EXPERIMENTAL STUDY ON THERMAL STRESS WITHIN STEEL-FRAMES

by

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ABSTRACT

About 16 experiments were made with model steel-frames of three stories in which one or two girders were heated in constant heating rate by electric furnace. These experiments made it possible to analyze thermal stress within the steel-frames. It can be summarized that large thermal stress appeared in the frame corresponding to binding modulus of the frame. In some cases, the bucklings of heated girders were occurred. When heated girder didn't buckle, yield parts sometimes appeared in the non-heated columns which restrained expansion of it.

1. INTRODUCTION

The accepted method of deciding the fire resistance of structural elements is based on the standard fire resistance test. But the method has the following problems.

- performance of the fire resistance test for any structural elements needs the considerable expenses.
- The test procedure is insufficient with respect to the heat-flow characteristics of the furnace and the restraint conditions of the test specimen in it.
- A fire resistance test only gives a information on the fire resistance of structural elements. It is difficult to extend the results to structural frames.

Because of these problems there is a strong

need to move from methods based on fire resistance tests of structural elements towards analytical structural fire engineering design methods and several such methods have been proposed^[1]. To investigate the availability of these methods the experimental study based on heat test of the two-dimensional model steel-frame was carried out at last year^[2].

Since then a series of fire tests have been carried out with the three-dimensional model steel-frame.

2. EXPERIMENTAL ARRANGEMENTS

2-1 Experimental Set-up

(1) Model steel-frame

Fig. 1 shows a three-dimensional model steel-frame used in this study. The columns

steel-frame

Fig. 1 Elevation of high inertia section of the three-dimensional model steel-frame (B-section)

and girders have H-shaped sections, and the braces are made of steel bar (13 ϕ). Each element is connected by High-Tension Bolts. Therefore it is possible to change the damaged element for new one.

The followings are the mechanical properties of the steel which was used in the model steel-frame. They are experimental values obtained by tension test.

(a) Elastic modulus

$$E = 1.86 \times 10^6 \text{ kgf/cm}^2$$

(b) Tensile strength

$$\sigma_p = 5.00 \times 10^3 \text{ kgf/cm}^2$$

(c) Yield strength

$$\sigma_s = 4.01 \times 10^3 \text{ kgf/cm}^2$$

(d) Expansion rate at failure

$$\delta = 20.2\%$$

(2) Electric furnace

As shown in Fig. 2, the box-shaped furnace is composed of thermal insulating boards in which electric heat panels (1kw $\times$ 6) are set. Fig. 3 shows the temperature distributions of the girders which are heated by the electric furnace.

Fig. 2 Detailed planes of the furnace

(3) Loading set-up

The loading set-up is composed of oil jacks and loading frame. The compressive loads are applied on the tops of columns by the jacks.

Fig. 3 Temperature distribution

2-2 Experimental procedure

(1) Experimental model

Fig. 4 shows the types of the frame and the positions of the electric furnace for each experiment. Two sections 2 and B in this frame are chosen as the subject to the experiments. These 16 experiments can be classified into the following 5 groups.

- Group A: preliminary tests (using two-dimensional model steel-frame),
- Group B: heating tests on the frame with high stiffness columns (2 section),
- Group C: heating tests on the frame with low stiffness columns (B section),
- Group D: heating tests on the frame with slender girders (2 section),
- Group E: heating and load bearing tests on frame with low stiffness columns (B section),

Fig. 4 Experimental models

Note;

a) Loading of A-2 is 23.9(ton) after 120 (min).

b) Δ: furnace.

Column

H-100x100

H-150x150

[H]: high stiffness

[L]: low stiffness

Girder

H-100x50

H-150x100

H-200x100

(2) Experimental measurements

(a) Temperature

The room temperature, the non-heated steel temperature, the temperatures of heated girder and the ambient temperature in the furnace are measured by thermo-couples (CA).

(b) Strain

The compressive and tensile strains of non-heated members are measured by the strain gauges (length: 10 mm) which are attached on the surfaces of the steel-frame. These were located at the tops and bottoms of the columns and near the both ends of the girders.

(c) Horizontal displacements

The horizontal displacements of the column-girder contact points are measured by the dial gauges (stroke: 10 mm).

2-3 Experimental Results

Bending moment diagrams were obtained from the measured strains and deformation diagrams from horizontal displacements of the contact points in the frame. The examples of them are shown in Fig. 5.

Fig. 5 Bending moment and deformation diagrams (Group-B)

3. THEORETICAL ANALYSIS

3-1 Thermal Stress

(1) Thermal stress in heated girder

The validity of the theoretical formula (3.2) was investigated in regard to the heated girder in steel-frame.

