Fire-Resistance of Steel Beam Joints Connected by High Strength Bolts

by

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ABSTRACT

Full-scale fire resistance experiments on protected steel beams with a bolted connection were conducted to investigate the collapse modes and flexural strength of the beam connection at elevated temperatures. Each of the five beam specimens had a beam-to-beam connection at the centerline. The connection was fastened by high-strength bolts. The beams were heated in a furnace by the standard fire temperature curve following the procedures prescribed in ISO834. In each experiment, the beam collapsed in either of two collapse modes: bending collapse due to shear fracture of high-strength bolts at the bottom flange, or flexural collapse of the net section. In particular, for the case of the 'full strength' bolted connection, the beam with a lower load collapsed in the bolt fracture mode; however, the beam with the same configuration collapsed in the net section mode when a larger load was applied. It was found that the collapse temperature of the beam was higher for lower loads. The shift in collapse modes could be attributed to the relatively sharp decrease in strength of high-strength bolts at higher temperatures. It was verified that the bending strength of the steel beam joints such as tested in this investigation can be estimated by theoretical formulae based on the simple plastic theory.

KEYWORDS: Fire-Resistance, Full Scale Experiment, Steel Beam, High Strength Bolt, Connection

1. INTRODUCTION

In order to evaluate the fire resistance of a steel building, detailed considerations must be made on the behavior of both the members and the entire structure at elevated temperatures. One of the key issues related to the fire resistance of members is the evaluation of a joint connected by high-strength bolts. The characteristics of material strength of high-strength bolts at elevated temperature resemble those of steel; however, the tension or shear strength of bolts decreases along with temperature rise at a more remarkable rate than that of ordinary steels. Several tension tests of high-strength bolts and bolted connections have been conducted to investigate such characteristics.[1-5] Ozaki and Suzuki [6] proposed an analytical method for estimating the collapse temperature of bolt-connected joints based on the simple plastic theory. They also proposed an FEM model of joints connected by high-strength bolts to investigate the fire resistance of steel frames that incorporate such joints. To the best of our knowledge, fire resistance of a full-scale member with bolt-fastened joints has not been investigated experimentally. Thus, fundamental information such as load-bearing and deformation capacities of those members at elevated temperature is not available.

In this research, full-scale fire resistance experiments on protected steel beams with a bolted connection were conducted to investigate collapse modes and bending strength of the beam joints at elevated temperatures. The collapse temperatures obtained by the experiments are compared to collapse temperatures calculated by analytical methods.

2. EXPERIMENTS

2.1 Equipment

The horizontal furnace in the Building Research Institute (Tsukuba, Japan) was used for the experiments. The space inside the furnace is 4 000 mm × 4 000 mm × 2 000 mm (depth). The furnace lining consists of ceramic fiber block

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(CF block), which covers all the internally exposed surfaces of the furnace. Liquefied natural gas (LNG 13A, 46.0 MJ/m^3) is used for fuel. Loading is introduced by a 1 000-kN hydraulic jack with a maximum stroke of 500 mm.

2.2 Test Specimens

The steel beam specimens were fabricated from wide-flange H-488×300×10×18 section steel. Length of the test specimen is 6 000 mm; the span between the supports is 5 400 mm; and the exposed length is 4 000 mm as illustrated in Fig. 1. Each specimen has a joint at the centerline. SN400B grade steel was used for both the beam and the splice plates.

Five fire-resistance tests were conducted. Table 1 summarizes the conditions of each experiment. There are 3 types of specimens, i.e., A1, A2, and B, each having a different joint. The details of the configuration are illustrated in Fig. 2. The bolts used for the specimens were torque shear type high-strength bolts S10T-M20, which were supplied from the same production lot. The diameter of bolt holes was 22 mm. The size of the splice plates was determined so that the strength of the splices would be larger than that of the beam section. Splice plates 12 mm thick were used for both the web and flange connections.

2.2.1 Specimens A-1 and A-2

For Specimens A1 and A2, the number of bolts was unrealistically reduced so that the bolt fracture would precede the net section failure at elevated temperature. The bolts in the web were removed for Specimen A2 from Specimen A1. The flexural strength ratio γ at normal temperature is defined by Eq. (1).

$$\gamma = \frac{\overline{M}_J}{\overline{M}_p}, \quad (1)$$

where

$\overline{M}_J$: Flexural strength of the beam joint due to bolt fracture at normal temperature, and

$\overline{M}_p$: Full plastic moment of the beam at normal temperature.

