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Fire Resistance of Concrete-Stiffened Steel Structures

Résistance à l'incendie des structures en acier renforcées de béton

Feuerwiderstand betonversteifter Stahlbauten

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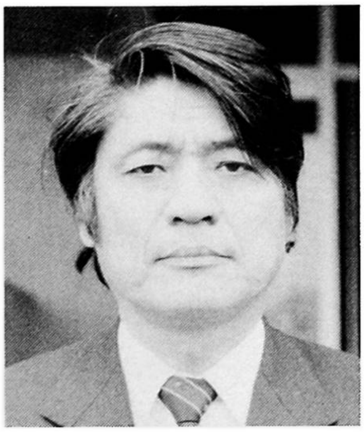
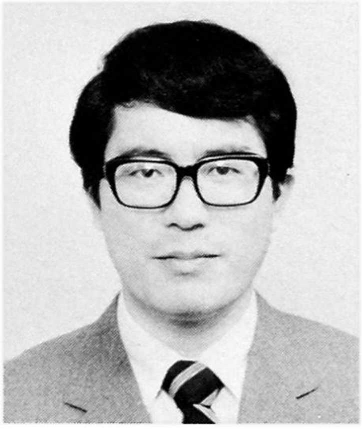




Toshiro Suzuki, born in 1936, received his doctor of engineering degree from the University of Tokyo. His major research activities include buckling, ultimate strength and plastic behaviour of steel structures. He was awarded the Prize from the A.I.J. for his study in 1981.

Mamoru Kimura, born in 1944, received his masters degree in engineering from Nagoya Institute of Technology. Since then he has been engaged in researches on the inelastic behaviour of steel structures, especially torsional problems. In recent years he has also been involved in composite structures.

Akio Kodaira, born in 1945, received his masters degree in engineering from Chiba University. His research is mainly concerned with structural fire safety, particularly with respect to analytical evaluation of fire resistance, water filled steel columns, fire-proofing materials.

SUMMARY
This report is concerned with the development of concrete-filled square steel pipe structures, particularly the fire resistance of such columns. When fire resistance is evaluated for the collapse of the member, load transfer to filled concrete can be expected to cope with the lowering of steel pipe strength at high-temperatures. This report clarifies mainly the basic behavior for this case.

RESUME
Ce rapport traite du développement des structures en tubes d'acier à section carrée remplis de béton, en particulier quant à leur résistance à l'incendie. Lorsque la résistance à l'incendie est évaluée par la rupture d'un élément, le transfert de la charge sur le béton de remplissage doit pouvoir compenser la diminution de résistance du tube en acier provoquée par le chauffage à haute température dans l'incendie. Ce rapport éclaircit principalement le comportement fondamental dans ce cas.

ZUSAMMENFASSUNG
Diese Arbeit befasst sich mit der Entwicklung von betongefüllten Vierkant-Stahlrohren für Bauwerke, insbesondere mit dem Feuerwiderstand solcher Stützen. Es ist zu erwarten, dass das Abnehmen der Festigkeit des Stahlrohrs im Laufe der Erhitzung durch das Feuer durch Übertragung der Last auf die Betonfüllung ausreichend ausgeglichen wird, wobei der Feuerwiderstand auf den Kollaps des Bauteils bezogen wird. Die Arbeit untersucht im wesentlichen den Grundmechanismus dieser Lastübertragung.

1. INTRODUCTION

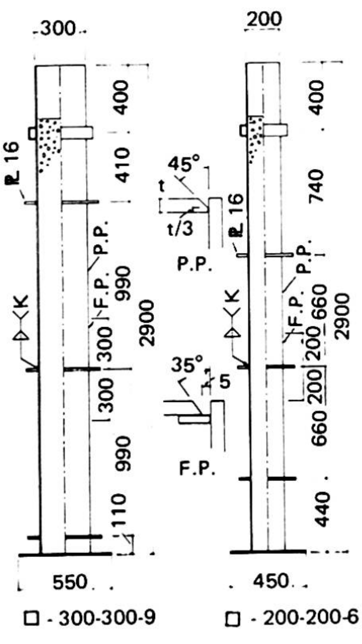
Steel structures have many advantages, but also have the following drawbacks in addition to corrosion: 1) Liability to buckle, 2) lower elastic rigidity and 3) liability to be deteriorated by high-temperature heating. One of the effective measures to improve these drawbacks is the concrete-stiffening of steel structural members. This report has investigated the development of the concrete-filled square steel pipe structures for this purpose, particularly the fire resistance of such columns.

