Load-bearing Capacity of H-shaped Steel Columns under Local Buckling at Elevated Temperature

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ABSTRACT

When a compartment fire occurs in a building of steel structure, large bending deformations are produced at the ends of columns and beams, inducing local buckling at these points. In this study, the load-bearing capacity of H-shaped steel columns under local buckling is clarified from pure compression tests and bending compression tests at constant temperatures ranging from room temperature to 600°C. On the basis of the tests, we propose, in relation to the fire resistance of H-shape steel stub columns, a relation between safety usable steel temperature and constant axial load ratio.

KEYWORDS: fire resistance, H-shaped steel member, stub column, local buckling, pure compression test, bending compression test

INTRODUCTION

The basic principle in fire engineering design of a building is to contain any fire that occurs, by dividing the interior of the building into compartments. When a compartment fire occurs in a building of steel structure, as shown in Fig. 1, large bending deformations are produced at the ends of steel structural members, because of thermal elongation of steel members exposed to fire and restraint by adjacent structural members. As discussed in a previous paper [1] on numerical study of fire resistance of steel structures of 48 high-rise buildings exposed to compartment fire, steel structures designed against seismic load exhibit fire resistance up to 600°C. However, the paper also indicates that when temperature approaches 600°C, large curvatures are produced at the tops and bottoms of outer columns and at both ends and in the middle of beams, and this phenomenon induces local buckling at these points. However, the standard fire test [2] for a column is the pure compression test, which does not consider thermal elongation of beams exposed to fire.

Another previous paper [3] describes bending compression tests of so-called fire-resistant steel tubular stub columns at elevated temperature, and indicates that the fire-resistant steel tubular columns exhibit sufficient load-bearing capacity between room temperature and 650°C. In the present study, pure compression tests and bending compression tests are carried out at constant temperatures ranging from room temperature to 600°C, in order to clarify the load-bearing capacity of H-shaped conventional steel stub columns under local buckling.
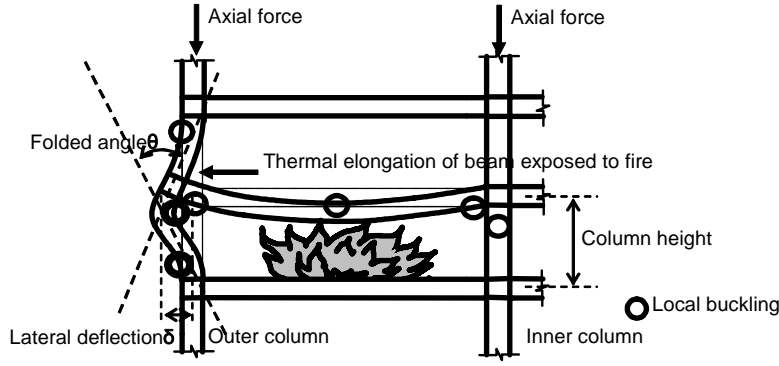
Fig. 1. Thermal deformation of steel structure exposed to fire.

TENSILE TESTS OF ROLLED STEELS

Tensile tests are performed on rolled steel in order to obtain the stress-strain curves of specimens about pure compression tests and bending compression tests. The steel employed in the present study is rolled steel SM490A for welded structures. The specifications of SM490A are as follows: yield stress $\geq$ 325 N/mm2, 490 N/mm2 $\leq$ tensile strength $\leq$ 610 N/mm2, and elongation $\geq$ 22%. Tensile tests are carried out under the following temperatures.

Plate Thickness 4.5 mm and 6 mm: R.T., 400, 500, 550, 600°C

Plate Thickness 9 mm: R.T., 100, 200, 300, 400, 450, 500, 550, 600, 700, 800°C

The specimens are cut out from H-shaped steel flange in the same direction as that of hot rolling. The gauge length is 50 mm. The temperatures at the midpoints of specimens are within $\pm 3^{\circ}$C of the target temperatures. Velocity of deformation is controlled in a loading machine. Specimen deformation is measured by transducers and amplifiers. The rate of strain is 0.3%/minute in the elastic range and is 10%/minute in the plastic range.

