THERMAL STRESS OF STEEL STRUCTURES OF TALL BUILDINGS IN FIRE

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ABSTRACT

Behaviors of thermal stress in fire are analysed about 29 multistory steel structures in Japan. These analyses suggest that the yielding of structural elements occur firstly at the top of exterior column between 94°C and 720°C and almost under 350°C. These yielding temperatures are approximate to ones drawn from the model analysis and statistical approach.

1. INTRODUCTION

In Japan, the existing fire protection codes¹⁾ require that the temperature of steel structures in fire should be controlled under 350°C on the average and 450°C at the maximum. These codes apply to only the steel structural elements which are carrying the allowable stress for long sustained loading and simply supported with pin and roller.

However, the actual allowable temperature is influenced with the generation of thermal stress and the supporting conditions of both sides of the element. Therefore, it is necessary to study the behavior of the actual steel structures in fire. On this point of view, we have tried out the elastic thermal stress analysis as regards 29 multistory steel structures.

In this paper, we represent a part of the results of the analysis.

2. METHOD OF ANALYSIS

Table 1 shows the building names, properties, and the results which are calculated by the thermal stress analysis.

The computer program used in this analysis is based on the direct stiffness matrix method and developed by second author.

One typical frame is selected for the analysis in each building. This frame is supposed to be exposed to fire at the upper, middle, and lower floor, respectively, and the lower reinforced concrete or steel framed reinforced concrete structure is assumed to have a fixed base of column, as shown in Fig. 1.

In the frame it is assumed that the exteri-

Table 1 Building names & Properties

building name	number of spans	span(m)	floor height(m)	number of stories	yielding temperature ratio (model analysis/computation)		
					upper floor	middle floor	lower floor
shinjuku mitsui building	3	15.6	3.68	54	0.98	0.98	1.03
shinjuku center building	3	15.4	3.65	54	0.90	0.91	0.97
sunshine 60 (office)	3	15.6	3.7	57	0.94	0.97	0.99
ikebukuro prince hotel	3	8.8	2.95	37	0.93	0.86	0.86
shiba chokoso building	3	11.4	3.65	19	0.81	0.82	0.83
hitachi honsha building	3	12.0	3.9	16	0.90	0.88	0.85
aoyama building	3	12.0	3.75	13	0.81	0.81	0.81
toranomon mitsui building	2	13.65	3.7	15	0.80	0.86	0.83
nagoya toshikeikaku Al-tou	3	12.3	3.65	24	0.97	0.93	0.94
hamarikyu building	5	9.5	3.7	21	0.87	0.87	0.91
sapporo grand hotel	4	7.55	3.2	17	0.75	0.74	0.74
ns building	1	22.4	3.82	11	0.88	0.89	0.93
sendai kowa building	2	9.6	3.485	17	1.06	1.18	1.18
osaka terminal building	6	5.5	4.0	26	0.78	0.80	0.80
daiichi kangyo bank	3	16.5	3.95	33	0.92	0.93	0.99
sompo kaikan	2	8.0	3.5	18	0.72	0.71	0.77
osaka midosuji building	3	4.71	3.0	25	0.61	0.76	0.80
dai-21 mori building	5	7.2	3.75	22	0.88	0.86	0.77
shinjuku sanei building	2	12.0	3.35	15	0.56	0.87	0.88
shinjuku ns building	1	12.95	3.64	30	0.75	0.89	0.99
dai-2 hazama building	2	16.8	3.75	22	0.76	0.78	0.80
toyota motor tokyo building	3	22.0	3.88	19	0.49	0.61	0.65
hitachi oomori dai-2 bekkon	3	13.2	3.8	15	0.88	0.85	0.91
chiyoda seimei hukuoka building	3	10.8	3.6	15	0.62	0.86	0.98
shin-ochanomizu building	3	12.8	3.7	22	0.85	0.84	0.92
osaka oobayashi building	3	11.55	3.6	31	0.84	1.02	1.02
takiho marunouchi building	3	11.0	3.55	25	0.97	0.96	0.94
teijin shokusan edobori minami building	3	10.4	3.55	19	0.31	0.88	0.87
osaka ekimae dai-3 tou	3	14.7	3.7	34	0.99	1.08	0.98

or and interior column and the beam which consist of the fire compartment are heated and the temperature of these elements is elevated uniformly. According to this assumption, computational analysis was carried out with regard to the behavior of steel structural frames.

As one of the results of this analysis, the building moment developments corresponding to the heating temperature are shown in Fig. 2-A ~ Fig. 2-C.