Filled concrete is effective in achieving excellent fire resistance in the following two points: (1) When fire resistance is evaluated by the steel-pipe temperature, the heat capacity of filled concrete contributes to the suppression of a temperature rise of the steel pipe [1] [2] and (2) when fire resistance is evaluated by the collapse of the member, load burden transfer to filled concrete can be expected to cope with the lowering of steel pipe strength due to high-temperature heating in fire [3]. This report clarifies mainly the basic behavior of concrete-filled steel pipe for the latter case.

2. HEATING EXPERIMENT FOR CONCRETE-STIFFENED STEEL COLUMNS UNDER A CONSTANT AXIAL FORCE

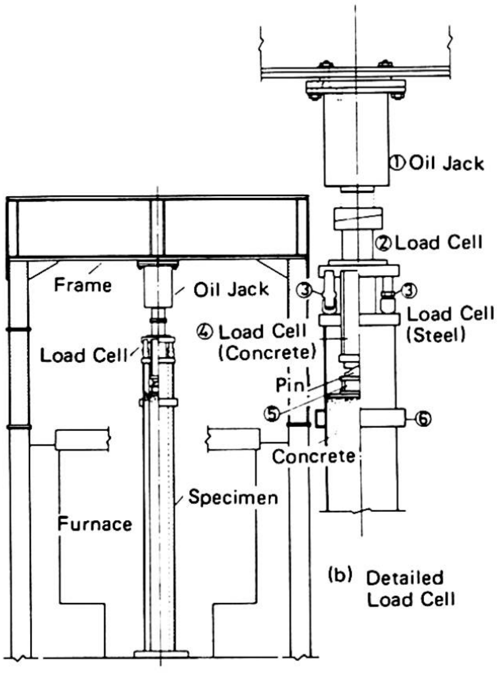
2.1 Parameters in the Experiment and Specimens

With the selection of sectional dimensions, axial force, heating time, and the presence or absence of



(in mm)

Fig. 1 Specimen



(a)

Fig. 2 Experimental Equipment

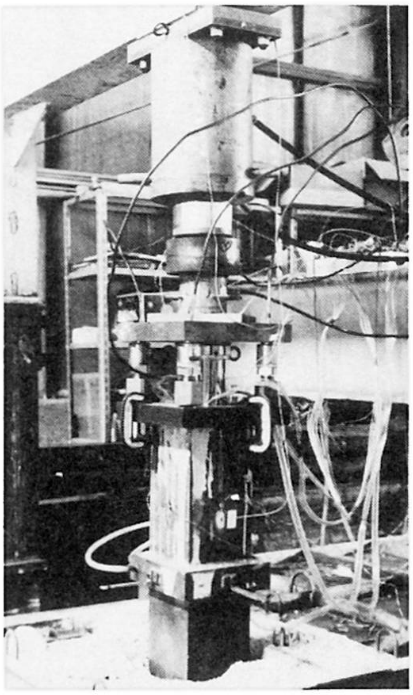


Photo 1 Loading System

Specimen No.	Heating Time (min.)	Pipe Width (mm)	Fire-Proofing Thickness (mm)	Axial Load (sPy*)
1	60	200	0	0.2
2	60	200	30	0.4
3	60	300	0	0.4
4	60	300	30	0.2
5	120	200	0	0.2
6	120	200	30	0.4
7	120	300	0	0.4
8	120	300	30	0.2

* sPy = A·F (A: Sectional Area of the Steel Pipe, F = 235 N/mm²)

Table 1 Parameters of Experiments

Steel Pipe Thickness (mm)	Yield Stress (N/mm²)	Tensile Strength (N/mm²)	Elangation (%)
6	351	468	25.9
9	333	455	25.7

Filled-Concrete	Comp. Strength (N/mm²)	Tensile Strength (N/mm²)	Young's Modulus (KN/mm²)
Wax Curing	27.4	1.99	28.9

Table 2 Mechanical Properties at Normal Temperature

fire proofing as parameters affecting the properties of members of a concrete-stiffened steel structure when it encounters fire and after it is cooled by fire extinguishing, eight specimens were made as shown in Table 1. Figure 1 shows shapes and dimensions of concrete-filled square steel column models whose sizes were 1/2.5 to 1/3 of actual members. Table 2 shows mechanical properties of materials used in the experiment.