Figure 2 shows the results of elevated-temperature tensile tests. Proof stress and tensile strength at 600°C are 0.3-0.4 times those at room temperature. Figure 3 shows stress-strain curves for specimen having a plate thickness of 9 mm. Stress increases when the rate of strain is increased from 0.3%/minute to 10%/minute at 0.005 strain. This phenomenon is apparent at high temperature. Stress-strain curves for use in calculation of pure compression tests and bending compression tests are given by Eq. 1 [4].

$$\varepsilon = \frac{\sigma}{E_T} + \left(\frac{\sigma}{\sigma_K}\right)^k \tag{1}$$

In Eq. 1, E_T is Young's modulus at temperature T, and the values of σ_k and k are determined for each temperature from the results of tension tests. Table 1 shows the values of E_T, σ_k and k of plate thickness 9 mm. As shown in Fig. 3, the calculation models of stress-strain curve roughly agree with the experimental results.
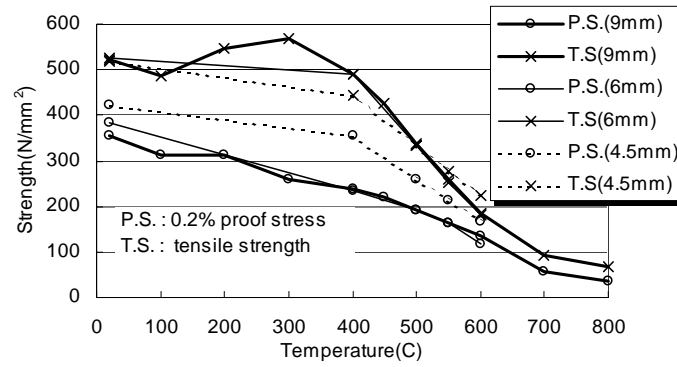
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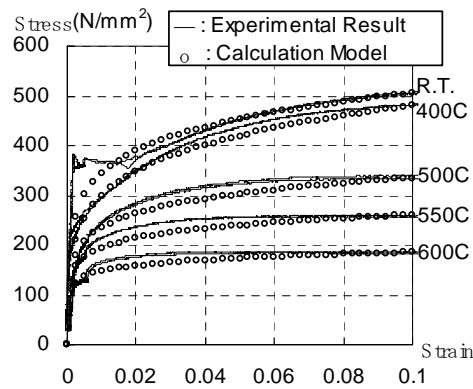Fig. 2. 0.2% proof stress and tensile strength.

Fig. 3. Stress-strain curves
(Plate thickness: 9mm).

Table 1. The value of E_T, σ_k and k used to
draw Fig. 3. (Plate thickness: 9mm).

Temp. [°C]	E_T [kN/mm²]	σ_k [N/mm²]	k [-]
R.T.	206	594	12.4
400	174	595	6.8
500	155	390	8.6
550	145	286	10.9
600	133	191	17.1

PURE COMPRESSION TESTS OF H-SHAPED STEEL STUB COLUMNS

Test Plans and Specimens

The purpose of subjecting stub columns to pure compression tests is to obtain the residual compressive strength of H-shaped steel members under local buckling. As shown in

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Table 2, the parameters of pure compression tests are width-thickness ratio of H-shaped steel flange and specimen temperature; tests are carried out on 8 specimens.

Table 2. Parameters of pure compression tests.

