Large Scale Fire Tests of a 4-Story Type Car Park

Part 2: Analysis of the thermal stresses and deflections

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ABSTRACT

The Large-scale fire test is carried out in a 4-story type car park at the deepest part of the ground floor. This experimental results indicate that car fire spreads one after another, the steel temperature of the beam located above the combusted vehicle reaches near to 700℃ and the frame stability is maintained [1].

This paper presents the two-dimensional structural analysis of the thermal stresses and deflections about this experiment.

KEYWORDS: car park, steel structure, numerical analysis, frame stability, fire

INTRODUCTION

Previous reports indicate that there is a little risk in an open car park building exposed to developed fire, because the fire is likely to be constrained to the burning car or at most be spread to one or two adjacent cars and the temperature of steel members without fire protection reaches less than 400℃ [2-4]. In Japan, a 4-story type car park of steel structure with 4000m^2 area per floor is allowed without fire protection. In the case of a fire at the deepest part of 4000m^2 area, it is considered a high-temperature gas layer is accumulated under a ceiling. Then, naked steel members are subjected to severe heating. This frame receives the large thermal stress, thermal deflection and the decrease of the strength. In consequence of these phenomena, this frame stability is possible not to be maintained. Therefore, the large-scale fire test is carried out in a 4-story type car park at the deepest part of the ground floor. This experimental results indicate that car fire spreads one after another, the steel temperature of a beam located above the combusted vehicles reaches near to 700℃, frame stability is maintained during developed fire and the residual deformation is not observed after the fire [1].

Following to the report Part 1 [1], this paper presents the two-dimensional structural analysis of the thermal stresses and deflections about this experiment. The followings are the conceivable factors as the reason which this structure is not damaged. One is that the service load is very low for the strength of structural members designed against seismic load. Another is that the column bases of the frame are not restraint by footings because they could not be connected to the ground beam in this experiment. It is considered that the thermal stress is relieved by this weak restraint conditions. The analysis of thermal stresses and deflections are carried out, therefore, assuming four kinds of support conditions about the column bases in this paper.

LARGE SCALE FIRE TEST

Fig.1 shows the external view of the experimental structure and the view of the spreading car fire during the experiment. Fig.2 shows the plan of the ground floor. This experiment is performed by starting a fire at the deepest part of the thermally insulated corner on the ground floor. The structural members are covered with no fire protection. The maximum allowed floor area for prefabricated parking structure is 4000m^2 by a floor in Japanese specification. If the area is square, the dimensions are 63m x 63m. A fire started in the center of the floor is thought as the most violent type possible. In order to achieve the fire conditions described above, a thermally insulated structure is used to form a combustion space. This space is surrounded by the ceiling (floor of the second story) and walls on ⑤-line and E-line. Combustion progress is considered more severely because of heat radiated from the floor and walls to cars in the insulated space. Therefore, the corner side fire exhibits faster combustion and spreads wider than the open side fire. The purpose of the experiment is to understand the behavior of car combustion and structural frames under this extreme condition.

Table 1 shows the passage of fire spreading. As shown in Fig.2, the No.102 car is set on fire and car fire spreads to adjacent cars one after another.

FIGURE 1. The external view of the experimental structure and the view of the spreading car fire during the experiment

