameters are shown in Table 1.

Figure 2 shows the test specimen, and Table 1 shows the dimensions. The tubes which are used for the specimens are cold-formed mild steel tubes ("STK41" of the Japanese Industrial Standards). The cross sectional dimensions and properties of the tubes are shown in Table 2. The mechanical properties of tubes as shown in Table 3 are obtained by compression test of the stub columns, and tension test of the entire sections. The yield point σy is determined by the 0.2% strain offset method. The proportioning of concrete is shown in Table 4. The compressive strength of concrete is shown in Table 1.

Table 5 shows the mechanical properties of concrete-filled tubes by compression and tension tests. Three specimens are tested in each tests. Ny and Nu are the yield axial load and maximum axial load, respectively. E is Young's modulus which is obtained from N/As - strain relationships, where As designates

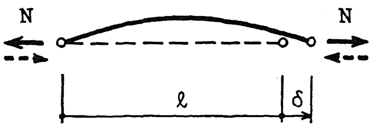
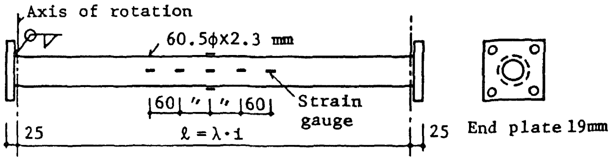


Fig.1 Model of Specimen



i : radius of gyration of steel tube

Fig.2 Test Specimen

Table 1 Dimensions and Parameters of Specimens

Series of Specimens	Tubes Dxt(mm)	ℓ (cm)	λ	Infill Concrete	Loading Program	Number	Fc (kg/cm^2)
B20	60.5ϕx2.3	41.2	19.9	fill or not	(A) or (B)	4	334
B40	60.5ϕx2.3	82.4	39.8	fill or not	(A) or (B)	4	334
B60	60.5ϕx2.3	123.6	59.7	fill or not	(A) or (B)	4	350
B90	60.5ϕx2.3	185.3	89.6	fill or not	(A) or (B)	4	350
B120	60.5ϕx2.3	247.3	119.5	fill or not	(A) or (B)	4	357

Notes D, t : Outside diameter and thickness of a tube (nominal value),
λ : Slenderness ratio of a tube, Fc : Compressive strength of concrete

Table 2 Dimensions of Tubes

Tubes	D* (mm)	t* (mm)	A (cm^2)	I (cm^4)	i (cm)	D/t
60.5ϕx2.3	60.6	2.10	3.86	16.5	2.07	28.9

Notes * : Measured values,
A : Sectional area,
I : Moment of inertia,
i : Radius of gyration

Table 3 Mechanical Properties of Steel Tubes

Test	σy (t/cm^2)	σu (t/cm^2)	E (t/cm^2)	εu (%)
Compression	3.21	3.82	2190	-
Tension	3.41	4.30	2190	30.5

Notes σy : Yield point,
σu : Maximum stress,
E : Young's modulus,
εu : Maximum elongation

Table 4 Proportioning of Concrete

W/C (%)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate* (kg/m^3)	Slump (cm)
53	170	321	781	1134	7.3

Notes * : The grain size is limited to 10mm.

Table 5 Mechanical Properties of Concrete-Filled Tubes

Test	Ny (t)	Nu (t)	E (t/cm^2)	εu (%)	ny	nu
Compression	23.5	27.0	-	-	1.90	1.83
Tension	14.2	18.1	2170	17.0	1.08	1.09

Notes Ny : Yield axial load, Nu : maximum axial load,
ny = Ny(concrete-filled tube)/Ny(hollow tube),
nu = Nu(concrete-filled tube)/Nu(hollow tube)

sectional area of a tube. As shown in the table, the value of E of the concrete-filled tube is nearly equal to the value of hollow one. The ny and nu are the ratios of Ny and Nu of concrete-filled tubes to those of hollow tubes, respectively. These values show that Ny and Nu in tension increase due to infill concrete, in the same manner as Ny and Nu in compression.

