Structural Behaviour of Steel Frame in Building Fire

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ABSTRACT

More than fifty experiments were made with model steel frames of two dimensional two story and of three dimensional three story in which girders or a column or both a girder and columns were heated by electric furnaces under a constant heating rate. These experiments made it possible to analyze thermal stress within the steel frame theoretically. Large thermal stress appeared in the frame corresponding to the "binding modulus" of the frame. The structure was more influenced by the thermal expansion generated by the heated girder than by that of the heated column in the elastic region. In some cases the buckling of heated girder or column occurred.

And also heated tests of columns in a six story full scale steel frame were made. The local buckling of column occurred from which the whole structure was influenced.

keywords: Thermal stress, Fire resistance, Building fire, Steel frame, Buckling

1. INTRODUCTION

As often pointed out, the accepted method of fire design based on standard fire resistance tests of structural elements has many problems. If fire design is going to keep pace with modern trends in other engineering design disciplines, we must appraise structural fire safety by an analytical structural fire engineering design method based on the structural behavior of the complete steel frames in fire. Recently, several such methods have been proposed.[1,2] These methods are important to the establishment of the analytical fire engineering design method. To investigate the applicability of these methods, a series of experimental studies based on heat tests of steel frames were started in 1981. These tests were:

1981: 22 Heat tests of a girder in a two dimensional two story model steel frame[3]

1982: 16 Heat tests of girders in a three dimensional three story
    steel frame[4]
1983: 13 Heat tests of girders or a column or both a girder and
    columns in the same frame[5]
1984: 2 additional tests of 1983 and 4 heat tests of a column in
    a full scale six story steel frame.

This paper summarizes the experimental results of these heat
tests.

2. EXPERIMENTS OF MODEL STEEL FRAME

2.1 Experimental Set-up

(1) Model steel frame
    Fig.1 shows the two-dimensional model steel frame tested in
1981. Many interesting results were obtained to use this frame[3],
but the test results showed us that the ratio of girder and column
length was not suitable for model tests and the effect of the
distortion of frame could not be eliminated. Then the new three-
dimensional model steel frame was designed as shown in Figs. 2-1
and 2-2. The columns and girders were connected by high-tension
bolts so that it is possible to change the element.
(2) Electric furnace
    Box shaped furnaces, composed of thermal insulation board in
which electric heat panels were set were used. Fig.3 shows
examples of the temperature distribution in the girder and column.
(3) Loading set-up
    The loading set-up was composed of hydraulic jacks and a
loading frame, as shown in Fig.2. The compressive loads were
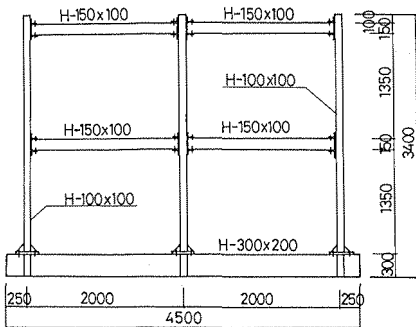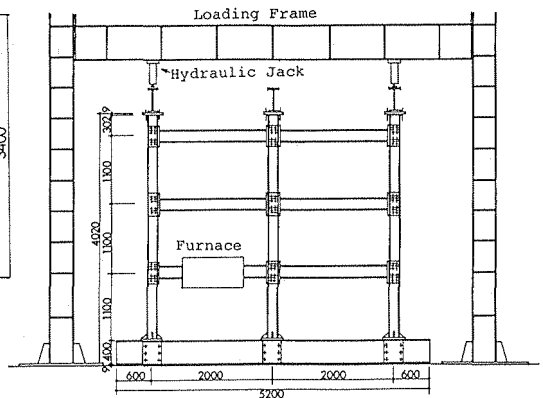applied on the top of columns by hydraulic jacks.

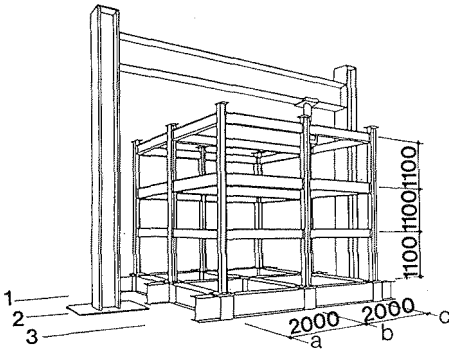Fig.1 Two dimensional model   Fig.2-1 Three dimensional model
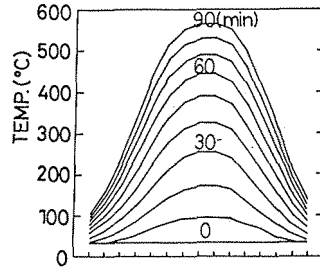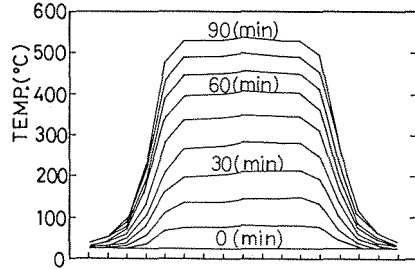
Fig.2-2 Three dimensional model