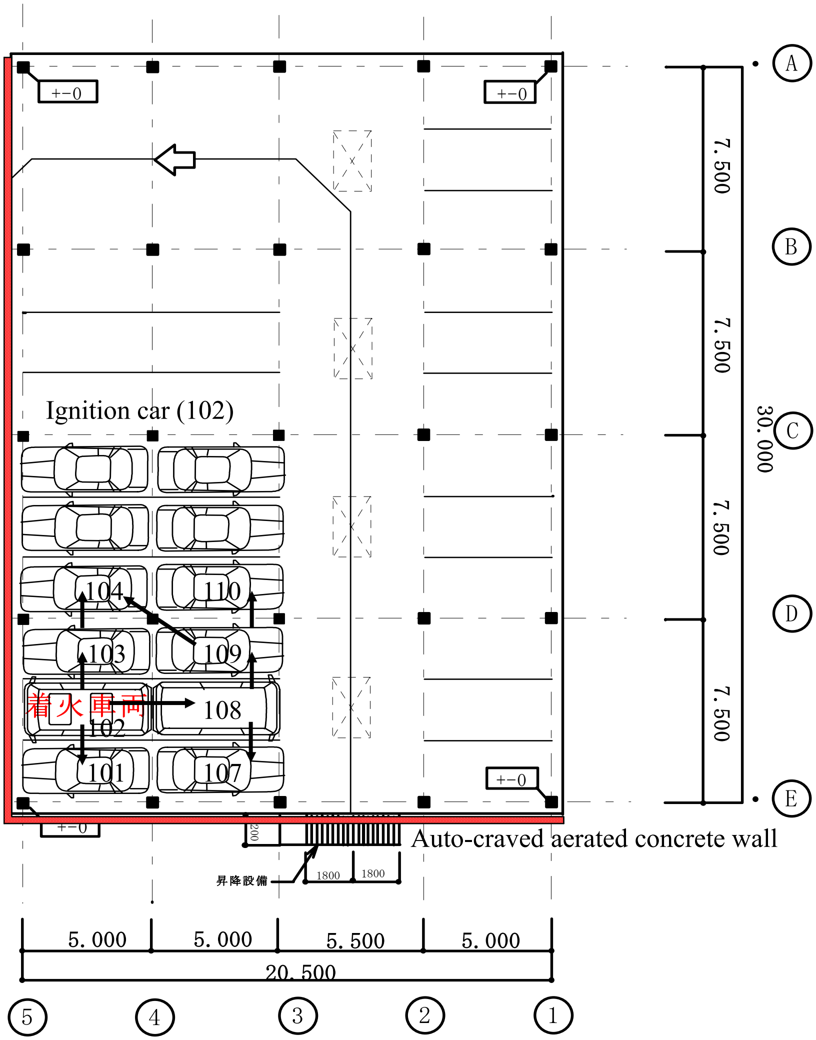


FIGURE 2. Plan of the ground floor

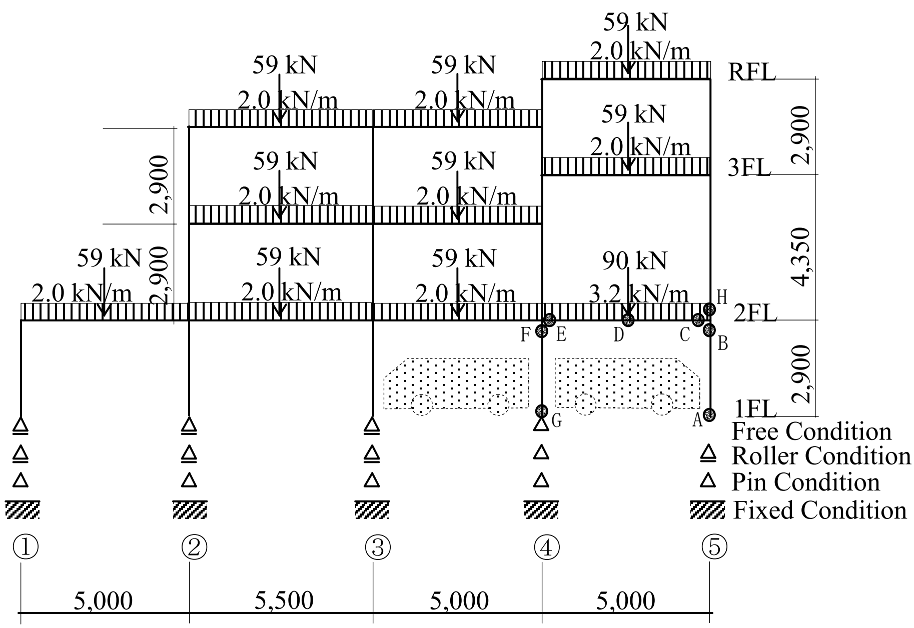
TABLE 1. Passage of fire spreading

	TIME	RECORD
Date: 26 January 1999	00'00"	Start of ignition (No.102)
Time of starting test: 10:54 a.m.	08'30"	Fire spread to left side car (No.101)
	19'15"	Fire spread to right side car (No.103)
Weather: Fine	23'45"	Fire spread to tail side car (No.108)
Temperature: 5℃	25'30"	Fire spread to No.108's right side car (No.109)
Direction and velocity of wind: NNW 2-3m/sec	25'45"	Fire spread to No.108's left side car (No.107)
	43'00"	Fire spread to cars (No.110 and No.104)
	43'45"	Start of fire fighting