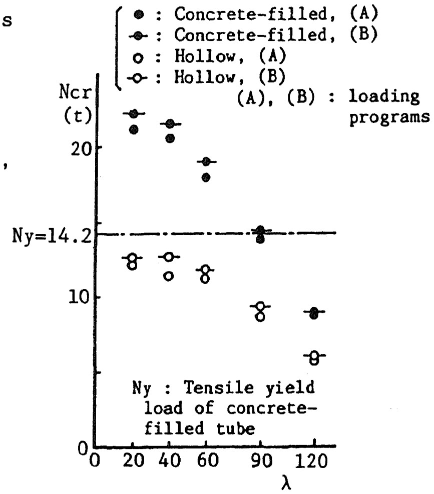


Fig.3 Buckling Strength Ncr

3. TEST RESULTS

3.1 State of Collapse The position of crack or breaking failure was always at the center of the member's length. The failure mainly occurred for the members subjected to loading program (B). In the case of hollow tubular members, crack took place at the sharply bent portion of the tube, in the early loading stages. After that, the crack rapidly spread in the half or entire section. In the case of concrete-filled tubular members, many waves due to local buckling were observed in the middle and wide range of the length. Then, one of the waves grew up slowly owing to repetition of loading, and the crack took place at the hill or dale of the wave.

3.2 Buckling Strength Figure 3 shows the experimental buckling load Ncr - slenderness ratio of a steel tube λ relationships of the concrete-filled and hollow tubular members. The dash-dotted line designates the tensile yield load Ny of concrete-filled tubes. From the figure, the buckling strength of the concrete-filled tubular members are larger than the tensile yield strength, if the values of λ are less than 90.

3.3 Behavior Under Loading Program(A) (repetition with large amplitude of axial deformation) Figures 4(a)-(e) show the experimental relationships between axial load and axial deformation under loading program(A). At the first compression stage, the buckling and post-buckling strength of concrete-filled tubular members are larger than the corresponding hollow ones. Furthermore, at the following loading stage, the concrete-filled tubular members show better behaviors than the hollow ones, because the strength of hollow tubular member deteriorates due to local buckling. In particular, the deterioration is radical, when its λ is smaller value. In this case, the improvement by infill concrete is remarkable.

3.4 Behavior Under Loading Program(B) (repetition with gradually increased amplitude of axial deformation) Figures 5(a)-(e) and 6(a)-(e) show the axial load - axial deformation relationships of the hollow tubular members and the concrete-filled tubular members under loading program(B), respectively. The occurrence of crack of the concrete-filled tubular member is fairly late to the hollow one. In the case of λ=60, the crack took place at the sixteenth loading cycle (amplitude of δ/ℓ = ±2%) for the concrete-filled tubular member, and at the seventh cycle (amplitude of δ/ℓ = ±1%) for hollow one. The members which values of λ are 40 cracked earliest in any series of concrete-filled or hollow tubular members. The concrete-filled tubular members which values of λ are 90 and 120 did not crack in the prearranged loading procedure.

3.5 Dissipated Energy Figures 7(a)-(e) show the relationships between dissipated energy W and accumulated plastic axial deformation δt of the specimens under loading program (B). From the figure, the dissipated energy up to collapse of concrete-filled tubular members are always larger than the energy of corresponding hollow members. Maximum ratio of the dissipated energy of concrete-filled one to hollow one is 3.2, where the values of λ are 60.

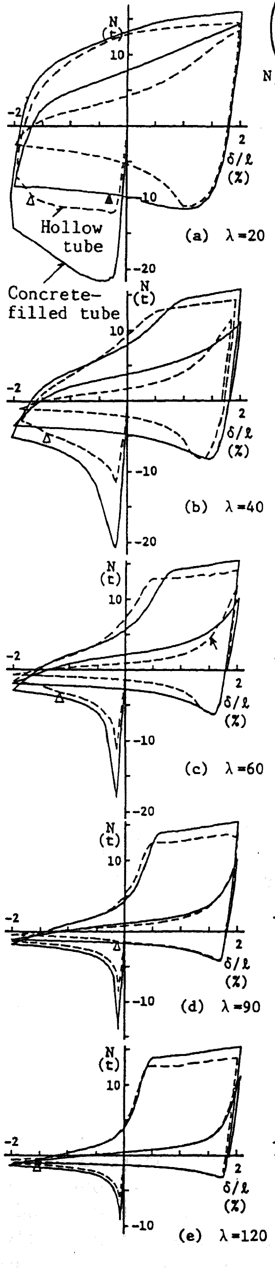


Fig.4 Behaviors under Loading Program (A)