The axial stress in the heated girder can be obtained from the following formula,

$$\sigma_t = k \times \Delta \ell / A \quad (3.1)$$

where,

k : coefficient of stiffness for expansion,

$\Delta \ell$: observed expansion of heated girder,

A : area of cross section of heated girder,

σ_t : stress occurring in heated girder

First of all, the thermal stress in the heated girder is obtained from the following formula^[3], using binding modulus K ,

$$\sigma_t = \alpha T / (1/K + 1/E_t) \quad (3.2)$$

$$K = k \ell / A \quad (3.3)$$

where,

- K : binding modulus for expansion,
- k : coefficient of stiffness for expansion,
- ℓ : length of heated girder,
- A : area of cross section of heated girder,
- E_t : elastic modulus at high-temperature,
- α : coefficient of thermal expansion at high-temperature

The coefficient of stiffness for expansion k is the value of the resistance of the steel-frame to expansion of the heated girder, it is obtained from stiffness tests.

Fig. 6 shows the relation between the thermal stress and mean temperature in each experiments. In Fig. 6, the symbols show the values obtained from the formula (3.1) and the solid lines show the values from the formula (3.2). Fig. 6 shows the followings;

- The bigger the binding module for expansion, the bigger the rate of increase of thermal stress,

Fig. 6 Relation between σ_t and T (Group-B)

Note; T : mean temperature

- In the absence of any initial value, it increase linearly,
- The values obtained from the formula (3.1) agree with the values from the formula (3.2) very well.

(2) Thermal stress in steel-frame

Theoretical values of the thermal stresses in the frame can be obtained from the formula (3.4). Supposing that the columns are supported elastically, each coefficient of stiffness for expansion k_i in the formula (3.4) is calculated from the formula (3.5).

(a) displacements

(b) axial loads

(c) bending moment diagram

Fig. 7 Fire behaviour of steel-frame (experiment B-1)

The validity of the theoretical formula (3.4) is investigated by comparing the theoretical values with experimental in regard to fire behaviour of the model frame (see Fig. 7).

From Fig. 7 it is seen that the theoretical values agree with the experimental values very well.

$$\begin{bmatrix} K_1 + \frac{E_{t1} A_1}{L_1} - \frac{E_{t1} A_1}{L_1} & 0 & \dots & 0 \\ K_1 & K_2 + \frac{E_{t2} A_2}{L_2} - \frac{E_{t2} A_2}{L_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ K_1 & K_2 & \dots & K_n + \frac{E_{tn} A_n}{L_n} - \frac{E_{tn} A_n}{L_n} \\ K_1 & K_2 & \dots & K_n & K_{n+1} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \\ X_{n+1} \end{bmatrix} = \begin{bmatrix} E_{t1} A_1 \left\{ at_1 + \epsilon_1 \left(1 - \frac{E_1}{E_{t1}} \right) \right\} \\ E_{t2} A_2 \left\{ at_2 + \epsilon_2 \left(1 - \frac{E_2}{E_{t2}} \right) \right\} \\ \vdots \\ E_{tn} A_n \left\{ at_n + \epsilon_n \left(1 - \frac{E_n}{E_{tn}} \right) \right\} \\ 0 \end{bmatrix} \quad (3.4) [4]$$

where, E_j ; elastic modulus
 E_{tj} ; elastic modulus at high temperature
 L_i ; length of heated girder
 K_i ; coefficient of stiffness for expansion
 A_j ; area of cross section
 X_i ; horizontal displacements

$$k = \left[\frac{(a+b)^3}{3} - \frac{1}{8} \frac{2(a+b) Z_1 Z_2 - b Z_1 - a Z_2 - (a+b)}{4 Z_1 Z_2 - 1} \right]^{-1} \times \frac{E I c}{(h_1 + h_2)^3} \quad (3.5)$$

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

$$a = \frac{h_1 h_2^2}{(h_1 + h_2)^3}, \quad b = \frac{h_1^2 h_2}{(h_1 + h_2)^3}$$

3-3 Mechanical Behaviour

(1) Brace

It is considered that the diagonal braces in the steel-frame restrain the thermal expansion of the heated girder, acting like columns. Table 1 shows that the brace has large values of the binding modulus for expansion. Compared with a steel-frame without braces (see Fig. 8 (a), (b)), larger thermal stresses occur in heated girder.