ANALYSIS OF THE THERMAL STRESSES AND DEFLECTIONS

The Frame

Fig.3 shows side elevation of analytical frame (E-frame). As shown in Fig.2, E-frame is subjected to severe fire because columns and beams at the ground floor are located between burning cars and auto-craved aerated concrete wall. In this experiment, the sets of two wide flange shapes with small section are put on the each line of ①-⑤ instead of footings which cannot be located in the ground. And the partial inner columns are connected to these wide flange shapes by high-tension bolts. Therefore, this analysis is conducted under the four kinds of support conditions of the column base as shown in Fig.3. At first, it is assumed that the point of ④line's column base, which move little in horizontal direction in this experiment, is fixed for horizontal movement. In case1, ⑤ line's column base is not supported at all and other ones are in roller bearing except ④ line's column base, named "Free Condition" in this paper. In case2, all column bases are in roller bearing except ④line's column base, named "Roller Condition". In case3, all column bases are in pin bearing, named "Pin Condition". In case4, all column bases are fixed on the ground, named "Fixed Condition". Free Condition and Roller Condition simulate roughly this experiment. Pin Condition and Fixed Condition simulate a general car park building structure.



1F Column : □-200×200×6 (①), □-300×300×12 (②-⑤)
2F・3F Column : □-300×300×9 (②-⑤)
Beam : H-300×150×6.5×9 (①), H-400×200×8×13 (②-⑤)

FIGURE 3. Side elevation of analytical frame (E-frame)

Steel Temperatures

Fig.4 shows the distribution of structural steel temperatures in this analysis. Temperatures of members for axial direction are given as uniform distribution and for sectional direction are given as variable distributions on the bases of experimental results. In this test, fire fighting is started at 44 minutes after ignition.

Stress-Strain Curves

Fig.5 shows stress-strain curves of the steel column at elevated temperature. The stress-strain curves of the steel beam are approximately as same as column's one. The analytical model of SS-curve is based on the tension tests of these materials.

The Method of Analysis

Elasto-plastic analysis of the frame is based on a non linear direct stiffness formulation coupled with a time step integration [5,6].