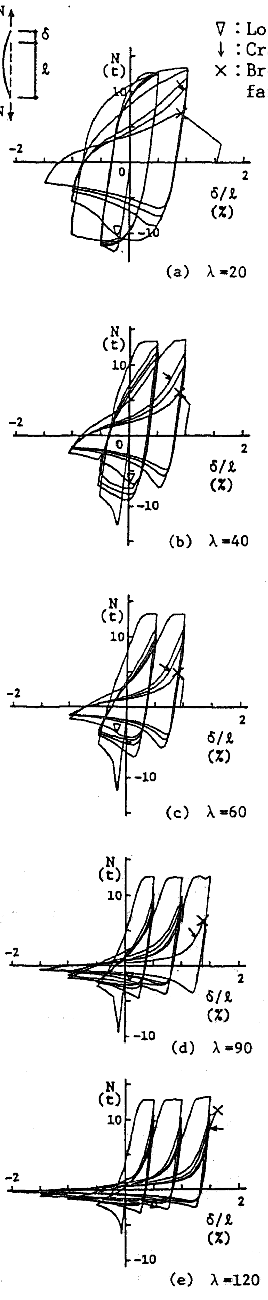


Fig.5 Behaviors of Hollow Tubular Members under Loading Program (B)

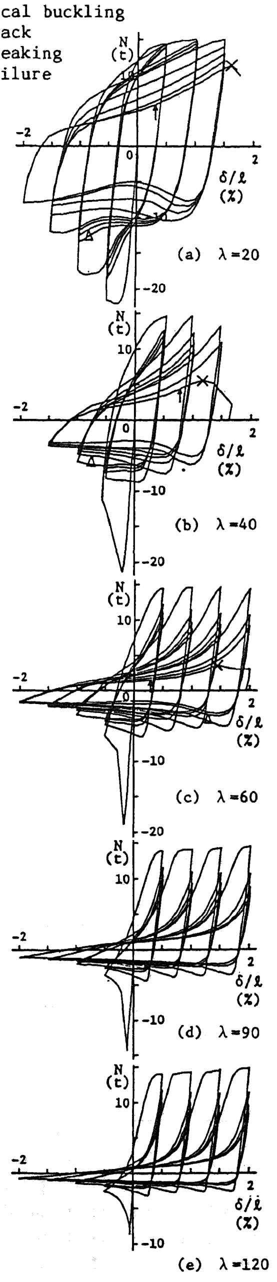


Fig.6 Behaviors of Concrete-Filled Tubular Members under Loading Program(B)

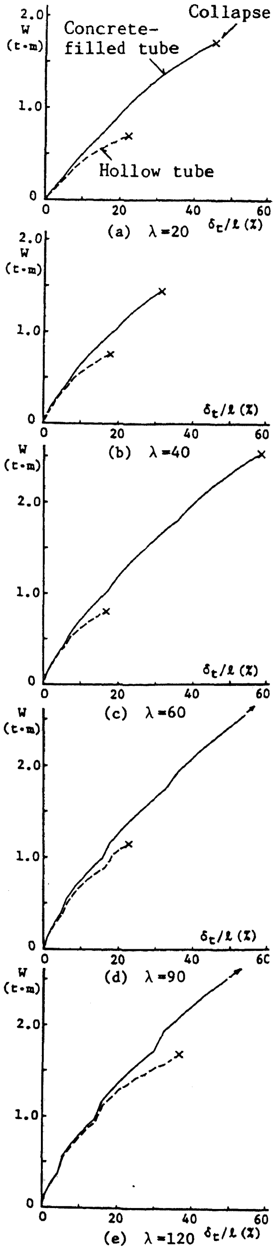


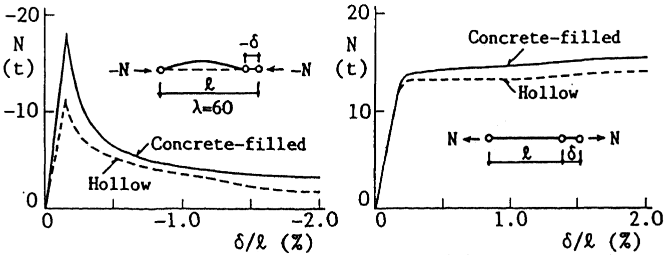
Fig.7 Dissipated Energy W-Accumulated Plastic Deformation δt Relationships

4. BEHAVIOR OF BRACED FRAME MODEL

Figure 8(a) shows load - deformation relationships of concrete-filled and hollow tubular members subjected to compressive load, where the values of λ are 60. Figure 8(b) shows the relationships subjected to tensile load. Figures 9(a), (b) show K-braced frame models (A) and (B), which bracings are the tubular members mentioned above. The beams and columns of the frames are rigid and connected with each other by pins. Accordingly, the horizontal behavior is all owing to the bracings. The point of difference of models (A) and (B) is whether the beams are not hinged or are hinged in the middle of the span.

