Title: Effects of Large Section Size and Fire Resistant Steel on Redundancy Improvement of Steel High-Rise Buildings in Fire

Authors: Mamoru Kohno, Building Department Head, National Institute for Land and Infrastructure Management
Yoshifumi Sakumoto, General Manager, Nippon Steel Corp
Mitsumasa Fushimi, Manager, Nippon Steel Corp

Subjects: Fire & Safety
Structural Engineering

Keywords: Fire Safety
Life Safety
Steel
Structure

Publication Date: 2004

Original Publication: CTBUH 2004 Seoul Conference

Paper Type: 1. Book chapter/Part chapter
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

© Council on Tall Buildings and Urban Habitat / Mamoru Kohno; Yoshifumi Sakumoto; Mitsumasa Fushimi
Effects of Large Section Size and Fire Resistant Steel on Redundancy Improvement of Steel High-Rise Buildings in Fire

Mamoru Kohno¹, Yoshifumi Sakumoto², Mitsumasa Fushimi³

¹ Head, Building Department, National Institute for Land and Infrastructure Management
² General Manager, Const. & Architectural Materials Development & Engineering Services Division, Nippon Steel Corporation
³ Manager, Const. & Architectural Materials Development & Engineering Services Division, Nippon Steel Corporation

Abstract
Structural safety of high-rise steel buildings in fire circumstances depends highly on the behavior of their columns. Real behavior of large section columns which are commonly used in such buildings, however, is not known well because of a lack of appropriate fire test facilities to conduct full-scale experimental investigation. Behaviors of a total of seven large steel columns in fire are investigated experimentally using a high-performance column furnace in the Building Research Institute of Japan. Several findings to improve the structural redundancy of steel buildings in fire circumstances are discussed. They include that properly protected large steel columns show high fire resistance; however, if a portion of fire protection is damaged, even a large section column can surrender far earlier than expected; ceramic fiber blanket is one of the good options for robust protection; keeping axial load ratio of columns smaller is effective for fire resistance improvements; usage of high-performance steel grade, such as fire resistant steel, improves the fire resistance of columns greatly hence the fire redundancy of a building.

Keywords: structural redundancy; steel column; fire resistance; full scale experiments; fire resistant steel

1. Introduction
Structural safety of high-rise steel buildings in fire circumstances depends highly on the behavior of their columns. These columns especially that in lower portion of a building usually have very large section size because they should sustain a large axial load. Traditionally, the fire resistance of protected steel columns has been investigated by loaded fire resistance tests; however, due partly to a lack of appropriate facilities few large section steel columns which are commonly used in high-rise buildings have been tested. Consequently, real behavior of such heavy section steel columns under fire situation is not known well.

Behaviors of a total of seven large section steel columns were investigated experimentally, and several findings to improve the structural redundancy of steel buildings in fire circumstances were reported in this paper.

Two series of full-scale experiments were conducted to investigate the behaviors of such columns in fire. A high-performance column furnace in the Building Research Institute of Japan (Figure 1.) was used for the experiments. The loading capacity of the furnace is 20 MN, which enables to simulate a realistic loading condition of columns in high-rise buildings.

In one series, series A, three columns with identical section, 580 mm square tube and 40 mm in plate thickness, were used as specimens. Fire resistant steel was used for one of the three columns. Each column was loaded and heated by the ISO834 standard or hydrocarbon fire temperature curves in the experiments. All columns were protected with ceramic fiber blanket; however, in some experiments a part of the protection was removed intentionally to investigate the effects of protection damage on fire resistance of heavy section steel columns.

In the other series, series B, four columns were loaded and heated by the standard or hydrocarbon fire temperature curves. The columns had the identical section; 600 mm press formed square tube and 28 mm in plate thickness. All columns were protected with ceramic fiber blanket. Fire resistant steel was used for two of the four columns and conventional steel was used for the remaining two columns. Other conditions of experiments were kept the same in order to compare the behaviors of fire resistant and conventional steel columns in fire situations.

Based on the results of the experiments, methods to improve structural redundancy in fire occasions are discussed.