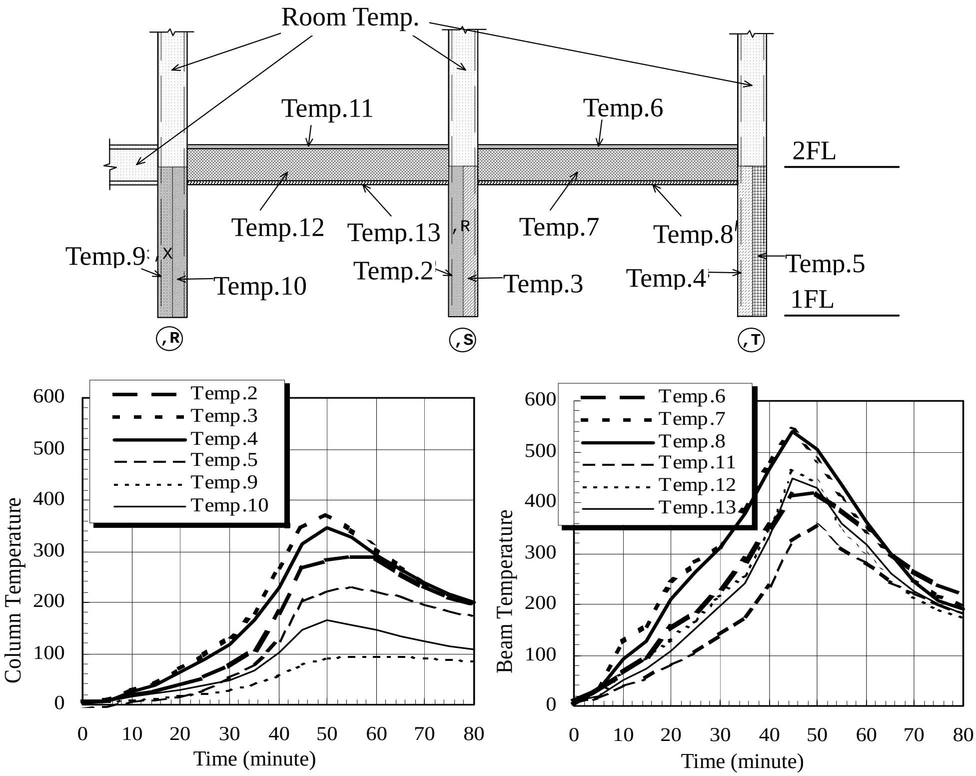


FIGURE 4. Structural steel temperatures

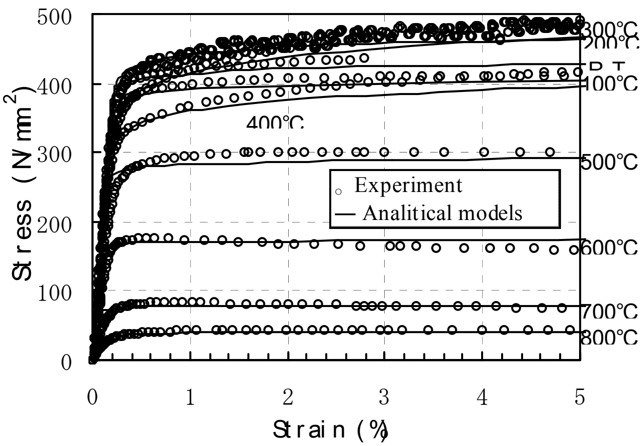
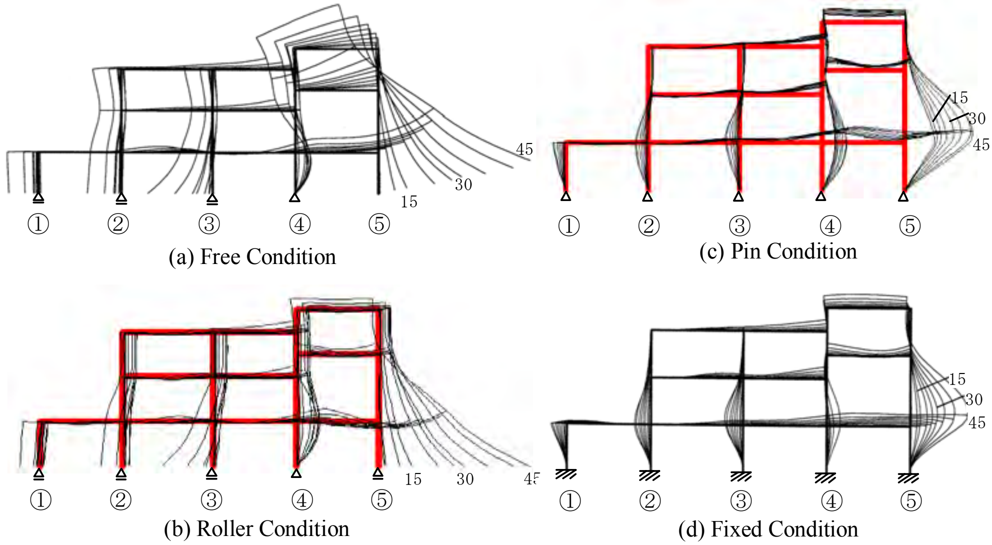


FIGURE 5. Stress-strain curves of the steel column

Deflection

Fig.6 shows thermal deformation of the frame. In this picture, frame displacement lines are drawn by 5 minutes during a heating phase. Fig.7 shows thermal deflection of outer column and beam exposed to fire. In Fig.7, the experimental results are compared with calculated ones. The symbols A, C, D and H denote the points as shown in Fig.3.