2.2 Experimental Equipment and a Method of the Experiment

Figure 2 and Photo 1 outline the experimental equipment. A specimen was to be laid in the center of the heating furnace installed in Takenaka Technical Research Laboratory. The column top of the specimen was protruded above the furnace cover and compression by the reaction frame joined to the heating furnace was applied to the top of the specimen through the oil jack with a constant loading facility and the load cells. Figure 2(b) shows the load cell in detail. The load applying system, including load cells, was provided with much higher rigidity than that of the specimen. The transfer of axial force from the steel pipe to the filled concrete was closely detected by the set of load cells so equipped. The axial force to the filled concrete was introduced through the cylindrical load cell ④. at the center and the axial force to the steel pipe was introduced through four bolt-type load cells ③ . Allotment of initial axial force was carried out by means of screw adjustment of ③ and ④ . In addition, load cells were water proofed and provided with heat resisting property.

Heating in the experiment was carried out in compliance with the standard temperature-time curve specified in JIS-A-1304 (ISO-834) which assumes fire. A predetermined axial force was introduced primarily in the steel pipe before heating was started and the entire load had been kept constant until heating was completed.

3. BASIC BEHAVIOR

3.1 Temperature Property

Temperature measurement was carried out using C.A. thermocouples. Figure 3 shows the heating temperature in the furnace. It approximately satisfied the standard temperature-time curve.