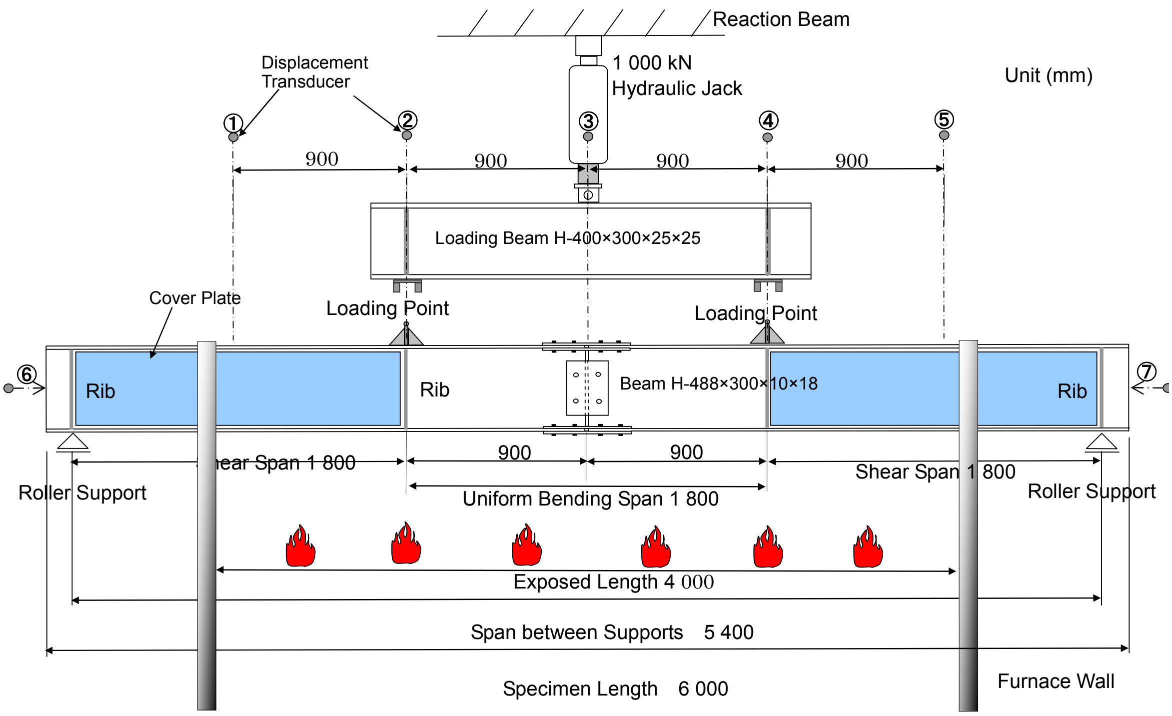


Fig. 1 Configuration of Experiments

Table 1 Experiment Conditions

Symbol	Specimen type	Description	Thickness of protection	Moment load (Applied load)
BJ-A1-1	A1	Figure 2(a) Joint/Beam Strength Ratio $\gamma = 0.91$, Number of bolts: flange = 4, web = 2	25 mm	$0.39\overline{M}_y$ (290 kN)
BJ-A1-2				$0.23\overline{M}_y$ (176 kN)
BJ-A2	A2	Figure 2(b) Joint/Beam Strength Ratio $\gamma = 0.81$, Number of bolts: flange = 4, web = 0	12.5 mm	$0.23\overline{M}_y$ (176 kN)
BJ-B-1	B	Figure 2(c) Joint/Beam Strength Ratio $\gamma = 2.13$, Number of bolts: flange = 10, web = 3	12.5 mm	$0.75\overline{M}_y$ (572 kN)
BJ-B-2			25 mm	$0.33\overline{M}_y$ (246 kN)

$\overline{M}_J$ in Eq. (1) is evaluated by Eq. (2).[8]

$$\overline{M}_J = 0.6\overline{\sigma}_B \left\{ A_{Bf}(d - t_f) + \frac{1}{4} A_{Bw} d_w \right\}, \quad (2)$$

where

A_{Bf} : Total effective area of shear planes of all bolts in the flange,

A_{Bw} : Total effective area of shear planes of all bolts in the web,

d : Effective depth of the beam,

t_f : Thickness of the beam flange,

d_w : Effective depth of the bolt group in the flange8), and

$\overline{\sigma}_B$: Nominal strength of high-strength bolt at normal temperature (1 000 N/mm^2 for F10T).

The values of γ defined by Eq. (1) are given in Table 1. In the calculation of $\overline{M}_p$, nominal yield strength 235 N/mm2 of SN400B grade steel was used.