Fig.3 Temperature distribution
(upper:girder, lower:column)

2.2 Experimental Procedure

(1)Experimental model
    Table 1 shows the types of frame and the positions of
electric furnaces for each experiment in the series of 1982, and
Table 2 shows one of in 1983.
(2)Experimental measurements
    (a)Temperature: Room   temperature,   non-heated steel frame
temperature, temperature of heated girder and column, and the
ambient temperature in the furnace were measured by thermo-
couples(CA). (b)Strain: The compressive and tensile strains of the
steel members were measured by strain gauges which were attached
on the surface of steel members. They were located at the top and
bottom of the columns and the near positions of both end of the
girders.   (c)Displacements: The   horizontal   and   vertical
displacements of the column-girder connection points were measured
by the dial gauges.

2.3 Experimental Results

    The   distribution of bending moment inside frame   were
calculated from the measured values of strain gauges and the
deformation of frame were obtained from horizontal and vertical
displacements measured at the column-girder connection points.
The examples of their diagrams are shown in Figs. 4 and 6.

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Table 1 Experimental model of 1982

A – 1	A – 2	B – 1	B – 2	B – 3	B – 4
15.1 ton	15.0 ton				
B – 5	C – 1	C – 2	C – 3	C – 4	D – 1
D – 2	D – 3	E – 1	E – 2	F – 1 F – 2 F – 3	
		17 34 15	15 30 15	P	F-1 0 t F-2 15.0 t F-3 23.7 t

COLUMN
H-100×100 ——— H ······· L
H-150×150 ——— H ······· L

GIRDER
H-100×50
H-150×100
H-200×100

Table 2 Experimental model of 1983

TEST NO.	FRAME TYPE	HEATED MEMBER	LOAD P	COLUMN	GIRDER
G-1	A	1		B	A
G-2	B	1		B	A
H-1	A	2		B	A
H-2	B	2		B	A
H-3	A	3		B	A
H-4	A	4		B	A
H-5	C	1	38.95t	B	A
I-1	A	1,2,3		B	A
I-2	B	1,2,3		B	A
I-3	A	1,2		B	A
J-1	A	1	28.29t	A	A
J-2	B	1	43.36t	A	B
J-3	B	1	31.50t	A	A

Type A

Type B

Type C

Column
(A)H-100×100 (Low Stiffness)
(B)H-150×150 (High Stiffness)

Girder
(A)H-200×200
(B)H-250×125

δ cm / Displacement / Nt ton / Thermal Stress / Bending Moment

△ Heated Member
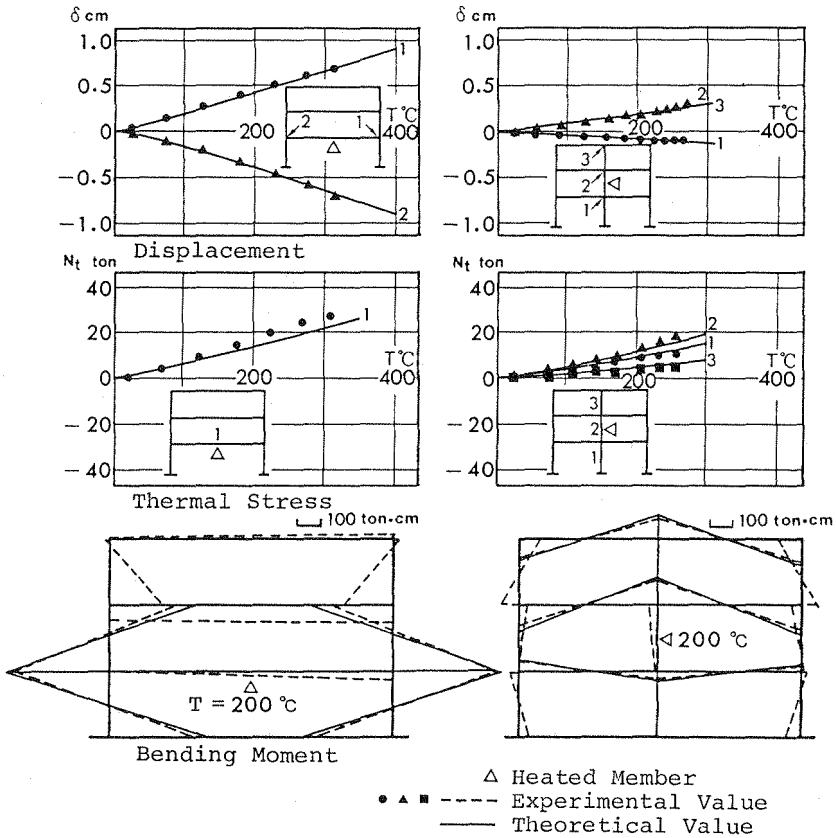● ▲ ■ ---- Experimental Value
———— Theoretical Value