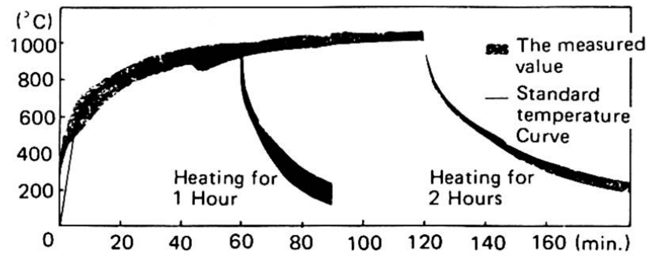


Fig. 3 Temperature inside the Furnace

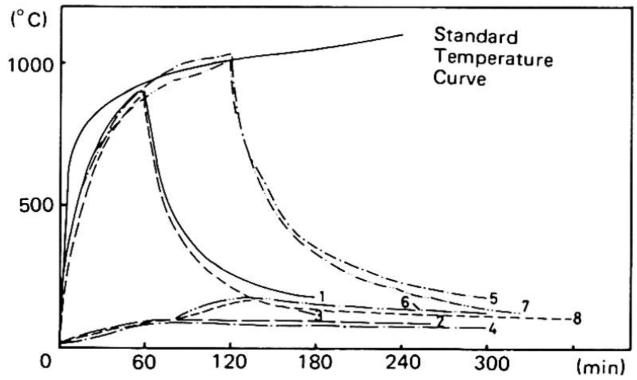


Fig. 4 Average Temperature on the Surface of Steel Pipe

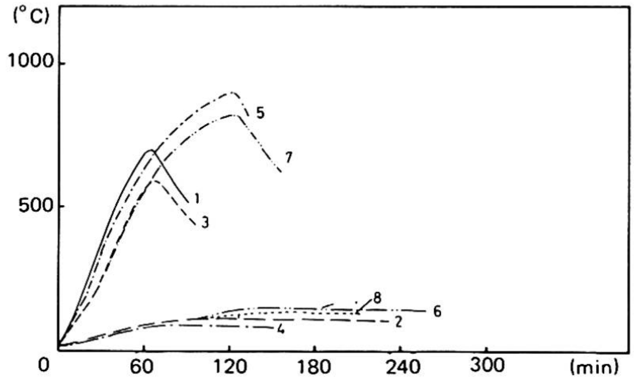


Fig. 5 Average Temperature at the Corner of Concrete

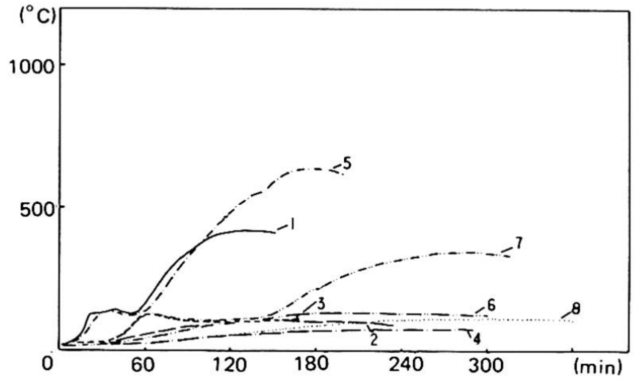


Fig. 6 Average Temperature in the Central Part of Concrete

Figure 4 shows the average temperature on the surface of the steel pipe of each specimen. The fire-proofed specimen presented the maximum temperature of 100°C after 60 minute heating and the maximum temperature of 180°C after 120 minute heating, which is extremely low. The temperature of the specimen without fire proofing rose somewhat later than the temperature rise inside the furnace, but approximately in parallel with the latter.

Figure 5 shows the average value of the observed temperature at a point in the corner of the square section of the concrete and 25 mm distant from the inner surface of the steel pipe, and Figure 6 shows the temperature at the center of the concrete. It proves that the temperature rise at the center of the concrete stopped rising once in the neighborhood of 150°C, and after that it restarted. This stagnation is considered to be due to the influence of free water contained in the concrete. The time duration of the stagnation was greatly different with the column size. The maximum reachable temperature at the point in the corner in the section of the concrete and that at the center of the concrete were both greatly different with the heating time and the column size. On the other hand, the temperature rise of the fire-proofed specimen was extremely moderate and the maximum reachable temperature of the specimen was lower.

3.2 Mechanical Properties

3.2.1 Axial Deformation of the Steel Pipe

Figure 7 shows the change in the length of the steel pipe with time. The deformation is the relative displacement between points which are located on the top of the specimen outside the furnace and on the top of a silica tube with a negligibly small thermal expansion elected on the pedestal base for the specimen inside the furnace and was observed by the water- and fire-proof displacement gages. The specimen without fire proofing presented an abrupt deformation due to heating expansion of the steel pipe after heating was applied, and the elongation of the steel pipe reached its maximum at 18 to 20 minutes after heating was started. The temperature of the steel pipe rose to 600°C then. After this, local buckling of the steel pipe caused an abrupt contractive deformation, but its degree was gradually reduced. After heating was terminated the steel pipe presented contractive deformation for long due to lowering of the temperature of the specimen. The steel pipe with fire-proofing was found to have a slight elongation due to the temperature rise of the steel pipe.

3.2.2 Axial Load Sharing of the Steel Pipe and the Filled Concrete

Figure 8 shows the change with time in load sharing ratio of the entire axial force to the axial force of the filled concrete. The specimen without fire proofing mostly maintained the sharing ratio of the beginning of heating. However, at 20 minutes after heating was applied when local buckling occurred in the steel pipe the load bearing capability of the steel pipe was greatly reduced and the load sharing of the filled concrete abruptly increased. After a predetermined time of heating was terminated, the contraction of the steel pipe took place due to sudden drop in the temperature inside the furnace, and the burden of the allotment of the axial force to the filled concrete further increased. However, specimen No. 7 as a whole lost its load bearing capacity at 106 minutes after heating was started. The fire-proofed specimen presented less temperature rise in its body and the initial load sharing ratio was maintained.