2.2.2 Specimen B

Specimen B is designed so that the bolted connection complies with the 'optimum' solution given in the AIJ recommendation.9) The optimum solution satisfies the following condition:

$${}_s\overline{M}_J = \overline{M}_y , \quad (3)$$

where

${}_s\overline{M}_J$: Slip strength of the bolted connection at normal temperature, and

$\overline{M}_y$: Elastic limit moment of the beam at normal temperature.

Bolted connections in actual steel beams are usually designed so that the left-hand side of Eq. (3) is greater than the right-hand side. For Specimen B, the number of bolts was adjusted to satisfy Eq. (3); however, as the number should be an integer, it was not possible to satisfy the equation exactly. The resulting relation was ${}_s\overline{M}_J \approx 1.04\overline{M}_y$ for Specimen B. At normal temperature, because the flexural strength ratio $\gamma = 2.13$ for Specimen B, the joint is supposed to fail by flexural failure of the net section before a bolt fracture occurs. Specimen B complies with the full-strength connection criteria.

All test specimens were protected by ceramic fiber blanket to avoid local failure due to excessive heat exposure. The thickness of the blanket was selected from 25 mm and 12.5 mm to control the length of heating so as not to exceed three hours.

2.3 Measurements

2.3.1 Temperature

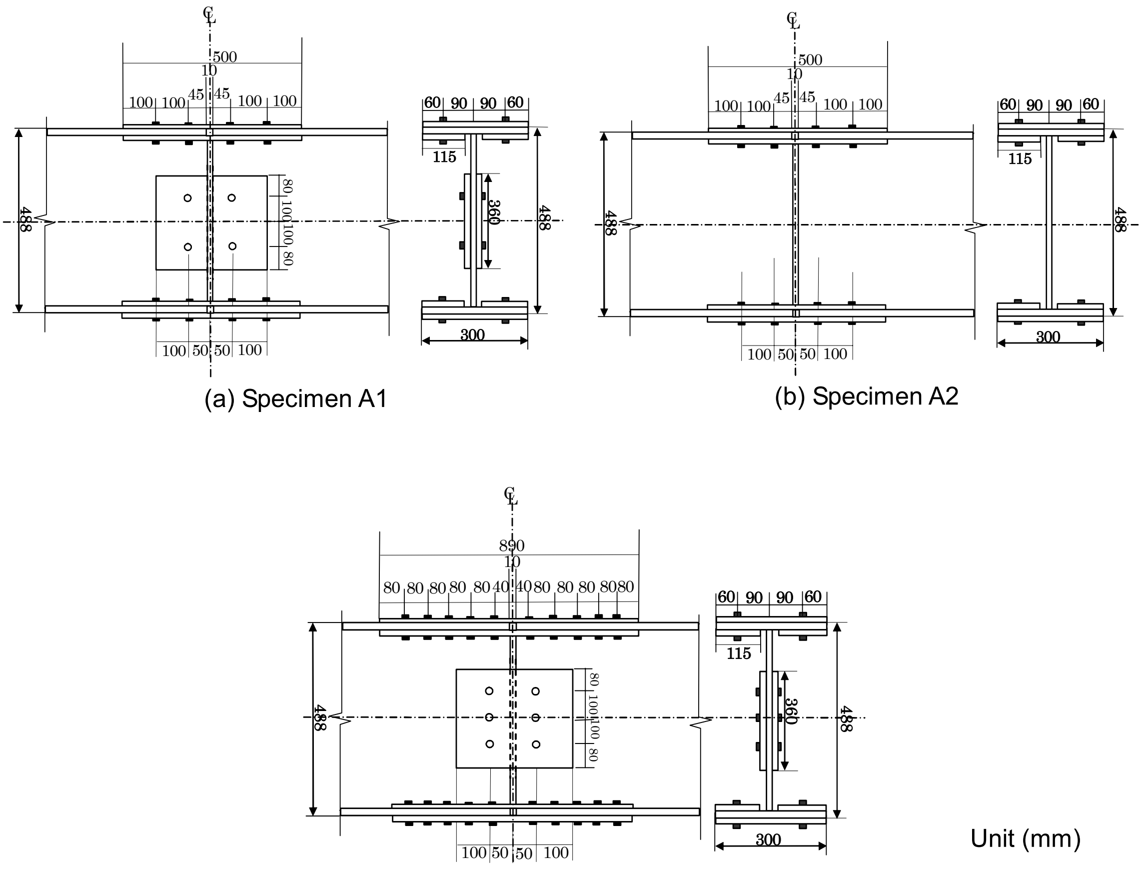
The temperature of steel surfaces and bolts was measured by thermocouples. The thermocouples were located on the surfaces of splice plates at joints, on beam sections under the loading points, on beam sections at the center of the span between a loading point and the centerline, and on all the bolts at the half-side of the joint. The locations of thermocouples are shown in Figs. 3 to 5. A 2-mm-diameter hole was drilled in the bolt head to install a thermocouple. Temperature data including furnace temperatures was recorded in 30-second intervals.