Section of specimen	Width-thickness ratio of flange (b/t)	Temperature of specimen			
		R.T.	400°C	500°C	600°C
H-135x135x6x9	7.5	•	•	•	•
H-120x120x4.5x6	10	•	•	•	•

Specimens are made from rolled steel SM490A for welded structures. Figure 4 shows the shape and dimensions of a specimen. Specimen length is 1200 mm, and the range of the testing portion where temperature distribution is rather uniform is 3 times member depth (a length of 405 mm or 360 mm).
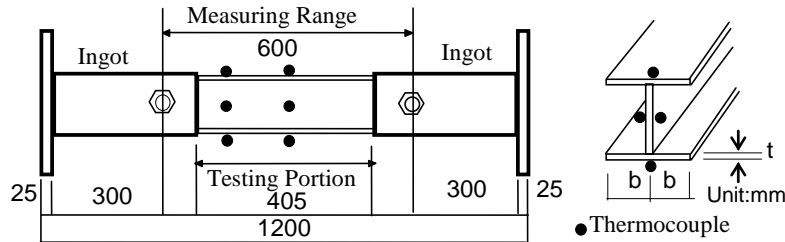

Fig. 4. Shape and dimensions of a specimen (b/t=7.5).

Test Conditions

Fig. 5 shows the loading system used in pure compression tests. The loading system consists of 2 steel struts and an oil cylinder. The oil cylinder for producing axial force is set horizontally. In order to maintain the loading direction as the center axis, the inclined plates are set between the load cell and the specimen.

Heating of the specimen is carried out with a box-shaped electric furnace. The box measures about 900 mm in length, 550 mm in width, and 600 mm in depth and has 3 windows on each side for measurement and observation. Heating panels are located on the top, bottom, and sides. Specimen temperature is controlled by 5 transformers and measured with Cromel-Almel thermocouples which are arranged at 8 points on the surface of the specimen and whose hot junctions are covered with stainless-steel foil for blocking radiant heat from the heating panels.

As shown in Fig. 6, axial deformation is measured out of the furnace by means of stainless transmitting bars bolted on the specimen.

In the experimental procedure for the pure compression test, the first step is to control the direction of axial force to produce a uniform stress distribution over the specimen cross-section. The next step is to heat the specimen without loading in such a matter as to reach and maintain the prescribed temperature. After attainment of steady-state temperature distribution of a specimen, axial loading starts. Loading forces and axial deformations are measured at each loading step, and tests are continued until specimen deformation reaches the limitations of the measuring device.
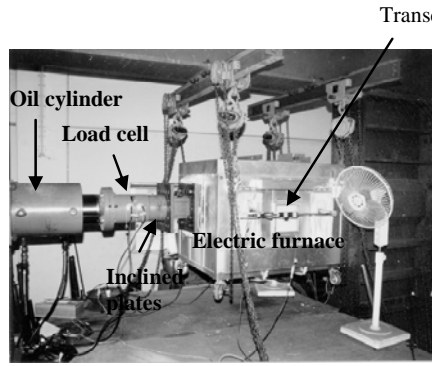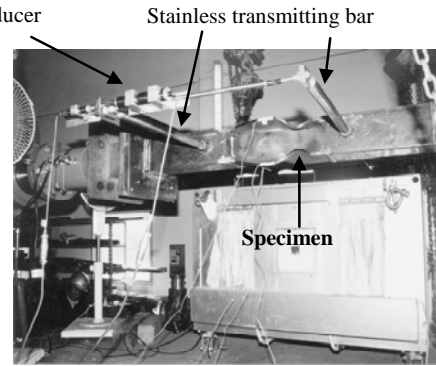
Fig. 5. Loading system.   Fig. 6. Measuring device.