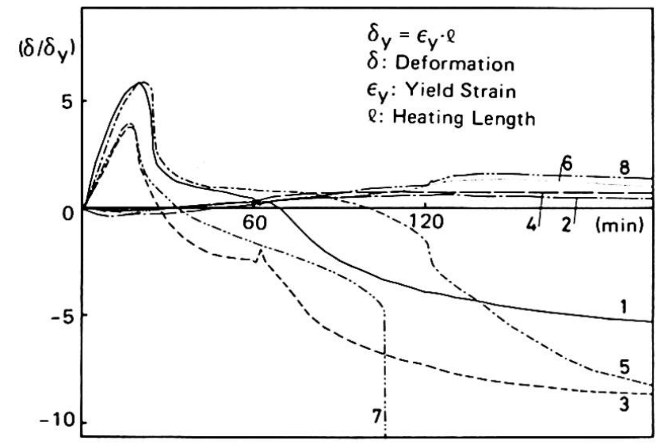


Fig. 7 Change in Length of Steel Pipe Columns

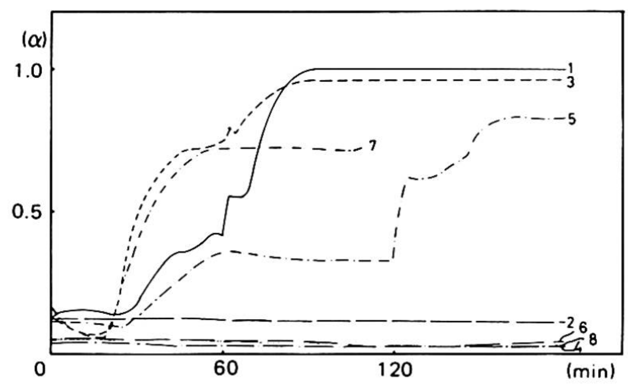


Fig. 8 Load Shearing Ratio of the Filled Concrete (α)

4. INVESTIGATION OF THE LOCAL BUCKLING

4.1 Specimens and Experimental Method

Three specimens were used in the experiment; one having a variable ratio of its width to thickness and the two others being stiffened with stud bolts. Tables 3, 4 and 5 shows these specimens. The stiffening stud bolts were designed assuming that the axial yield force of the steel pipe or the half of the axial yield force can transfer from the steel pipe to the filled concrete between story height. Therefore, the lower part of the specimen stiffened by stud bolts was fire-proofed in order to heat the ordinary story height. The method of applying compression, method of heating, and the method of measuring were the same as the preceding methods.

4.2 Influence of the Width-to-Thickness Ratio and of the Stud Bolt Stiffening

Figure 9 shows the change in length of the steel pipe in connection with the experimental result of the Specimen No. 1 (width-to-thickness ratio of 33.3) obtained in the preceding section. They are values converted into the magnitude of deformation for the ordinary story height. There is only a slight difference in the behavior between Specimen No. 9 (a width-to-thickness ratio of 44.4) and No. 1, and it was considered that the influence of the reduction in yield stress and that in Young's modulus accompanied by the temperature rise of the steel pipe were much greater than the influence of the width-to-thickness ratio. The effect of stud bolt stiffening could be seen to some extent of unification of concrete and steel pipe, and it was moderate in elongation and contractive deformation when compared with the unstiffened specimen, but no considerable difference in buckling behavior was observed between them. Photo 2 shows the behavior of the local buckling deformation of the steel pipe obtained after heating was applied. Specimen No. 11 having a stud bolt pitch of the half of the width of the steel pipe presented considerable constraint effect against local buckling deformation.

5. PRACTICAL FLOW OF THE EXTERNAL FORCE APPLIED TO THE SPECIMEN

5.1 Specimens and Experimental Method

Considering the practical flow of the external force to the column, the investigation was made for

Specimen No.	Heating Time (min.)	Width-to-Thickness Ratio	Stud Bolt Pitch	Axial Load (sPy)
9	60	44.4	–	0.2
10	60	33.3	B*	0.2
11	60	33.3	B/2	0.2

* B: Pipe Width (= 200 mm)

Table 3 Specimens without Fire-Proofing

Steel Pipe Thickness (mm)	Yield Stress (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)
4.5	287	451	36.6
6	319	452	27.4