2.3.2 Displacement

Deflection and longitudinal expansion of the beam were measured by displacement transducers at the locations shown in Fig. 1. The deflections were measured at both ends of the top flange at the center and loading points of the beam. The data was recorded in 30-second intervals.

2.4 Experiment Procedure

After setting up a test specimen, a specified load as is given in Table 1 was applied manually in several steps. The applied load was sustained for 30 minutes before the heating was started. Deformations were recorded during the loading period, and then they were adjusted to zero before starting the heating. After the commencement of heating, the furnace temperature was controlled automatically to follow the ISO 834 standard fire temperature curve. Meanwhile, the load was controlled manually by adjusting the stroke of the



(a) Specimen A1

(b) Specimen A2

(c) Specimen B

Fig. 2 Details of the Bolt Connections

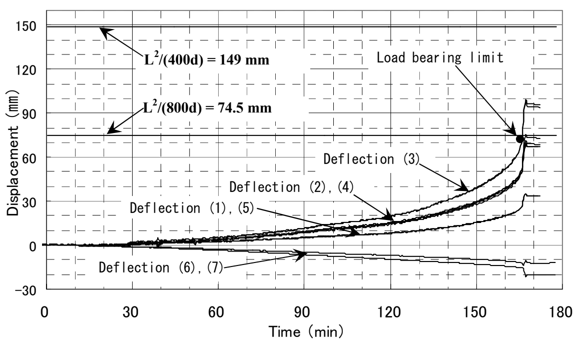
hydraulic jack. The heating was terminated when the applied load could no longer be sustained.

3. RESULTS OF EXPERIMENTS

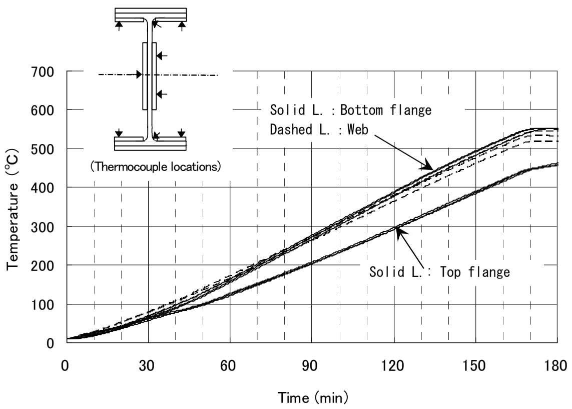
Beam deformation, and temperature of bolts, of splice plates in the joint, and of the furnace are plotted against elapsed time in Figs. 3(a) to 3(d), respectively. In Fig. 3(a), the number in parentheses corresponds to the point of transducer contact as shown in Fig. 1. The longitudinal deformations, (6) and (7), are plotted as minus when the beam expands. The temperatures of bolts or splice plates in the flange are plotted in solid lines in Figs. 3(b) and 3(c) and temperatures belonging to the web are plotted in dashed lines. The Robertson-Ryan deflection criteria [10], i.e. $L^2/(400d)$ and $L^2/(800d)$, are also shown in Fig. 3(a).

The furnace temperature is well controlled according to the ISO 834 standard curve as is shown in Fig. 3(d). Each measured temperature of the bolts and splice plates in the connection is also raised as time elapsed. The temperatures of the top flange are lower than those of the bottom flange or web as shown in Figs. 3(b) and (c). The difference is attributed to the boundary condition in which the top flange was covered by a precast lightweight concrete slab that was cooled by the exterior environment. It was found that the temperature difference between a bolt and adjacent splice plate is negligibly small.

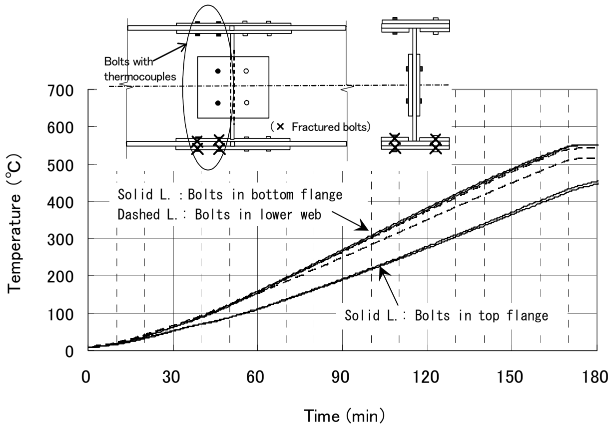
The beam lost its load bearing capacity at about 166 minutes after the start of heating. Two large sounds were heard following a sharp increase of the beam deflection. Four flange bolts in one side of the joint were found fractured after the