Table 1. Coefficient of stiffness for expansion

element	k (ton/cm)
column-high inertia	33.40
column-low inertia	15.63
brace	14.28

Thus, large reaction forces act on other parts of the steel-frame and are distributed toward the frame according to the size of each value. Fig. 8 (c), (d) shows that there is little influence on the distributions of moment and axial stress resulting from the presence of the braces.

(2) Girder

Usually, in the structural calculation, the girder is investigated as an element which resists bending force and it is not considered as an element which resists a compressive restraining force. But in fire, it seems to be probable that the restraining forces could cause girders to buckle. In the experiments

Fig. 8 Comparison of thermal stresses within steel-frames possessing braces and possessing non braces (experiment B-1, B-4, C-1, C-3)

with D type frames the center part of the heated girders buckled partially.

The temperature at which the buckling occurs in a heated girder was chosen as that temperature at which axial stress of the heated girder attains the maximum (see Fig. 9). Table 2 shows the buckling temperature obtained by this way. The theoretical buckling stress at high-temperature σ_k is shown in the following formula^[5],

Long column:

$$\sigma_k = \pi^2 E_t / \lambda^2 \quad (\lambda \geq \Delta_t) \quad (3.6)$$

Short column:

$$\sigma_k = \sigma_{yt} - \sigma_{yt}^2 \lambda^2 / 4\pi^2 E_t (\lambda < \Delta_t)$$

Table 2. Buckling temperature

experiment	K (ton/cm ²)	T in buckling (T max) (°C)
D-1	374.0	279 (578)
D-2	563.7	220 (480)
D-3	528.6	253 (550)

where,

E_t : elastic modulus at high-temperature,

σ_{yt} : yield strength at high-temperature,

$$\Delta_t = \sqrt{\pi^2 E_t / 0.6 \sigma_{yt}}$$

λ = slenderness ratio

E_t is obtained from 1.86×10^6 kg/cm² (tension test value) and Table 3⁶⁾, and σ_{yt} is also obtained from 4.01×10^3 kg/cm² (tension test value) and Table 3.

Fig. 9 Relation between axial loads of girders and T (Group-T)

Note; Axial loads of heated girders are calculated based on thermal stresses.

The comparison between experimental and theoretical values of the buckling stress is shown in Fig. 10. The sum of the bending stress and the thermal stress increase as the temperature rise increases and eventually reaches the theoretical values of the buckling stress which decreases as the temperature

risers. The thermal stress rapidly decreases. The displacement decreases for the girder breaks.

Table 3. Decrease rates of σ_y and E depending on high temperature

temperature (°C)	σ_y (%)	E (%)
0	100	100
100	88.5	100
200	76.9	97.0
300	65.8	90.0
350	57.7	86.5
400	50.4	80.5
450	42.3	72.5
500	33.7	65.0
600	8.7	55.0

Fig. 10 Relation between σ_k and Tmax (Group-D)

Note; Tmax: maximum temperature

Fig. 11 shows the horizontal displacements of the column-girder contact points for the D-2 experiment which possessed two heated girders and only left girder buckled. In Fig. 11, the experimental values are compared with the estimated values in consideration of the decrease of thermal stresses by buckling. The

estimated values are obtained from the formula (3.4) before the heated girder buckle and they are obtained from the formula (3.4), (3.6) after the heated girder buckle. It is shown that the estimated values exactly agree with the experimental values.

Fig. 11 Relation between δ and T (experiment D-2)

(3) Column

The damage of the binding columns are different from that of the heated girders.

This is demonstrated in the experiments of A-2 and E-2. Heated girders buckle as a result of failure in the middle of the span, but on the basis of measurements of the strain, the columns are expected to yield at their ends. This is shown in Fig. 12 which shows the relation between the measured strains of the column and the mean temperature of the heated girder. The following facts can be deduced;

- Bending strain in the column linearly increases as the temperature of the heated girder increases,
- The strain increase rapidly by occurring the limits for the A-2 experiment (1500μ).

Fig. 12 Relation between the measured strain of the column and T (experiment A-2)

4. CONCLUSIONS

Experiments were carried out to investigate the behaviour of a steel-frame in a fire using a model frame. The following conclusions may be drawn on the basis of the experimental results and analysis.

- (a) It is possible to expect the fire behaviour of structural steel-frame using the analytical theory of thermal stresses for frame.
- (b) Under some probable conditions, structural damage may actually occurred in a fire. It was shown experimentally that the damage due to thermal stress could occur not only to heated members but also to non-heated ones.
- (c) Braces which are included in order to increase the horizontal stiffness may be dangerous for heated girders.
- (d) As the decrease in the elastic modulus is low at 200°C , the superposition is suitable for the study of the effects of a fire.

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