Table 4 Mechanical Properties of Steel Pipe at Normal Temperature

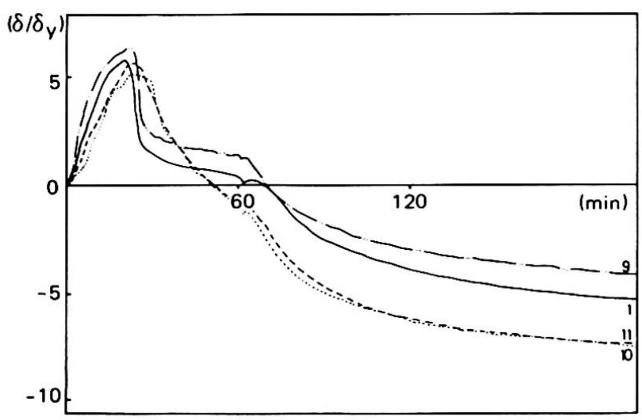


Fig. 9 Influence of the Width-to-Thickness Ratio and of Stud Bolt Stiffening

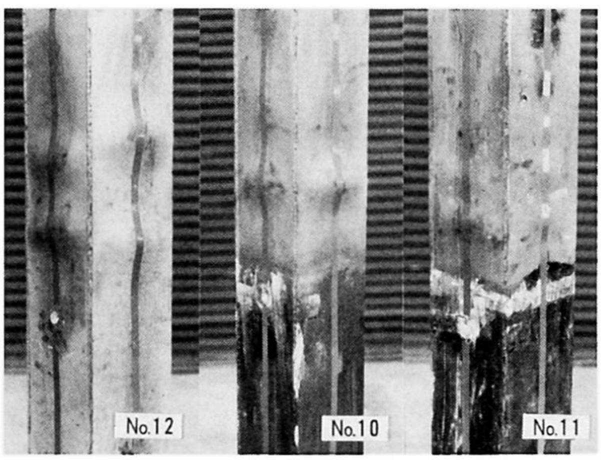


Photo 2 Local Buckling Deformation

the mechanical behavior of the specimen appearing when load was applied from the beam-to-column connection (external diaphragm type) to the column, and when the column was heated. With further consideration for the influence of the upper story of the column which was not heated, the column was extended upward by one more story height. Figure 10 and Tables 4, 5 and 6 show an outline of the specimen. Moreover, the external diaphragm connection aiming at force applying device was fire-proofed. Force was applied by four oil jacks to which the bolt-type load cell was mounted, which was used in the preceding section. When introducing only the axial force, the concentric compression by which the bottom of the specimen loaded was pressed flat was used and when loading the axial force and the constant bending moment, the eccentric compression was used which could be realized by inserting a pin bearing at the bottom.

Photos 3 and 4 show schematic views of the experimental equipment.

5.2 Comparison of the Behavior for Different Loading Conditions

Figure 11 shows the deformation characteristics of the external diaphragm type specimen in conjunction with the Specimen No. 1 which used flat holding. The difference between the external diaphragm type Specimen No. 12 and No. 1 could be observed to some extent in the neighborhood of the maximum elongation where they showed fairly good correspondence. The external diaphragm type specimen was measured for the relative displacement between the steel pipe and the filled concrete at the top of the specimen which corresponded to the column top of the upper story and no slippage was observed between the steel pipe and the filled concrete. Although a considerable amount of water was observed to rise between the steel pipe and the filled concrete, they behaved as a body. As a result the flat holding pressure type specimen was considered to enable evaluation of the practical loading of axial force.