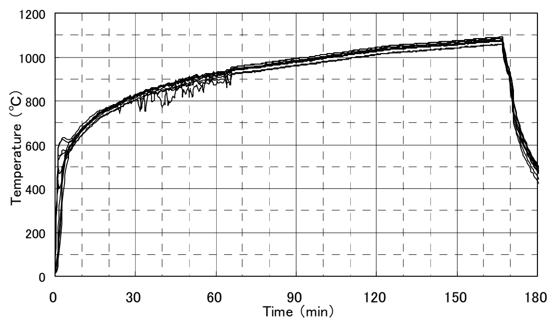
(a) Deformation vs. Elapsed Time.



(b) Bolt Temperature vs. Elapsed Time.



(c) Steel Temperature vs. Elapsed Time.



(d) Furnace Temperature vs. Elapsed Time.

Fig. 3 Results of Experiment BJ-A1-1

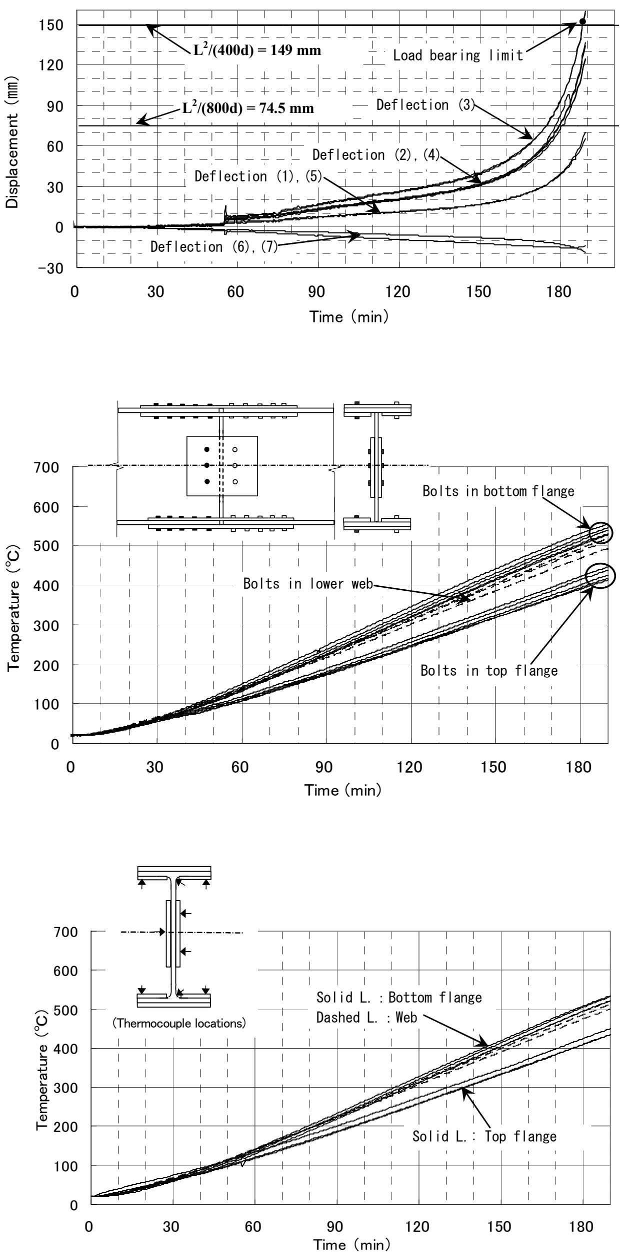


Fig. 4 Results of Experiment BJ-B-1

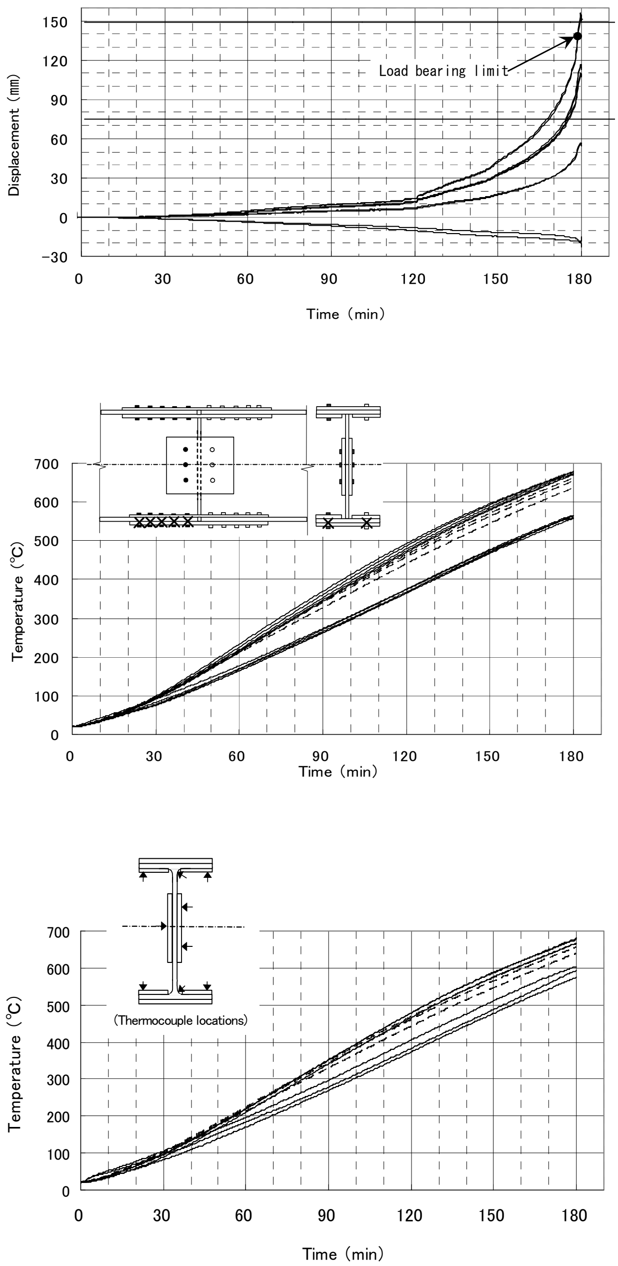


Fig. 5 Results of Experiment BJ-B-2

experiment. Each bolt was fractured in shear at two shear planes as shown in Fig. 6 (two of the four bolts in the figure). Flange bolts in the other side of the joint were not fractured but they showed significant residual shear deformation. The temperature of the bottom flange was approximately 540°C at the failure point.

3.2 BJ-B-1

Results of the BJ-B-1 experiments are shown in Fig. 4. The graph of furnace temperature is omitted because it is similar to that of Fig. 3(d). A large slip sound was heard when the bolts in the bottom flange reached 130°C at around 55 minutes after the start of heating. Peaks in Fig. 4(a) also indicate the occurrence of slip at that

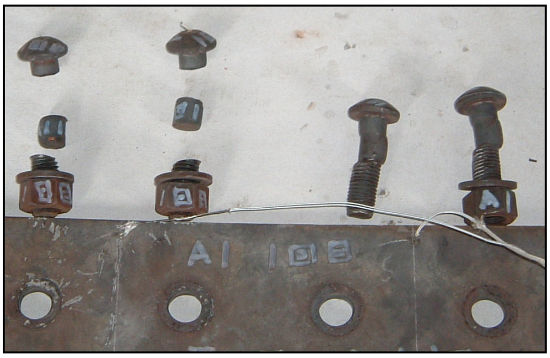


Fig. 6 Fractured and Deformed Bolts

time. Slip sounds were heard intermittently until about 180 minutes. Then, the deflection increased rapidly, and at about 188 minutes it became impossible to keep the load at the prescribed level.

Neither bolt fracture nor splice plate damage were observed after the experiment. The residual deflection was significant and the deformations were concentrated at the connected part. From these observations, it can be said that the beam collapsed due to the formation of a plastic hinge in the net section.

3.3 BJ-B-2

Results are shown in Fig. 5. The configuration of the specimen is similar to that of BJ-B-1; however, the load level is lower in the BJ-B-2 experiment. It should be noted that, as shown in Figs. 4(a) and 5(a), the temperature rise is quicker for BJ-B-2 than for BJ-B-1, because thinner (12.5 mm) protection is used in order to conduct the experiment within 3 hours.

At about 70 minutes after the start of heating, a large slip sound was heard for the first time. The temperature of the bolts in the bottom flange was around 300°C. Slip sounds continued intermittently until 170 minutes. At 177 minutes, two large sounds were heard successively and the load was abruptly reduced to zero.

The observation conducted after the experiment revealed that all bolts in the bottom flange of one side of the joint were fractured in shear as indicated in Fig. 5(b). Unlike in the case of BJ-A1-1, the bolts fractured in only one of the two shear planes. In this case, the fractured shear plane is in the threaded portion of the bolt. The beam failed by shear fracture of the bolts.