Contact Author: Mamoru Kohno, Head, Building Department, National Institute for Land and Infrastructure Management, 1 Tachihara, Tsukuba 305-0802, Japan
Tel: +81-29-864-4348 Fax: +81-29-864-6774 e-mail: kouno-m92ta@nilim.go.jp
2. Experiment series A

In CIB-CTBUH 2003 Kuala-Lumpur Conference, Kohno(2003) presented the details of this experiment series. A summary of the experiment series A is given in Table 2.

3. Experiment series B

Test Specimens: Press formed square steel columns, BCP325, were used for test specimens. Two of the four columns were fabricated by using the JIS G 3136 SN490B grade steel (conventional steel) and the remaining two columns were made of the JIS G 3136 SN490B FR (Fire Resistant) grade steel. The specified design strength is 325 MPa for both grades. The four columns had the identical geometrical dimensions; the length was 4.3 m, the cross-section was 600 mm square and 28 mm in plate thickness. Other parameters of the column specimen are listed in Table 1, and the configuration of the steel columns is illustrated in Figure 3.

Spray-applied rock wool is most often used for fire-protection to steel members in many countries. However, it requires relatively long conditioning time because of the water content. In order to avoid the sensitivity to water content of fire-protective material and to meet the time schedule, ceramic blanket was used for fire-protection in this experiment series as in the experiment series-A. The ceramic blanket used to protect the steel columns was Fireguard C-60, which is one-hour rated protection material for steel columns in Japan. A 30 mm thick blanket was used for all

---

Table 1. Parameters of Steel Columns

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Series A</th>
<th>Series B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section Shape</td>
<td>Weld built-up</td>
<td>□580×580×40</td>
<td>Press formed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Press formed</td>
<td></td>
</tr>
<tr>
<td>Specified Design Strength N/mm²</td>
<td>325</td>
<td>325</td>
<td></td>
</tr>
<tr>
<td>Cross-sectional Area mm²</td>
<td>8.64×10⁴</td>
<td>6.00×10⁴</td>
<td></td>
</tr>
<tr>
<td>Length mm</td>
<td>4 300</td>
<td>4 300</td>
<td></td>
</tr>
<tr>
<td>Second Inertia mm⁴</td>
<td>4.22×10⁶</td>
<td>3.14×10⁶</td>
<td></td>
</tr>
<tr>
<td>Slenderness Ratio</td>
<td>19.5</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>Shape Factor m⁻¹</td>
<td>26.9</td>
<td>39.0</td>
<td></td>
</tr>
<tr>
<td>Weight kg</td>
<td>2.92×10³</td>
<td>2.03×10³</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 1. Column Furnace of BRI

Fig. 2. Deformed Column Specimen after Experiment

Fig. 3. Specimen Configuration and Position of Temperature Measurements
specimens.

**Measurements:** Temperatures of steel surface were measured by type K thermocouples. The thermocouples were installed at 9 levels: Levels from Level-A through Level-H were evenly distributed along the column length inside the furnace and Level-I was located outside the furnace as in Figure 3. At three of the 9 levels, i.e. Level-C, -E and -G, temperatures were measured on both interior and exterior steel surfaces. Eight thermocouples were installed on both interior and exterior surfaces at these Levels. At the other 6 levels, the temperatures were measured only on the exterior surface. The total number of points of temperature measurement was 96 for each column specimen. The levels of the temperature measurement and thermocouple positions at each level are shown in Figure 3. The numbers from 1 through 16 in the figure correspond to the positions of thermocouples.

The ISO-type plate thermometers and the JIS type sheathed and exposed thermocouples were used for the measurement of furnace gas temperatures. The temperatures were measured at four evenly distributed levels and at four sides of the column specimen at each level. The readings of plate thermometers were used for the heating control.

Longitudinal deformation of a column was determined from the measurement of displacement of the hydraulic ram which was used for loading. The displacement was measured by a high-precision displacement transducer.

All measurements were done at 30 seconds interval and stored in a data-logger during an experiment.

**Loading and Heating Regime:** It is known that in the case of a column in high-rise buildings designed for earthquake, such as Japanese high-rise buildings, existing load ratios to sustained allowable load of the column are at the largest 0.6. So, load levels were set to either 1.0 or 0.6 of the sustained allowable load of the column specimens. It is assumed that load ratio 0.6 represents a typical condition and load ratio 1.0 is an extreme loading condition. In determining the sustained allowable loads, actual yield strengths given in the inspection certificate issued by the steel manufacturer were used instead of the specified design strength of 325 MPa. The yield strengths at normal temperature were 368 MPa and 397 MPa for the conventional and fire resistant steels, respectively. However, because fire resistant steel is supplied so that 2/3 of the specified design strength is guaranteed at 600 °C, the value of the yield strength at 600 °C in the certificate multiplied by 1.5(=3/2), 250×1.5=375 MPa, was used to determine the allowable load of the fire specimens.