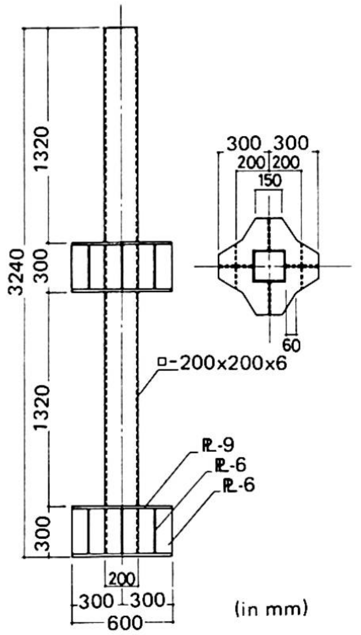


Fig. 10 External Diaphragm Connection Type Specimen

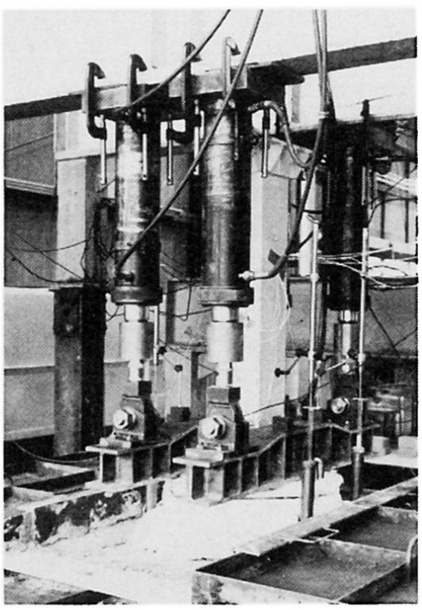


Photo 3 Loading Equipment

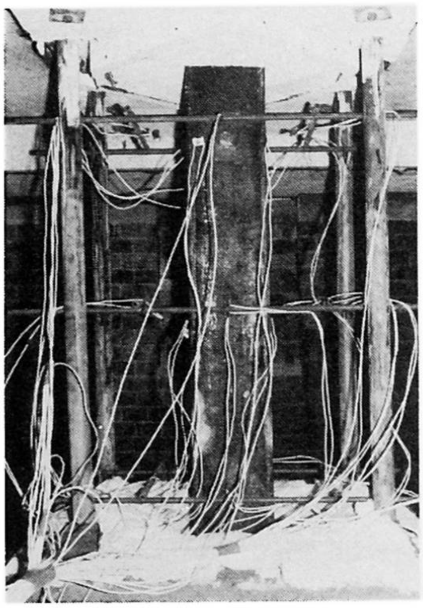


Photo 4 Internal View of the Furnace

Specimen No.	Heating Time (min.)	Pipe Width (mm)	Bending Moment (sMy*)	Axial Load (sPy)
12	60	200	0	0.2
13	120	200	0	0.4
14	60	200	1/3	0.2
15	60	200	1/6	0.2

* sMy = Z·F (Z: Sectional Modulus)

Table 5 External Diaphragm Type Specimen without Fire-Proofing

Filled-Concrete	Comp. Stress (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modulus (KN/mm^2)
Wax Curing	28.2	2.33	28.7

Table 6 Mechanical Properties of Filled-Concrete at Normal Temperature

5.3 Introduction of Bending Moment

A constant bending moment was introduced, whose strength is 1/6 or 1/3 of the yield bending moment of the steel pipe. The specimen under 1/6 yield bending moment lost its load bearing capacity at 40 minutes after heating was started, while the one under 1/3 yield bending moment, 30 minutes (Fig. 11). Figure 12 shows the change in the rotation of the specimen in the external diaphragm connection, with time. The rotation was non-dimensionalized by an elastic rotation of θp corresponding to the plastic moment of the steel pipe at the normal temperature. When 20 minutes passed after heating was started, it caused local buckling in the steel plate element on the compression side and the rotation increased, but eventually the steel plate exhibited deformability until the rotation reached to 5 θp. Considering the framed structure at the occurrence of fire, it would possibly be expected that due to the sufficient rotational capability of the connection the movement to the pin bearing condition is possible and the amount of bending moment introduced into the column can be reduced.

5.4 Fire Resistance

Fire resistance of the concrete-filled steel pipe column without fire-proofing can be evaluated as the capability that the load which acts in fire transfers to the filled concrete. Therefore, it can be considered that the greater the ratio of load bearing capacity of the filled concrete to the steel pipe is, the more it is advantageous. A steel pipe having a width-to-thickness ratio of 33.3 falls within the range having a sufficient plastic rotational capacity at normal temperature and it is safer than a thin steel pipe, considering the load in terms of the ratio of axial yield force of the steel pipe. As a result of the experiment for Specimen No. 13 shown in Figure 11 and that for Specimens No. 5 and No. 7 shown in Figure 7, it was found that the steel pipe had sufficient fire resistance of longer than 2 hours for 20% of the axial yield force of the steel pipe and longer than 1 hour for 40% of the axial yield force.

It was also found that the temperature of the column immediately above the external diaphragm connection was nearly equal to normal temperature and that the influence of heat transmission on the upper story of the column was very small.

6. BENDING CAPACITY OF THE COLUMN AFTER COOLING

6.1 Test Member and Experimental Method

Investigation was made for the bending capability of the column in order to evaluate the earthquake resistance of the column after suffering fire. Specimens were taken from those used in the experiments described in Chap. 2. Mechanical properties of steel material used are as shown in Table 8 and tension coupons were cut out of the specimens without fire-proofing. A simple-beam was loaded with central concentrated type load and the bending span was set to the assumed ordinary story height.