Fig.4 Theoretical and experimental Values of displacement, thermal
stress and bending moment

3. RESULTS AND DISCUSSION

3.1 Heat Tests of Column or Girder

Fig.4 shows some examples of the theoretical and experimental
values of displacement, thermal stress and bending moment when a
girder or a column was heated. The theoretical values were
obtained from the method of Saito[6-8] based on the idea of
coefficient of stiffness for expansion as shown in Appendix. T in
Fig.4 means the mean temperature rise of heated steel member. The
theoretical values agree with the experimental ones very well in
the elastic region.[4]

The buckling of heated girder occurred in the case of D-1,2
and 3 in Table 1. The comparison between experimental and
theoretical values of the buckling stress is shown in Fig.5. The
sum of the thermal stress increases as the temperature rise
increases and eventually reaches the theoretical values of the
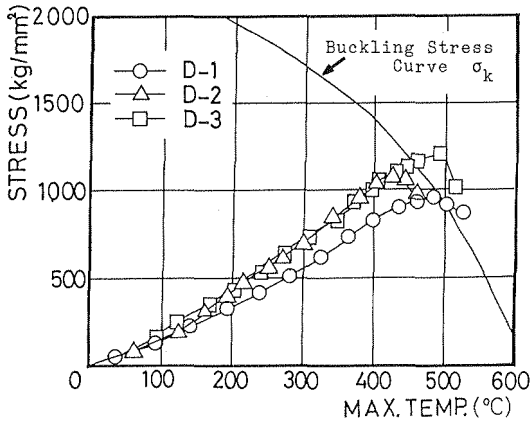buckling stress which decreases as the temperature rise.

Fig.5 Comparison between experimental and theoretical values of buckling stress

3.2 Heat Tests of Both Columns and a Girder

The correlations between the theoretical values and the experimental ones of deformation and bending moment when columns and a girder were heated are shown in Fig.6. In this case, the theoretical values were obtained from a more sophisticated method named "direct stiffness method".[5] From Fig.6, it is seen that the theoretical values agree with the experimental values and that the thermal stresses resulted from the thermal expansion of the heated girder and the restriction of heated members imposed by the remainder of the frame. The results also show that the structure is more influenced by the thermal stress induced by a heated girder than that of heated columns in the elastic region.

Deformation   ⌐ 2mm   Bending Moment   ⌐ 100 t·cm
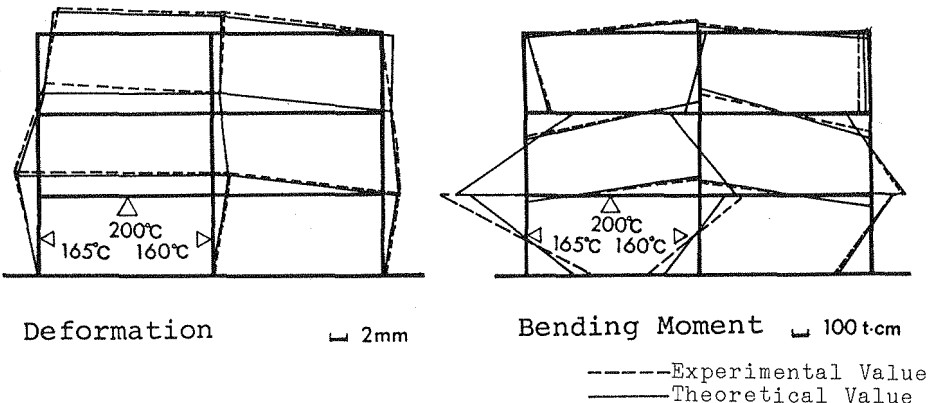
------Experimental Value
———Theoretical Value