Results

The results of pure compression tests are shown in Figs. 7a and b. In these figures, the vertical axis shows average compressive stress at the testing portion, and the horizontal axis shows average strain in the testing portion up to the maximum stress. After maximum stress, the horizontal axis represents the value obtained by dividing deformation in the testing portion by specimen depth, because local buckling width is roughly equal to specimen depth. The post-testing specimens are shown in Figs. 8a and b.
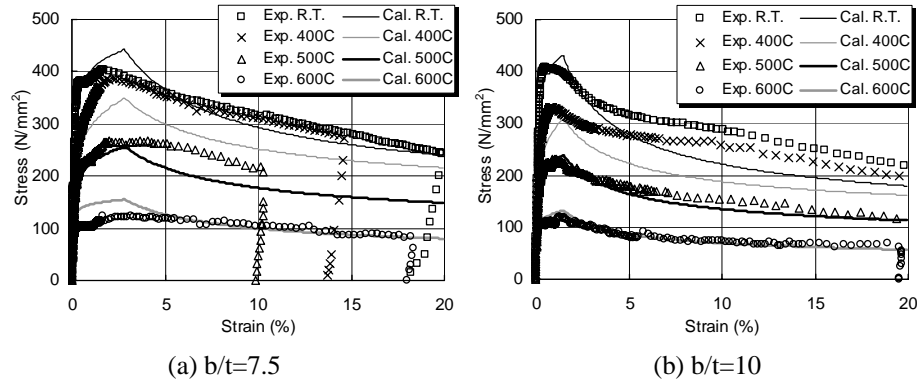

(a) b/t=7.5   (b) b/t=10

Fig. 7. Results of pure compression tests of H-shaped steel stub column.

(a) b/t=7.5 , 600°C   (b) b/t=10 , 600°C

Fig. 8. Post-testing specimens of pure compression tests.

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As shown in Fig. 7b, for H-shaped steel members where b/t=10, residual compressive strength at 15% strain at 500°C is about 0.4 times reference strength (325 N/mm^2), and that at 600°C is about 0.2 times reference strength.

Suzuki et al. propose the formulation of stress-strain curves for square tubular steel members in consideration of local buckling [5]. In this study, on the basis of Suzuki's formulation we propose Equation 2 for the stress-strain curve for an H-shaped steel member in consideration of local buckling.

$$\sigma(\varepsilon_0) = \frac{\sigma_0(\varepsilon_0)}{b/t} \sqrt{\frac{1.2}{\varepsilon_0}} + 1.0 \tag{2}$$

ε_0 : compressive strain [-].

$\sigma(\varepsilon_0)$: compressive stress under local buckling.

$\sigma_0(\varepsilon_0)$: tensile stress corresponding to compressive strain ε_0.

In Fig. 9, the vertical axis represents non-dimensional stress multiplied by width-thickness ratio, and the horizontal axis represents average strain, as in Fig. 7.

As shown in Fig. 9, these curves obtained by pure compression tests for H-shaped steel members approximately converge. For stress-strain curve of compressive region, Eq. 1 is used in the case where local buckling does not occur, and Eq. 2 is used in the case where local buckling occurs. Equation 2 is convenient because this equation takes into account steel grade, temperature, and width-thickness ratio. As shown in Fig. 7, the calculation models of stress-strain curve approximately agree with the experimental results. In fire engineering design, Eq. 2, expressing strength of steel structural members under local buckling, can be employed in numerical analysis using a fiber model.
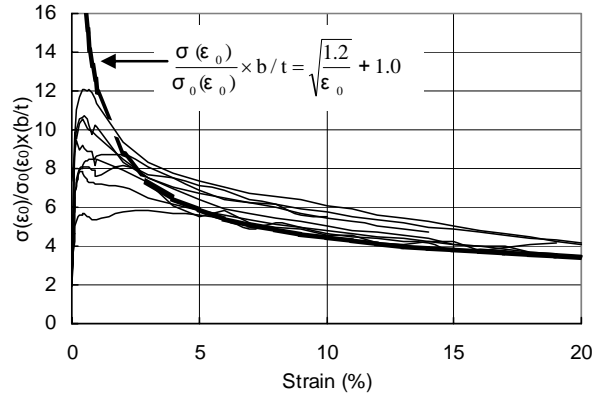

Fig. 9. Relation between non-dimensional
stress and average strain.