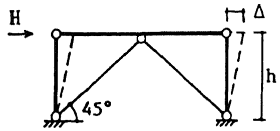
Figure 10(a) shows the behaviors of frame models (A) of which bracings are concrete-filled tubular members or hollow ones. The bracings of these frames always buckle, whichever the bracings are filled with concrete or not. Then the both of frames have almost same behaviors and the horizontal strengths deteriorate due to buckling of the bracings. However, under repeated horizontal loading, the frame with concrete-filled tubular bracings can be expected to have superiority over the frame with hollow tubular bracings, because the concrete-filled tubular members hold the strength for more loading cycles than the hollow ones, as shown in the preceding section.

Figure 10(b) shows the behaviors of frame models (B). The figure shows that the frame with the concrete-filled tubular bracings has a stable behavior without deterioration of strength, in comparison with the frame with hollow tubular bracings. In the frame model (B), the absolute values of each axial loads of compression and tension bracings are same, from the equilibrium condition about the middle point of the beam in the vertical direction. If the bracings are the concrete-filled tubular members, the bracings never buckle. The reason is that the yield strength of the tension bracing is lower than the buckling strength of the compression bracing, where the values of λ are 60.

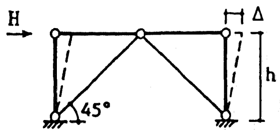


(a) Compression (b) Tension

Fig.8 Behaviors of Tubular Members under Monotonic Axial Loading

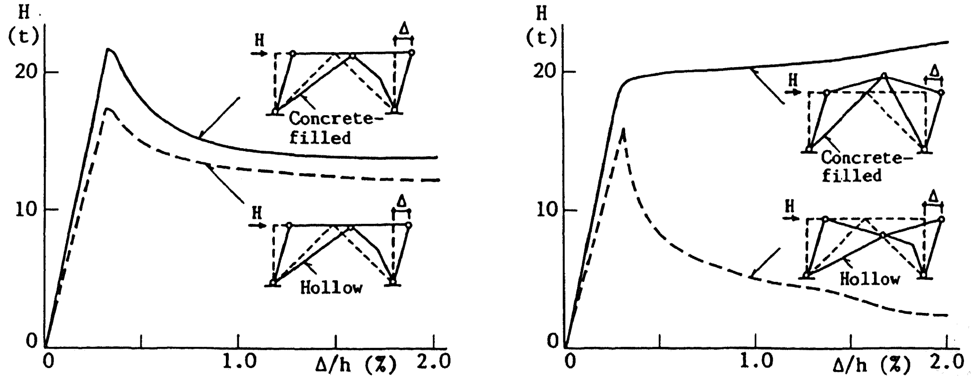


(a) Frame Model (A)



(b) Frame Model (B)

Fig.9 K-Braced Frame Models



(a) Frame Model (A) (b) Frame Model (B)

Fig.10 Horizontal Load-Deformation Relationships of Frame Models

5. CONCLUSION

(1) The experimental buckling loads of the concrete-filled tubular members, which slenderness ratios of steel tubes are less than 90, are larger than the experimental tensile yield strength.

(2) The strengths of hollow tubular members deteriorate owing to local buckling. The deterioration is particularly radical, when the member has the smaller slenderness ratio. In the case, the improvement of the behavior due to infill concrete is remarkable.

(3) The concrete-filled tubular members are cracked fairly late in comparison with the corresponding hollow ones. For instance, the concrete-filled tubular specimen, which slenderness ratio of steel tube was 60 (this value is considered to be practical for bracings), was cracked at the sixteen loading cycle (amplitude of $\delta/\ell = \pm 2\%$), and the hollow one at the seventh cycle (amplitude of $\delta/\ell = \pm 1\%$).

(4) The dissipated energy up to breaking failure of concrete-filled tubular specimens are considerably larger than the corresponding hollow ones under repeated axial loading. For instance, the energy of concrete-filled tubular specimen which slenderness ratio of steel tube was 60 had 3.2 times as the energy of the corresponding hollow one.

(5) According to the theoretical investigation, the K-braced frame of which bracings are concrete-filled tubular members can be expected to have a stable behavior without buckling phenomena of the bracings.

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REFERENCES

1) S. C. Goel : Seismic Stability of Braced Steel Structures, SSRC Annual Technical Session Proceedings, 189-200, 1986.4.

2) C. Matsui and A. Kawano : Study on Elasto-Plastic Behavior of Concrete Filled Steel Tubular Members under Alternately Repeated Axial Loading, Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, 1283-1284, 1987.10.

3) C. Matsui and A. Kawano : Elasto-Plastic Behavior of Concrete Filled Steel Tubular Members under Alternately Repeated Axial Loading, Technology Reports of the Kyushu University Vol.60, No.6, 721-728, 1987.12.