At first, the frame doesn't collapse as same as the experiment. In the case of Free Condition, ⑤line's column is lifted up according to fire development time as shown in Fig.6 (a). About the vertical displacement at the end of beam as shown in Fig.7 (c), the calculated values approximately agree with the experimental values during a heating phase. As shown in Fig.6 (a) and (b), in the case of Free Condition and Roller Condition, outer column is pushed out due to the thermal elongation of the beam exposed to fire. About the horizontal displacement at the outer column base as shown in Fig.7 (a), the calculated values are somewhat larger than the experimental values. As shown in Fig.6 (c) and (d), in the case of Pin Condition and Fixed Condition, large bending deflections are developed at the top of outer column due to the thermal elongation of the beam and the restraint of column base displacement for horizontal direction. About the horizontal displacement at the top of column as shown in Fig.7 (b), the calculated values agree with the experimental values. As shown in Fig.7 (d), vertical displacement at center of beam exposed to fire is yielded downward in the experiment, but this displacement is yielded upward in the analysis. It is considered that the deflection of beam is influenced largely by the three-dimensional factors due to the behavior of the fire exposed slab and beam meeting at right angles. It is difficult to describe the experimental deflection of the beam exposed to fire by two-dimensional analysis.



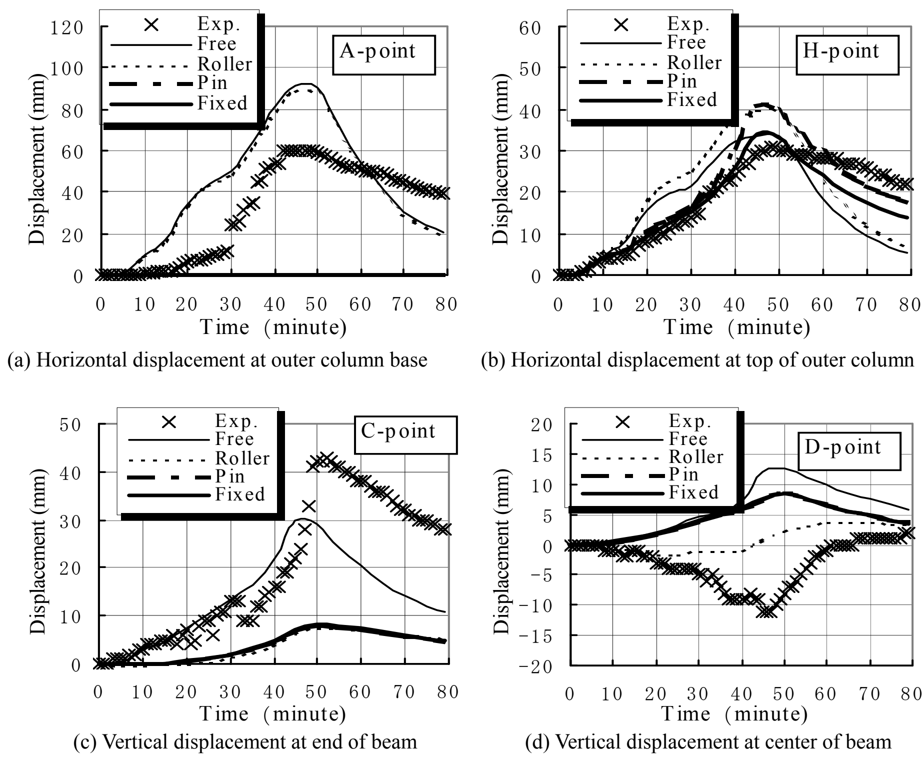
(a) Free Condition

(b) Roller Condition

(c) Pin Condition

(d) Fixed Condition