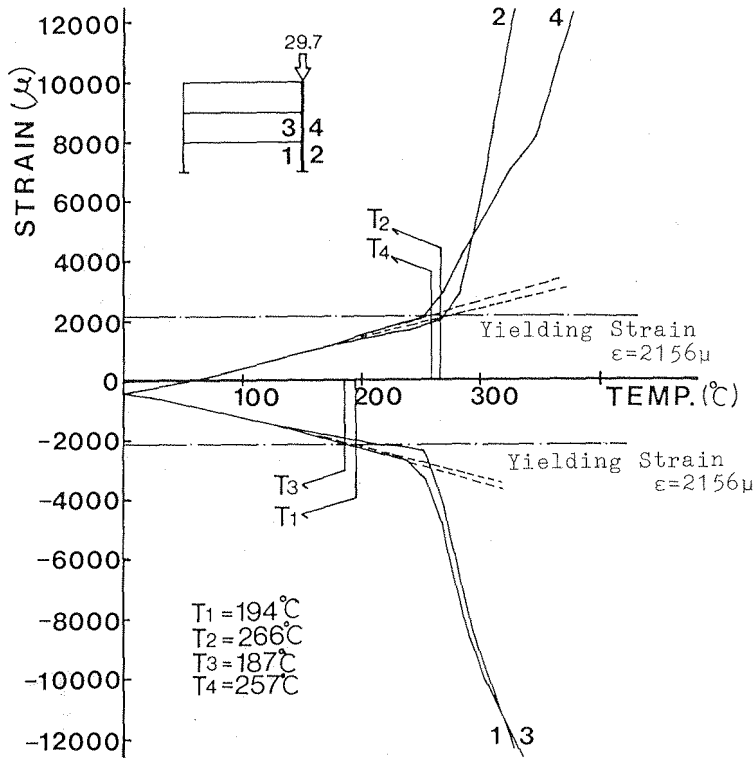Fig.6 Correlation between theoretical and experimental value of deformation and bending moment

Fig.7 Relation between measured strain of column and estimated mean temperature of heated girder

3.3 Yield of Restraining Column

Damage to the restraining columns was different from that of the heated members. This was demonstrated in the experiment in 1984 as shown in Fig.7. On the basis of measurement of strain, it could be expected that the column would yield at their end. Fig.7 shows the relation between the measured strain of the column and the estimated mean temperature of heated girder. The following facts could be deduced; the bending strain in the column increases linearly as the increase of temperature of the heated girder, and the strain increases rapidly after the yielding occurs.

4. EXPERIMENTS OF FULL SCALE STEEL FRAME

Fig.8 shows the full scale six story steel frame of two spans used in heat tests. This structure was originally elected for the US-Japan cooperative study on the structural behavior under the

earthquake force. After the completion of their tests, heat tests were made in this structure. The connected part of the columns and the girders was pin joint in one plane and rigid joint in another plane. The composite floor was composed of wide-flange steel girders and light weight reinforced concrete slabs. Four columns were heated separately by the above mentioned furnace which place are shown in Fig.8. No loading was applied. The vertical displacements of the column-girder connected points were measured by dial gauges, and the strain of the steel members were measured by strain gauges.

In all heated tests, local buckling of column occurred, as shown in Photo.1. The correlation between vertical displacements of top of the column and the mean temperature T is shown in Fig.9. The buckling of heated column started when the mean temperature T reached 350~430 °C. This local buckling occurred at the part where the maximum steel temperature was about 550 °C same as the model test of H-5.

It is important to attention that after the stop of heating the buckling displacement still continued under the cooling stage. For this shrinkage of column, whole braces from second floor to sixth floor in same plane of heated column buckled remarkably in case of K-2.