4. DISCUSSIONS

4.1 Collapse Mode and Collapse Temperature

Collapse modes and collapse temperatures obtained by the experiments are summarized in Table 2. The collapse temperature is higher for lightly loaded cases. It is noteworthy that the collapse temperature of BJ-A1-2 is 25 K higher than that of BJ-A2, even though the load levels are identical for the two experiments. The difference in collapse temperatures can be attributed to the contribution of the web bolts to the fire resistance of the joint.

For the B-type specimen, whose bolted connection satisfies the full-strength connection criteria, the collapse mode changes depending on the load level, as shown in Table 2. For higher load levels, the connection fails due to the flexural failure of the net section (BJ-B-1);

Table 2 Summary of experimental failure temperatures

Symbol	Moment load	Failure mode	Failure temperature
BJ-A1-1	$0.39\overline{M}_y$	Shear fracture of bolts	536°C *
BJ-A1-2	$0.23\overline{M}_y$	Shear fracture of bolts	618°C *
BJ-A2	$0.23\overline{M}_y$	Shear fracture of bolts	593°C *
BJ-B-1	$0.75\overline{M}_y$	Flexural failure of base steel	533°C **
BJ-B-2	$0.33\overline{M}_y$	Shear fracture of bolts	672°C *

* Average temperature of bolts in the bottom flange.

** Average temperature of the bottom flange in joint zone.

however, in the case of low load levels, the collapse mode is the shear fracture of bolts (BJ-B-2). As mentioned in Section 2.2.2, the connection will not collapse by bolt fracture at normal temperature regardless of the load level. However, because the strength reduction of high-strength bolts at elevated temperature is sharper than that of steel, bolt fracture may precede at higher collapse temperature. It is noteworthy that even the full-strength bolt connection can fail by bolt fracture at elevated temperature.

4.2 Analytical Model

The temperature distribution of a cross-section of steel beam subject to three sides heating is not uniform. As the top flange is cooler than the bottom flange, the former is relatively stronger than the latter. Thus, the neutral axis of the heated beam moves upward from the center of the web. Nakagawa and Suzuki [12] proposed a method for evaluating the full plastic moment of the beam taking into account the temperature gradient in the cross-section. Assuming the neutral axis laying on the boundary of the top flange and the web, the full plastic moment of a beam cross-section at elevated temperature is given by:

$$M'_p = \kappa(T)\overline{\sigma}_y \left\{ A_f(d - t_f) + A_w \frac{d - t_f}{2} \right\}, \quad (4)$$

where

$\kappa(T)$: Strength reduction factor of steel at temperature T

A_f : Cross-sectional area of the beam flange, and

A_w : Cross-sectional area of the beam web.

Similarly,

$$M'_{pe} = \kappa(T)\overline{M}'_{pe}, \quad (5)$$

$$M'_J = \kappa_B(T)\overline{M}'_J = \kappa_B(T) \cdot 0.6\overline{\sigma}_B \left\{ A_{Bf}(d - t_f) + \sum A_{Bwi}\left(d_{wi} + \frac{t_f}{2} \right) \right\} \quad (6)$$

where

$\kappa_B(T)$: Strength reduction factor of high-strength bolt at temperature T,

$\overline{M}'_{pe}$: Effective full plastic moment of beam at normal temperature, assuming the neutral axis at the boundary of top flange and web,

$\overline{M}'_J$: Flexural strength of the bolted joint at normal temperature, assuming the neutral axis at the boundary of top flange and web,

A_{Bwi}: Effective area of shear planes of a bolt in the web, and

d_{wi}: Distance between the neutral axis and a web bolt.

The summation in Eq. (5) represents the sum over all web bolts. Theoretical limit temperatures corresponding to collapse modes are given by solving the following equations.

Limit temperature for beam collapse:

$$T'_1 : \tilde{m} = \chi \cdot \kappa(T), \quad (7)$$

Limit temperature for collapse by net section:

$$T'_2 : \tilde{m} = \chi_e \cdot \eta \cdot \kappa(T), \quad (8)$$

Limit temperature for collapse by bolt fracture:

$$T'_3 : \tilde{m} = \chi_J \cdot \gamma \cdot \kappa_B(T), \quad (9)$$

where $\tilde{m}$ is the moment load normalized by $\overline{M}_p$, $\chi = \overline{M}'_p / \overline{M}_p$, $\chi_e = \overline{M}'_{pe} / \overline{M}_{pe}$, $\chi_J = \overline{M}'_J / \overline{M}_J$, and $\eta = \overline{M}_{pe} / \overline{M}_p$.