FIGURE 6. Thermal deformation of the frame



(a) Horizontal displacement at outer column base

(b) Horizontal displacement at top of outer column

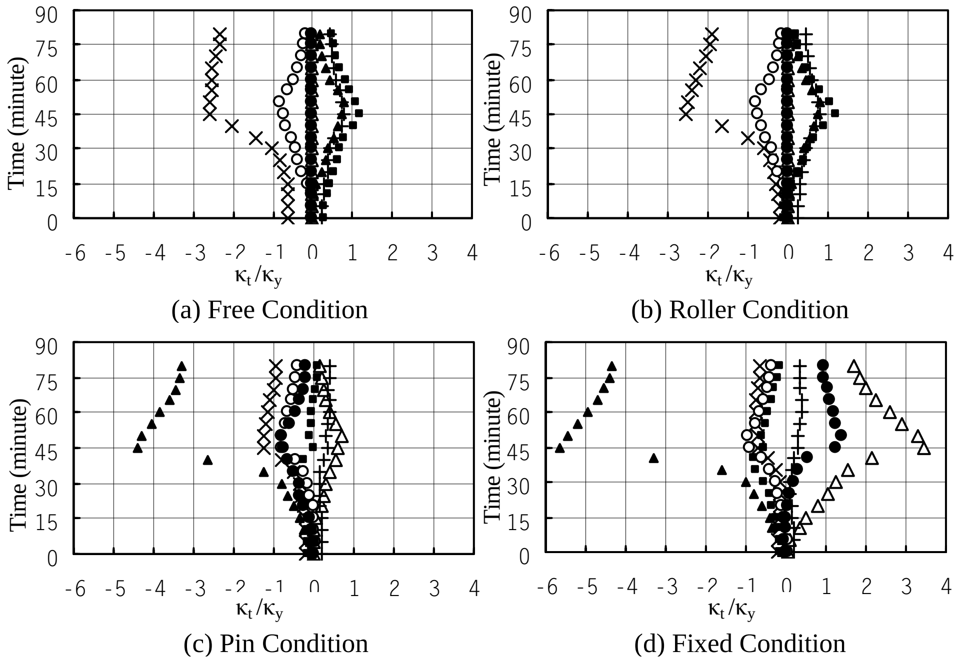
(c) Vertical displacement at end of beam

(d) Vertical displacement at center of beam

FIGURE 7. Thermal deflection of outer column and beam exposed to fire

Curvature

The curvatures of fire exposed column and beam are shown in Fig.8. The symbols from A to G denote the points as shown in Fig.3. As shown in Fig.8 (a) and (b), in the case of Free Condition and Roller Condition, the value of beam's curvature at the inside end reaches 2.5 times of the room temperature's yielding curvature at 45 minutes after ignition and remains near to 2 times at 80 minutes after ignition. As shown in Fig.8 (d), in the case of Fixed Condition, the value of the outer column's curvature reaches 5.5 times of the room temperature's yielding curvature at 45 minutes after ignition and remains 4.5 times at 80 minutes after ignition. When the column bases of a frame are restrained for the horizontal displacement by footings, large curvatures are developed at the top of outer columns due to the thermal elongation of the beam exposed to fire, and they remain after a fire.

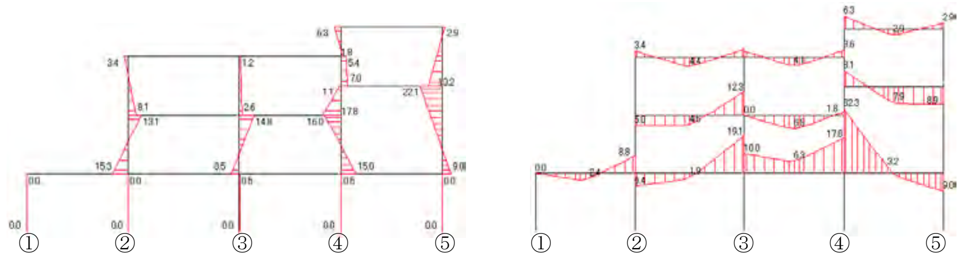


κ_t : Curvature at Elevated Temperature ,κ_y : Yielding Curvature at Room Temperature
:outer column base (A), ▲:top of outer column (B), ■:outside end of beam (C), +:center of beam (D), ×:inside end of beam (E), ○:top of inner column (F), ●:inner column base (G)

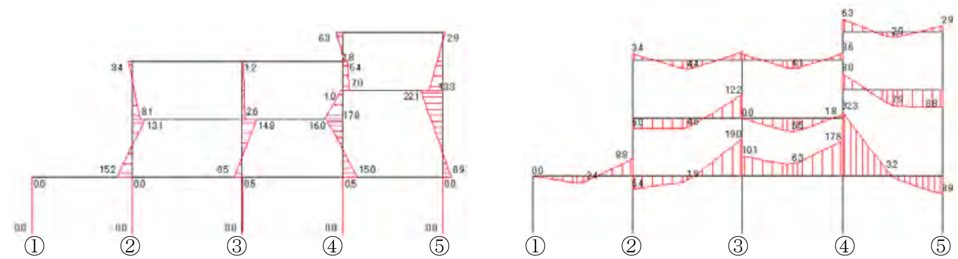
FIGURE 8. Curvatures of fire exposed column and beam