These phenomenon shows that the fire protection of column is very important for the structural fire safety.
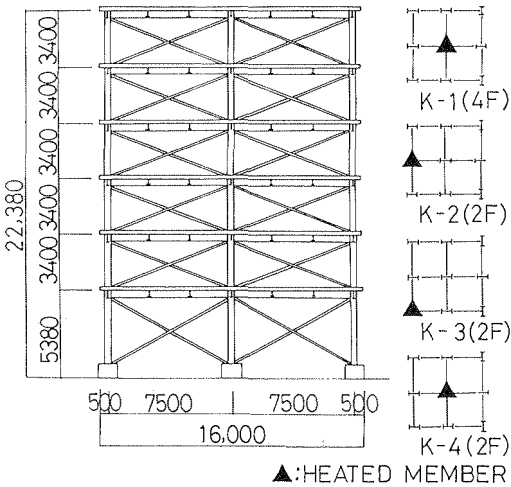

Fig.8 Full scale six story
steel frame of two spans
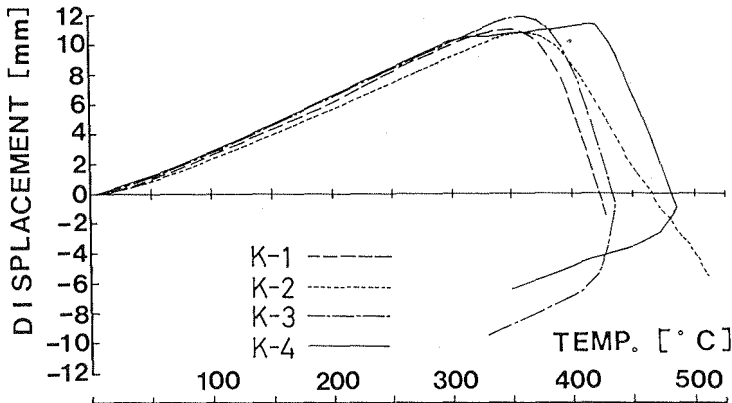

Photo.1 Local buckling of
column (K-1)

Fig.9 Correlation between vertical displacement of top of column
and mean temperature

5. CONCLUSIONS

The following conclusions may be drawn on the basis of
experimental results and analysis described above.
It is possible to predict the behavior of a structural steel
frame under a fire using the analytical theory on thermal stress
inside frame. Under some probable conditions, the structural damage
may actually occur in a fire due to large thermal stress.

6.ACKNOWLEDGMENTS

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APPENDIX

Thermal stress in steel-frame

Theoretical values of the thermal stresses in the frame can be obtained from the formula (1). Supposing that the columns are supported elastically, each coefficient of stiffness for expansion k in the formula (1) is calculated from the formula (2).

$$
\begin{bmatrix}
K_1+\frac{Et_1A_1}{L_1} & -\frac{Et_1A_1}{L_1} & 0 & \cdots & 0 & 0 \\
K_1 & K_2+\frac{Et_2A_2}{L_2} & -\frac{Et_2A_2}{L_2} & \cdots & 0 & 0 \\
\vdots & \vdots & & \vdots & & \vdots \\
K_1 & K_2 & \cdots & K_n+\frac{Et_nA_n}{L_n} & -\frac{Et_nA_n}{L_n} \\
K_1 & K_2 & \cdots & K_n & K_{n+1}
\end{bmatrix}
\begin{Bmatrix}
X_1 \\ X_2 \\ \vdots \\ X_n \\ X_{n+1}
\end{Bmatrix}
=
\begin{Bmatrix}
Et_1A_1\left\{\alpha t_1+\varepsilon_{11}\left(1-\frac{E_1}{Et_1}\right)\right\} \\
Et_2A_2\left\{\alpha t_2+\varepsilon_{12}\left(1-\frac{E_2}{Et_2}\right)\right\} \\
\vdots \\
Et_nA_n\left\{\alpha t_n+\varepsilon_{1n}\left(1-\frac{E_n}{Et_n}\right)\right\} \\
0
\end{Bmatrix}
\quad (1)
$$

where, E_i; elastic modulus
Et_i; elastic modulus at high temperature
L_i; length of heated girder
K_i; coefficient of stiffness for expansion
A_i; area of cross section
X_i; horizontal displacements

$$
K_1=\left[\frac{(a+b)^3}{3}-\frac{1}{8}\frac{2(a+b)Z_1Z_2-bZ_1-aZ_2-a+b}{4Z_1Z_2-1}\right]^{-1}\times\frac{ZI_c}{h_1+h_2} \quad\text{——}(2)
$$

where, $Z_1=\dfrac{\bar{k}_1+\bar{k}_2+\bar{k}_3+\bar{k}_4}{\bar{k}_4}$, $Z_2=\dfrac{\bar{k}_4+\bar{k}_5+\bar{k}_6+\bar{k}_7}{\bar{k}_4}$

$a=\dfrac{h_1h_2^2}{(h_1+h_2)}$, $b=\dfrac{h_1^2h_2}{(h_1+h_2)}$

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