In Fig. 2, it is remarkable that the moments at the top of the exterior columns are increasing as the temperature of structural elements is rising. This behavior is distinctly shown in Fig. 3. The maximum stress at each temperature, σ_{yt} , can be evaluated from the stress determined by this analysis. The ratio of σ_{yt}/σ_y , in Fig. 3 is expressed by the maximum stress, σ_{yt} , divided by the yield stress, σ_y . On the other hand, the yield point is decreasing against the temperature rising as

sown in Fig. 4²⁾. The descending line of the of least squares. And there are little differences among the strength ratio of steel kind.

In Fig. 3, the yielding temperatures are

Fig. 1 One example of Analysed frames

shown as the intersections of the ascending lines and the descending line of the yield stress.

$T=0^{\circ}\text{C}$

Fig. 2-A Moment development according to Heat Temperature

Fig. 2-B Moment development according to Heat Temperature

Fig. 2-C Moment development according to Heat Temperature

Fig. 3 Thermal stress development and Yield point decrease

3. ANALYTICAL RESULTS

The yielding temperature at upper, middle and lower floors depends on the temperature at which the yielding causes at the top of the exterior column (see Fig. 6). Generally, building No. 10, 6, 3, 14, 11, 9 which have high yielding temperature at upper, middle and lower floors have rather short spans or one span frame with long span length. And building No. 6, 10, 25 which have extremely high yielding temperature at upper floors are ones which are exposed to fire at the top floor or on the floor which has small restraint of the interior column.

Fig. 4 Yielding Point of Stress at Elevated Temperature

4. EXAMINATION BY MODELING

As the results of computer analysis, a little change of stress was observed at the floors which locate more than 2 stories far from fire-exposed floor. So, we suppose a simple model (see Fig. 5). We have compared the computational results with the model ones, and examined factors which give great influences to the yielding of the structural elements.

The conditions assumed in this model are as follows:

- i) The sectional geometry of the columns and beams are the same as the upper floor and lower one.
- ii) Only one beam is heated.

iii) The decrease of Young's modulus is neglected at elevated temperature.

We have modeled structures in this way, because the principal factors of yielding at the top of the exterior column are the beam extension caused by the thermal expansion, the end restraint of the column and the initial existing stress. The ratio of model analysis to computational ones is shown in Table 1. Both results show us a relatively good approximation. However, we don't obtain a good approximation about the upper floor at Shijuku San'ei Building, Chiyoda Seimei Fukuoka Building, Osaka Midosuji Building, Teijin Shokusan Edobori-Minami Building. Because the model of these buildings does not take an equivalent form to the assumed one.

Fig. 5 Model of Frame

Fig. 6 Yielding Temperature

5. MULTIPLE REGRESSION ANALYSIS

We have done the multiple regression analysis as regards the yielding temperature. The objective variable is the yielding temperature ($^{\circ}\text{C}$), and other variables are as follows:

$$R_{nm} = (N/N_y + M/M_y)$$

where N_y — yield axial force at room temperature

M_y — yield bending moment at room temperature

N — axial force caused by vertical load

M — bending moment caused by vertical load

HL: beam length exposed to fire

SR: ratio of the column stiffness, I_1 , to the total column stiffnesses, ΣI_i (referred to Fig. 7)

Fig. 7

$$(SR = I_1 / \Sigma I_i)$$

AD: coefficient associated with the deflection of column at yielding (referred to Fig. 8)

Fig. 8

SC: coefficient associated with the beam stiffness, A/l

A: area of the beam section (cm^2)

l: beam length (cm)

Using the above variables, we may express the yielding temperature which is the objective variable in a simple polynomial form as,

$$T = 144.74 - 73.20 \times R_{nm} - 0.1252 \times HL + 182.35 \times SR + 173.297 \times AD + 35.88 \times SC$$

The results which have been analysed by the computer are compared with the above temperature, T and shown in Fig. 9. Fig. 10 represents the frequency of the regression value divided by the observations.

Fig. 9 Regression line

Fig. 10 Frequency

In this multiple regression analysis, we have excluded the data concerning the building of which the maximum temperature is more than 350°C in fire.

6. CONCLUSION

We have analysed the behavior of the thermal stress about many multistory steel structures in fire using the computer of Chiba Univ.

These results are compared with ones drawn from the model analysis and statistical approach, and the former are approximate to the later.

Thermal stress analysis of many steel structural frames suggests that the yielding of structural elements occur at the top of the exterior columns between 94°C and 720°C. This yielding temperature is evaluated by the appropriate model analysis and statistical approach.

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