BENDING COMPRESSION TESTS OF H-SHAPED STEEL STUB COLUMNS

Test Plans and Specimens

When a fire occurs in a building structure, large deformations are produced at the tops and bottoms of outer columns in response to thermal elongation of beams exposed to fire (see Fig. 1). Under ECCS recommendations [6], lateral deformation criterion for the top of a column is 1/30 column height. Therefore, in our bending compression tests, steel structural members are given constant axial load and lateral deformation exceeding 1/30 column height. The purpose of subjecting stub columns to bending compression tests is to clarify the load-bearing capacity of H-shaped steel outer column subjected to severe thermal elongation of beams exposed to fire. Therefore, we focus on folded angle at the tops of outer column in Fig.1.

Parameters in the bending compression test are set as follows:

- Width-thickness ratios of flange b/t : 7.5 and 10.

- Constant axial load ratios P/P_y : 0.3, 0.4 and 0.5
  (=constant axial load divided by reference axial strength).

- Temperatures of steel: R.T., 400°C, 500°C, 550°C, and 600°C.

As shown in Table 3, with these parameters, tests are carried out on 24 specimens.

Specimens are made from rolled steel SM490A. Figure 10 shows the shape and dimensions of a specimen. Specimen length is 1200 mm, and the range of the measuring portion where temperature distribution is rather uniform is 600 mm long.

Table 3. Parameters of bending compression tests.

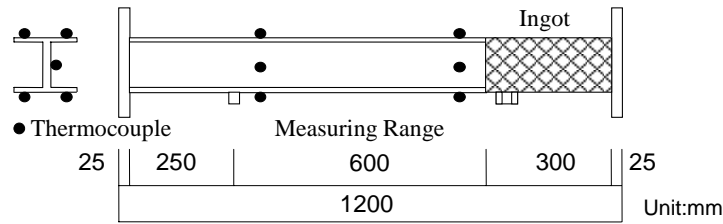| Section of specimen	Width-thickness ratio of flange b/t	Axial load ratio P/P_y	Temperature of specimen [°C]				
			R.T.	400	500	550	600
H-135x135x6x9	7.5	0.3	●	●	●		●
		0.4	●	●	●	●	
		0.5	●	●	●	●	
H-120x120x4.5x6	10	0.3	●	●	●		●
		0.4	●	●	●	●	
		0.5	●	●	●	●	

Fig. 10. Shape and dimensions of a specimen (b/t=7.5).

Test Conditions

Figure 11, and 13 show the loading system used in the bending compression tests. The loading system consists of 2 steel frames, a load-bearing wall and a floor made of reinforced concrete, and 3 oil cylinders. One cylinder is set horizontally for producing axial force in the specimen, and the others are set vertically for producing a bending moment. As shown in Fig. 13, in order to maintain the loading directions in the central and vertical planes, 8 mechanical stoppers are fixed to the steel frames and connected to the transmitting beams. The heating system and temperature measurement are completely the same as those employed in the pure compression tests.

The first step of these experiments is to heat a specimen without loading, in order to reach and maintain the prescribed temperature. After attainment of steady-state temperature distribution in the specimen, the axial force is applied and the prescribed load maintained. Subsequently, the bending moment is applied by the right-side oil cylinder under controlled incrementing of deflection, and the-left side oil cylinder is maintained at the initial position (see Fig. 13). The enforced bending deflection produced by the right-side oil cylinder corresponds to thermal elongation of beams exposed to fire. Loading force, bending deflections, and axial deformations are measured at each loading step. Enforced bending deflection is increased until specimen deflection reaches the limitations of the measuring device or the specimen becomes unable to support the prescribed axial force.