4.3 Comparison of Experiments and Snalytical Model

The collapse temperatures calculated by the analytical formulae in the previous section and obtained by the experiments are compared in Fig. 7. In the figures, solid and dashed lines are drawn by using Eqs. (8) and (9). $\kappa(T)$ and $\kappa_B(T)$ are calculated using the actual data from the tension tests of the bolts and steel coupons. The tension test results are given in Table 3. The solid and open circles in Fig. 7 represent the moment load level and the collapse temperature in respective experiments.

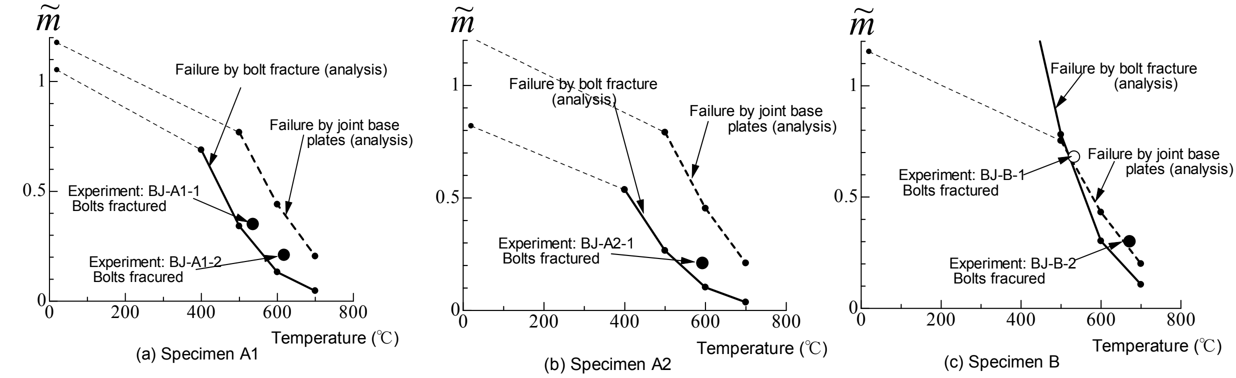


Fig. 7 Comparison of analytical and experimental collapse temperatures

In the case of Specimens A1 and A2 (Figs. 7(a) and 7(b)), the estimated (analytical) collapse temperature is lower for the bolt fracture mode at any load level. This corresponds to the experimental results. In the case of Specimen B (Fig. 7(c)), the estimated collapse temperature by flexural failure of the net section (dashed line in the figure) is lower at higher load levels, and the collapse temperature by bolt fracture becomes lower at lower load levels. This tendency also corresponds to the experiment results.

The experimental collapse temperatures of bolt fracture are slightly higher than the estimated temperatures in all cases. One reason for the difference is that, in the experiments, bolts in the web are cooler than those in the bottom flange. Another possibility is that the shear strength of bolts at elevated temperatures is higher than $0.6\sigma_B$.

5. CONCLUSIONS

In this research, fire resistance experiments on the high-strength bolt connection provided inside a steel beam were conducted to investigate the collapse mode and flexural strength of the bolted beam joint at elevated temperatures. The major findings obtained from this research are:

The collapse mode of Specimens A1 and A2 is flexural collapse of the beam joint due to shear fracture of the bottom flange bolts. On one hand, the collapse mode of Specimen B is the flexural failure of the net section for higher load levels; however, as the load level becomes small the collapse mode changes to the shear fracture of the connecting bolts in the bottom flange.
The collapse temperature of the bolted joint is lower for higher load levels. Namely, fire

Table 3 Tension test of bolt and steel

Temperature	Steel: SN400B Strength at 1% strain (N/mm^2)	Bolt: S10T Tensile strength (N/mm^2)
RT	277	1012
400°C	---	662
500°C	181	328
600°C	104	127
700°C	48	48

Strength is the average of two tests. Strain rate is 0.3%/min. throughout test.

resistance of the beam joint, as with other steel members, depends on the level of load.

For the beam joint where many bolts are installed, such as in Specimen B, the shear fracture of bolts may precede at elevated temperatures. A beam joint that can withstand high temperature, because the load level is small, corresponds in this case. This is because the strength decrease of bolts is considerable at high temperature; hence, the strength of bolt in shear becomes relatively small. As Specimen B satisfies the full-strength connection criteria to which actual steel frames are commonly designed, there is a possibility that a bolt fracture will precede in the actual construction in a case of fire.

Assuming collapse modes by bolt fracture and by flexural failure of net section, analytical collapse temperatures of the beam joint were evaluated. These analytical solutions were verified by the experimental results in this research.

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