**Table 2. Summary of Experiment Series A**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Steel grade</th>
<th>Fire protection</th>
<th>Applied Load (Ratio*)</th>
<th>Heating Curve</th>
<th>Result Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>SN490C</td>
<td>Ceramic fiber blanket, 80 mm thick</td>
<td>10.1 MN (0.5)</td>
<td>hydrocarbon</td>
<td>Heating stopped at 180 min.</td>
</tr>
<tr>
<td>A-1a</td>
<td>SN490C</td>
<td>Blanket was taken off partially (25 % in area) after Exp.A-1</td>
<td>10.1 MN (0.5)</td>
<td>hydrocarbon</td>
<td>Buckling started at 27.5 min.</td>
</tr>
<tr>
<td>A-2</td>
<td>SN490C</td>
<td>Ceramic fiber blanket, 30 mm thick</td>
<td>9.8 MN (0.49)</td>
<td>ISO-834</td>
<td>Buckling started at 330 min.</td>
</tr>
<tr>
<td>A-3</td>
<td>NSFR490C</td>
<td>Ceramic fiber blanket, 30 mm thick</td>
<td>12.9 MN (0.6)</td>
<td>ISO-834</td>
<td>Heating stopped at 240 min.</td>
</tr>
<tr>
<td>A-3a</td>
<td>NSFR490C</td>
<td>Blanket was taken off partially (25 % in area) after Exp.A-3</td>
<td>6.5 MN (0.3)</td>
<td>ISO-834</td>
<td>Buckling started at 105 min.</td>
</tr>
</tbody>
</table>

* Load ratio to the sustained allowable load.

**Table 3. Summary of Experiment Series B**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Steel grade</th>
<th>Fire Protection</th>
<th>Applied Load (Ratio*)</th>
<th>Heating Curve</th>
<th>Result Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-CS06</td>
<td>SN490B-BACP325</td>
<td>Ceramic fiber blanket 30 mm (Fireguard C-60)</td>
<td>8.60 MN (0.6)</td>
<td>ISO-834</td>
<td>Buckling started at 210 minutes. Steel temperature was 550 °C.</td>
</tr>
<tr>
<td>B-FR06</td>
<td>SN490B-FR-BACP325</td>
<td>Ceramic fiber blanket 30 mm (Fireguard C-60)</td>
<td>8.67 MN (0.6)</td>
<td>ISO-834</td>
<td>Buckling started at 290 minutes. Steel temperature was 680 °C. (80 minutes longer, 130 °C higher)</td>
</tr>
<tr>
<td>B-CS10</td>
<td>SN490B-BACP325</td>
<td>Ceramic fiber blanket 30 mm (Fireguard C-60)</td>
<td>14.19 MN (1.0)</td>
<td>hydrocarbon</td>
<td>Buckling started at 135 minutes. Steel temperature was 410 °C.</td>
</tr>
<tr>
<td>B-FR10</td>
<td>SN490B-FR-BACP325</td>
<td>Ceramic fiber blanket 30 mm (Fireguard C-60)</td>
<td>14.45 MN (1.0)</td>
<td>hydrocarbon</td>
<td>Buckling started at 215 minutes. Steel temperature was 600 °C. (80 minutes longer, 190 °C higher)</td>
</tr>
</tbody>
</table>

* Load ratio to the sustained allowable load.
resistant steel column.

In the BRI column furnace, a column is pin supported both at top and bottom ends of loading system. A buckling length of 4.6 m was used to determine the allowable load, because the distance between the centers of rotation of end supports was 0.3 m longer than the actual length, 4.3 m, of the installed column specimen.