Thermal Stress

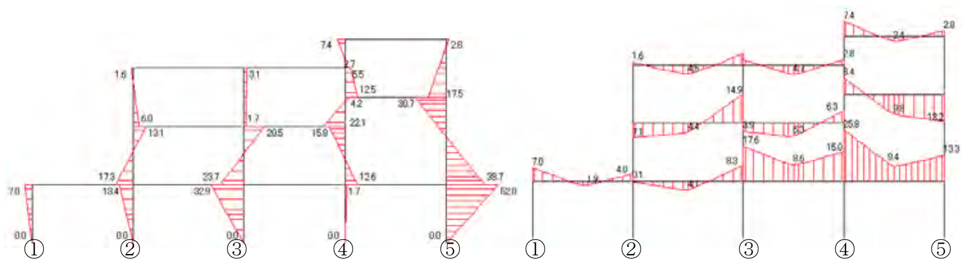
Fig.9 shows moment distribution of the frame at 45 minutes after ignition. Fig.10 shows development of the thermal stresses resultant in steel members. The symbols B, D and E denote the points as shown in Fig.3. As shown in Fig.9 (a) and (b), in the case of Free Condition and Roller Condition, development of the bending moment is remarkable at the inside end of the fire exposed beam between ④ and ⑤. It is considered that this part supports the service load between ④ and ⑤. As shown in Fig.10 (b), bending moment at the inside end of beam (E-point) increases according as axial force at the top of outer column (B-point) decreases during a heating phase. The reverse phenomenon occurs during a cooling phase and the value of bending moment at the end of beam is less than the value before ignition. So, it is indicated that the value of bending moment at center of beam increase before ignition as shown in Fig.10 (a) and (b). In the case of Pin Condition, development of the bending moment is remarkable at the top of ground floor's column and at the top and bottom of the upper floor's column as shown in Fig.9 (c). In the case of Fixed Condition, development of the bending moment is remarkable at the top and bottom of most columns as shown in Fig.9 (d). This bending moment is developed due to the thermal elongation of the beam exposed to fire. As shown in Fig.10 (c) and (d), bending moment at the top of outer column (B-point) increases according as axial force of beam increases during a heating phase. The reverse phenomenon occurs during a cooling phase and the value of bending moment at the top of outer column is the same value before ignition. As shown in Fig.9 and Fig.10, development of the negative bending moment is remarkable at the beam exposed to fire. It is considered that this negative bending moment is developed due to the restraint of around members against the deflection of the fire exposed beam which has different temperature between the upper flange and the under flange.