As shown in Fig. 12 and 13, specimen deformation is measured directly by an L-Frame. The L-Frame is fixed to an ingot portion of a specimen with stainless bolts and maintained at the same rotational position as an ingot portion. With this device, the vertical relative deflection of a specimen is measured out of the furnace. Figure 14 shows the deformation model in this test. The vertical relative deflection δ_{CD} between point C and point D is measured with transducer 1. The folded angle θ_{CD} at point D is obtained by dividing relative deflection δ_{CD} by the distance between measuring points C and D (600 mm length). The vertical absolute displacement δ_D at point D is measured with transducer 2. Meanwhile, the axial deformation is obtained by measuring the inside movement of the horizontal oil cylinder.
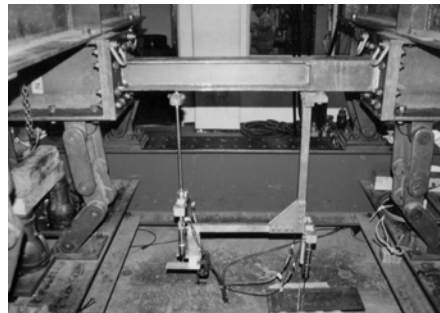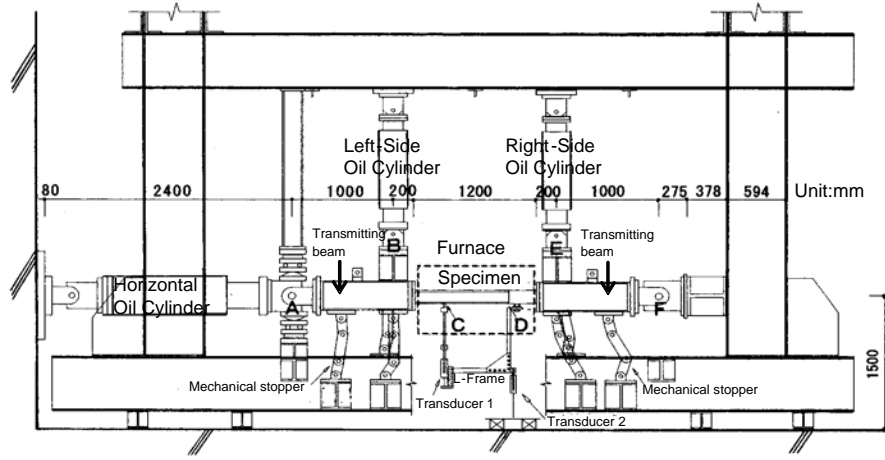

Fig. 11. Loading system.

Fig. 12. Measuring device.

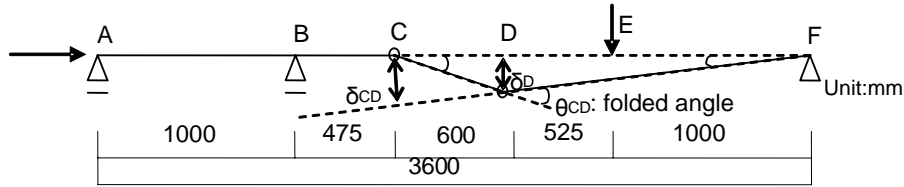Fig. 13. Loading system and measuring device in bending compression test.

Fig. 14. Deformation model in bending compression test.

Results

The post-testing specimens are shown in Fig. 15. Local buckling is observed at portions near point C and point D shown in Fig. 13. In this loading system, the top of outer column corresponds to point D.

The results of bending compression tests are shown in Fig. 16. In these figures, the vertical axis shows the ratio of the measured bending moment M at point D (see Fig. 13) to the plastic bending moment M_p obtained by reference strength (325 N/mm^2) at room temperature. This moment ratio M/M_p includes the effect of additional bending moment due to axial force; namely, the effect of P-δ. Bending moment M at point D is given by following Equation.

$$M = \frac{1000}{3600}\left(\ 2075L_1 \quad 1525L_2\right) + P\delta_D \ \ [\text{kNmm}] \tag{3}$$

L_1:   Load of the right-side oil cylinder shown in Fig. 13.
L_2:   Load of the left-side oil cylinder shown in Fig. 13.
P: Load of horizontal oil cylinder shown in Fig. 13 (= axial force).
δ_D: The vertical absolute displacement δ_D at point D shown in Fig.14.

In Fig. 16, the horizontal axis shows the preceding folded angle θ_{CD} at point D.