The furnace gas temperature was controlled either by the ISO837 standard temperature/time relationship or more severe hydrocarbon temperature/time relationship (EN 1991-1-2:2002). The relationships are given by the following equations:

Standard temperature/time relationship;

\[ T_g = 20 + 345 \log(8t + 1) \]  
(1)

Hydrocarbon temperature/time relationship;

\[ T_g = 20 + 1080\left(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}\right) \]  
(2)

Where;

\( T_g \) is the mean gas temperature in the furnace (°C)
\( t \) is the time from ignition (minutes).

Test procedures prescribed in the ISO 834-1 and ISO 834-7 were basically followed in each experiment. The conditions of the experiments are summarized in Table 3.

**Results of Experiments:** Gas temperatures (16 data) in the furnace and steel temperatures (16 data) at Level-E after the commencement of heating are shown in Figure 4 and Figure 5. In each experiment, steel temperature/time relations at Levels B, C, D, F and G were very close to that of Level-E. Steel temperatures were slightly lower at Levels A and H than at Level-E.

Deformations, or longitudinal elongations, of columns are illustrated in Figure 6. In the figure, the deformation/time and deformation/average steel temperature relations are plotted in (a) and (b), respectively. In the latter plot, the average temperature is the mean of all the steel temperatures measured at Levels from A through H (a total of 88 points).

A photo of the deformed column specimen after the experiment is shown in Figure 2.

**Comparison of CS06 and FR06:** It is assumed that the loading and heating conditions are commonly encountered cases in the real world, because the applied load ratio to the sustained allowable load is 0.6 and the heating follows ISO834 standard temperature/time relationship. As the conditions had been identical for the two experiments, the difference in fire resistance between two steel grades can be
compared directly from the experiment results. The conventional steel column started buckling when steel temperatures at Level-E went up to about 550 °C as shown in Figures 4(a) and 6(a). On the other hand, the fire resistant steel column could sustain the applied load until steel temperatures at Level-E became around 680 °C, which was 130 °C higher than that of the conventional steel column. In the time domain, the times of the beginning of buckling were 210 minutes and 290 minutes respectively for the conventional and fire resistant steel columns. This means the fire resistant steel column could support the axial load as long as 80 minutes longer than the conventional steel column. The longitudinal deformation of the columns increased as the temperature of steel being elevated, and the deformation/time curves of the two experiments were similar till 180 minutes from the ignition of heating as shown in Figure 6(a).

Comparison of CS10 and FR10: Extreme fire conditions were simulated in the two experiments. The applied load ratio was 1.0 to the sustained allowable load, and the columns were heated by the hydrocarbon temperature/time relationship which was more severe than the standard temperature/time relationship. Buckling started when the temperatures of steel at Level-E reached 410 °C and 600 °C respectively for the conventional and fire resistant steel columns. Thus, the difference between the two steel grades in the load carrying capacity was 190 °C in the temperature domain. In the time domain, it took 135 minutes to start the conventional steel column buckling by the hydrocarbon curve heating. As the fire resistant steel started buckling at 215 minutes, it could sustain the applied load 80 minutes longer than the similarly configured conventional steel column. The furnace gas temperatures were controlled slightly higher in the experiment FR10 than in the experiment CS10 as shown in Figure 5. This might be a factor of the larger longitudinal elongation of the fire resistant steel column in earlier stage of the heating as in Figure 6(a). Even taking the gas temperature difference into consideration, the deformation curves of the experiments FR10 and CS10 were quite different. Furthermore, as illustrated in Figure 6(b), the deformation/average steel temperature relations of the experiments CS06, FR06 and FR10 are very close in the earlier stage of heating; however the curve of CS10 is separated from other curves. So far, the reason of this difference is not explained well.

Conclusion
Following points have been found by the full scale fire resistance experiments of two types of heavy section steel columns:

- Properly protected large steel columns showed high fire resistance.
- However, if a portion of fire protection is damaged, even a large section column can surrender far earlier than expected. Thus robustness of fire protection in fire occasion is very important. Ceramic fiber blanket is one of the good options for robust protection.
- Keeping axial load ratio of columns smaller is effective for fire resistance improvement.
- Usage of high-performance steel grade, such as fire resistance steel, improves the fire resistance of columns greatly hence the fire redundancy of a building.

Acknowledgements
This research was done under a research program of the Department of Fire Engineering, Building Research Institute of Japan. This research was partially supported by a grant from the Japan Iron and Steel Federation. The authors are thankful for their support.

References