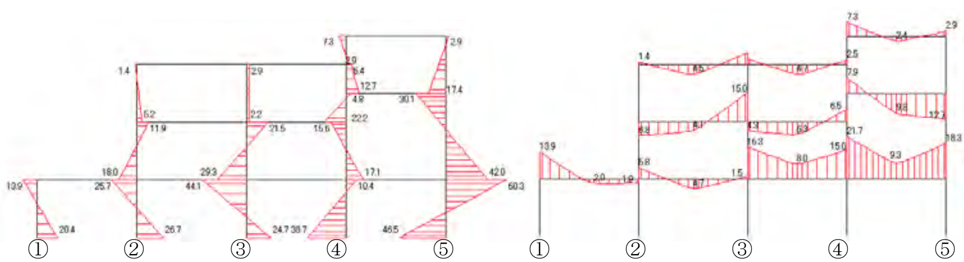
(a) Free Condition



(b) Roller Condition

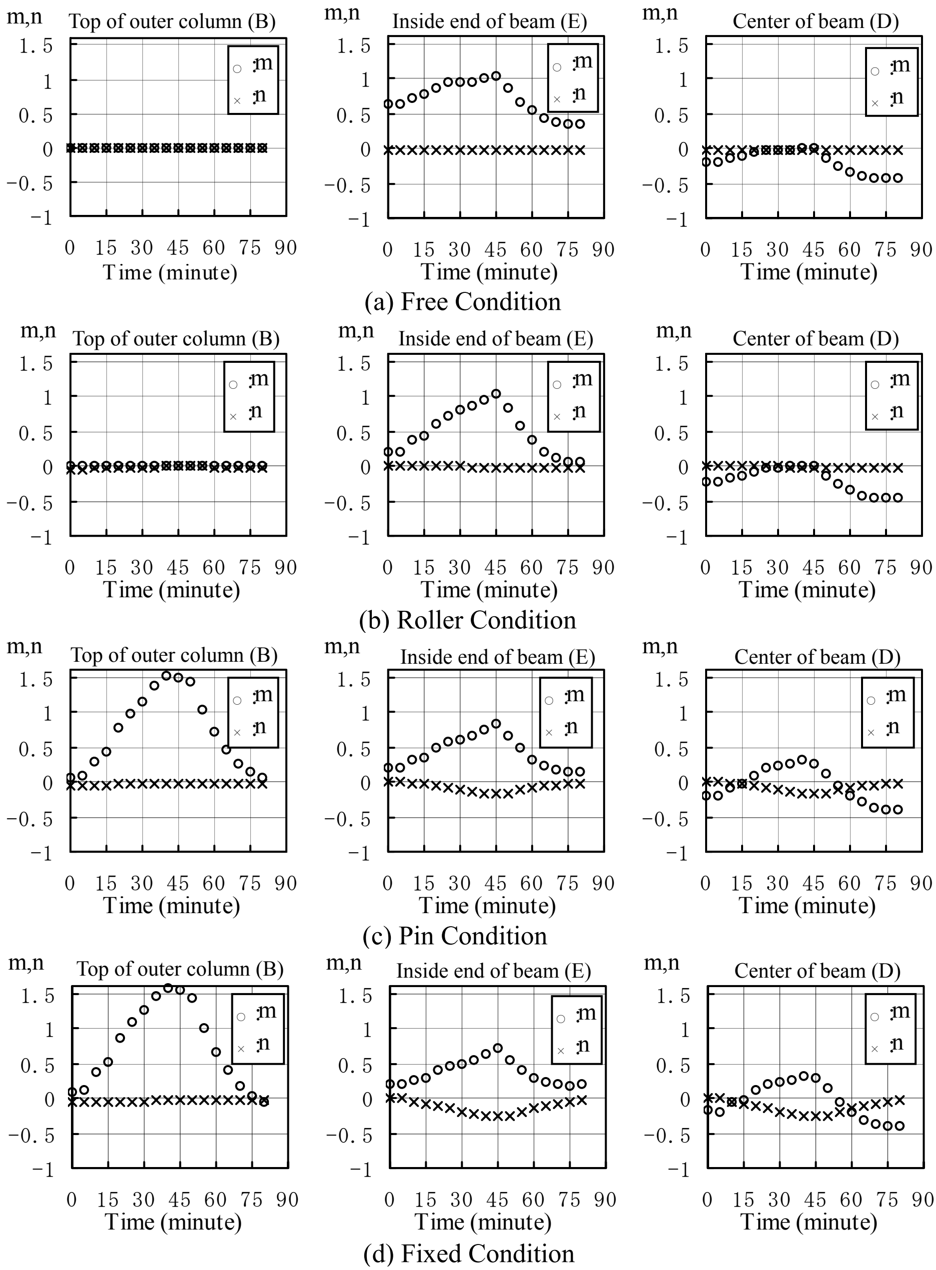


(c) Pin Condition



(d) Fixed Condition

FIGURE 9. Moment distribution (Left: Column, Right: Beam, unit: t・m)



m=bending moment as resultant of thermal stress / yielding moment at room temperature
n=axial force as resultant of thermal stress / yielding axial force at room temperature

FIGURE 10. Development of the thermal stresses resultant

CONCLUSIONS

The following results are obtained by the numerical analysis of the large-scale fire test.

(1) The frame does not collapse as same as the experiment. It is considered that a steel frame exposed to a cars fire without fire protection is stable in case of members connected rigidly and designed against seismic load in Japan.

(2) But when the column bases of a frame are restrained for the horizontal displacement by footings, large curvature is developed at the top and bottom of outer columns due to the thermal elongation of the fire exposed beam and it remains after a fire.

(3) The calculated values of the displacements of frame approximately agreed with the experimental values.

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