As shown in Fig. 16, up to about half of maximum bending moment, bending moment ratios M/M_p increase in proportion to folded angle θ_{CD}. After maximum bending moment,

M/M_p slowly decreases with increasing θ_{CD}, because of development of local buckling. M/M_p decreases with increasing temperature. The physical meaning of negative values of M/M_p is that tensile stress-resultant yields in the beam exposed to fire, due to decrease in strength of columns subjected to lateral deflection under local buckling.

The purpose of this experiment is to clarify the load bearing capacity of H-shaped steel columns under local buckling caused by thermal elongation of beams exposed to fire. Under ECCS recommendations [6], lateral deformation criterion for the top of a column is 1/30 column height. The previous paper [1] on numerical study of steel structures of 48 high-rise buildings exposed to compartment fire indicates that lateral deformations for the top of columns don't reach the criterion of 1/30 column height. If plastic hinges develop at the top and bottom of columns, the criterion of 1/30 column height corresponds to the value of 2/30 about folded angle θ (see Fig.1). In most of the test results, prescribed axial force is supported by the specimen beyond 2/30 about θ_{CD}. On the other hand, as shown in Fig. 16f, for the test result at 550°C, prescribed axial force cannot be supported by the specimen near 1/30 about θ_{CD}. This phenomenon is important in this experiment. If we define a steel column as having load-bearing capacity when the column maintains constant axial load while receiving lateral deformation exceeding 1/30 column height, the following results are obtained regarding the relation between safety usable steel temperature and axial load ratio, which is constant axial load divided by reference axial strength.

[In the case of H-shaped steel stub column with width-thickness ratio less than b/t=10]
- When axial load ratio is less than 0.3, safety usable steel temperature is 600°C.
- When axial load ratio is 0.3 to 0.4, safety usable steel temperature is 550°C.
- When axial load ratio is 0.4 to 0.5, safety usable steel temperature is 500°C.

These results provide the criteria for conventional steel columns in fire engineering design based on numerical analysis. Steel columns maintain fire resistance if we restrict steel temperature to that corresponding to constant axial load ratio, and numerical analysis of thermal stress deformation confirms that deformation of steel column due to thermal elongation of beams exposed to fire is less than 1/30 column height.

Comparison with Numerical Analysis Results

Numerical analysis is carried out for the bending compression tests, using the stress-strain curves obtained from tension tests and pure compression tests, and a computer program developed for structural steel frames exposed to compartment fire [7,8]. As shown in Fig. 16d-f, the calculated values approximately agree with the experimental values in consideration of the decrease in strength of steel columns under local buckling. This agreement presents reliability of numerical analysis for frame structure composed of steel stub columns and beams exposed to fire.
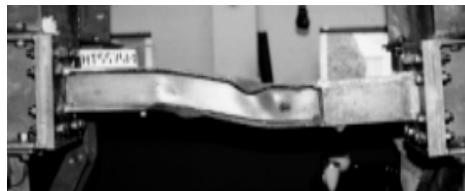
(a) b/t=7.5, P/P$_y$=0.4, 550°C   (b) b/t=10, P/P$_y$=0.3, 600°C

Fig. 15. Specimens after bending compression tests.