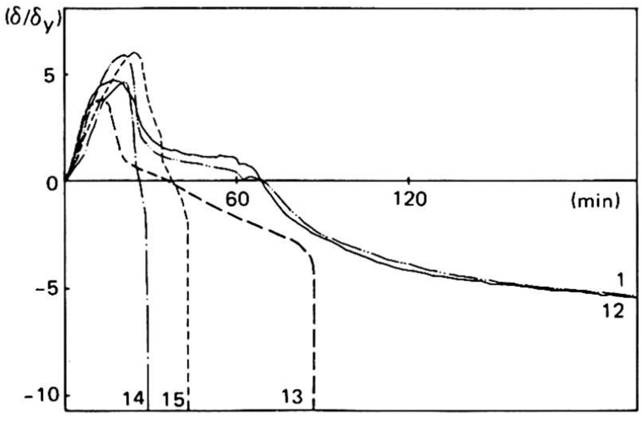


Fig. 11 Influence of Loading Conditions and Bending Moment

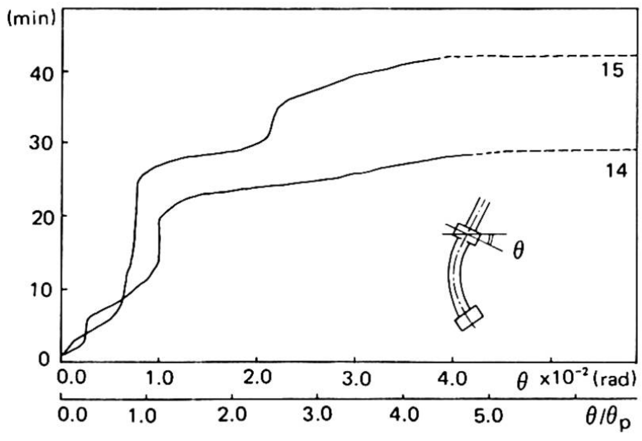


Fig. 12 Rotation Capacity

Specimen No.	Steel Pipe Width (mm)	Bending Span (mm)
1, 2, 5, 6	200	1320
3, 4, 7, 8	300	1980

Table 7 Specimens for Bending Test

Steel Pipe Thickness (mm)	Yield Stress (N/mm²)	Tensile Strength (N/mm²)	Elongation (%)	Heating Time (min.)
6	228	375	26.9	60
6	202	386	22.8	120
9	268	399	35.7	60
9	201	396	34.4	120

Table 8 Mechanical Properties of Steel Materials after Cooling

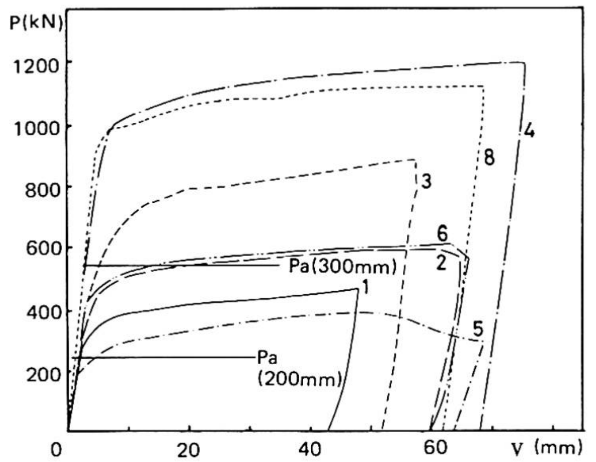


Fig. 13 Load-Deformation Relationship

6.2 Flexural Behavior

Figure 13 shows the results of the experiments. If the fire-proofed specimen was evaluated to have characteristic of the specimen obtained before heating, the yield strength of the specimen without fire-proofing was reduced down to 60% to 70% when the central deflection presented 6 v_p, where, v_p is the elastic deformation corresponding to the plastic moment of the steel pipe at normal temperature. In Figure 13, design load, P_a, is shown which corresponds to the seismic load.

7. CONCLUSION

This paper has introduced the investigation carried out experimentally for temperature characteristics of the concrete-filled square steel pipe column in fire, its mechanical characteristics, and flexural characteristics after cooling, and clarified the following items.

(1) If the square steel pipe column is fire-proofed equivalent to that applied to a steel structure, the pipe column is sufficed redundant characteristics.

(2) If the square steel pipe column is without fire-proofing, when about 20 minutes passed after heating starts, local buckling occurs in the steel pipe and presents abrupt contraction. However, if the compression is 20% of the axial yield force of the steel pipe, the column maintains fire resistance over two hours, and if the ratio is 40%, it maintains fire resistance over longer than one hour.

(3) The presence of the upper story of the column makes it possible to transmit the load introduced from the beam sufficiently to the filled concrete.

(4) Sufficient rotational capacity of the column top would be able to reduce the bending moment from the beams.

(5) Although the bending characteristics of the column without fire-proofing is reduced by about 60% to 70%, the column strength still sufficiently exceeds the design load corresponding to the seismic load.

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