(a) b/t=7.5, P/P$_y$=0.3

(d) b/t=10, P/P$_y$=0.3

(b) b/t=7.5, P/P$_y$=0.4

(e) b/t=10, P/P$_y$=0.4
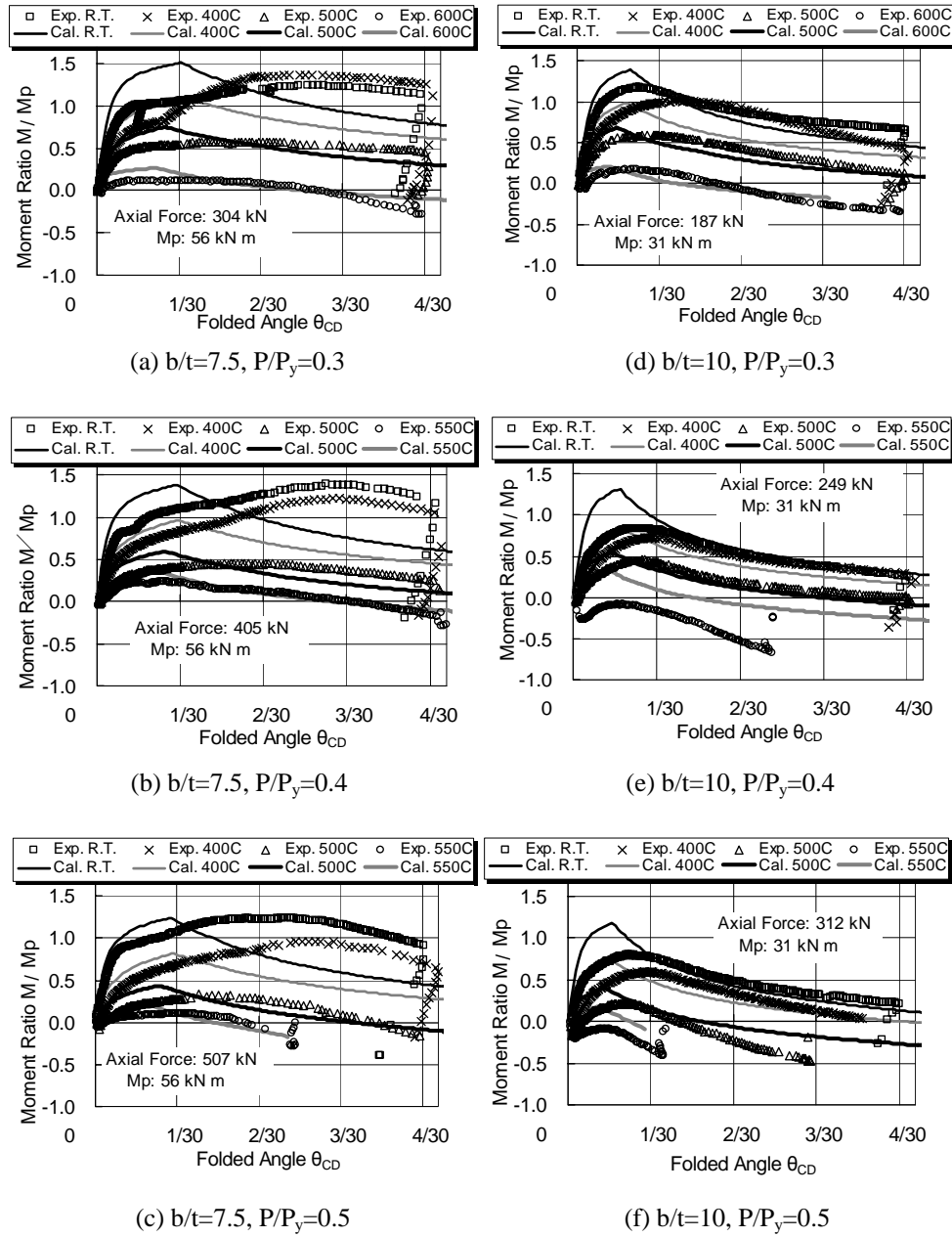
(c) b/t=7.5, P/P$_y$=0.5

(f) b/t=10, P/P$_y$=0.5

Fig. 16. Results of bending compression tests
of H-shaped steel stub column.

CONCLUSIONS

In this study, load-bearing capacity of H-shaped steel columns under local buckling is clarified from pure compression tests and bending compression tests at constant temperatures ranging from room temperature to 600°C. With the results of pure compression tests, we obtain the formulation of stress-strain curve for H-shaped steel members in consideration of local buckling. From the results of bending compression tests, we can determine the fire resistance of H-shape steel columns in term of the relation between safety usable steel temperature and constant axial load ratio.

ACKNOWLEDGEMENTS

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