The Seventh Asian-Pacific Symposium on Structural Reliability and Its Applications (APSSRA2020)
October 4–7 2020, Tokyo, Japan
T. Takada, I. Yoshida & T. Itoi (editors)

Estimation of fracture probability of a steel member subjected to localized fire and the code calibration for the current fire resistant design

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Abstract: The main purpose of this study is to estimate fracture probabilities of unprotected steel members subjected to localized fire by using Monte Carlo simulations considering dispersions of heat generation ratio, dead and live loads and steel strength at elevated temperatures. The collapse temperature of unprotected steel beam subjected to the localized fire of woody and plastic combustibles, respectively, and the fracture probability of that optimally designed by the AIJ Fire-Resistant Design Guidelines were evaluated by the parametric numerical analyses. From the analytical results, both reliability indexes for the steel beam and required performance standard due to the AIJ Fire-Resistant Design Guidelines codes were clarified.

Keywords: Localized fire, Steel structure, Fracture probability, Monte Carlo method, Code calibration.

1. Introduction

When designing a fire resistant steel structure, it is necessary to prevent the steel members from collapsing due to fire. In “Fire-Resistant Design Guidelines for Steel Structures” (hereinafter referred to as “Fire-Resistant Design Guidelines”, Japan Architectural Institute(AIJ) 2017), a comparison on performance of a steel member at fire is conducted in between the temperature of steel member risen by the fire and the collapse temperature at which that collapses, and the fire-resistance is verified by confirming that the latter exceeds the former. When evaluating those, each verification method must be taken into account the effects of the inevitable variations on the fire resistant design, which are represented by fire loads and the steel strength at the elevated temperature. The authors have examined the effects by using numerical analyses based on the Monte Carlo method (MC method) in a case of fully developed compartment fire(Ozaki et al. 2018), and clarified the fire resistance performance level of steel members required by Fire-Resistant Design Guidelines (Tezuka et al. 2018).

On the other hand, for a fire room in the case when the possibility of fire spread is small because the amount of combustible materials is small, a localized fire is often selected as the fire action of the fire resistant design. For the concrete kinds of fire load, desks and sofas in the room are, for instance, selected as the flammable materials. However, the detailed information of localized fires is unknown at the practical design and there is the possibility that the steel member collapses at the lower temperature than the design collapse temperature because of those unexpected variations.

In this paper, by focusing on the heat rate curve of the localized fire, steel strength at the elevated temperature, we conducted the numerical analyses based on the MC methods considering those variations and clarified the steel beam temperatures without fire proofing materials and the failure probability at the localized fire. Furthermore, for the unprotected steel beam subjected to the localized fire, the fire resistant performance level required by the Fire-Resistant Design Guidelines is clarified, by conducting the code calibration

2. Setting of Localized fire

2.1 Heat generation rate curve

The heat release rate curve for the localized fire is approximated by the curve shown in Fig.1 (Natori et al. 2018; AIJ 2013), which are determined by the four parameters, that is, the fire growth rate $\alpha[\mathrm{kW}/s^2]$, the maximum heat release rate $Q_{max}[\mathrm{kW}]$, the total heat release THR [kJ] and the fire decay rate $\alpha_d[\mathrm{kW}/s^2]$.

In the following analysis, according to “Recommendations for Design Fire Loads and Fire Actions in Buildings(Draft) (Architectural Institute of Japan 2013, hereinafter“ Fire Property Guidelines”), the above four parameters (Q_{max}, THR, α, α_d) are determined, respectively, from the information on simplified combustible material dimensions and their main constituent materials (plastic or wood).

The shape of combustible is given by a cubic circumscribed to that, which is defined by the dimensions of the combustible (bottom area: $D \times D[\mathrm{m}^2]$, height: H_{ob}). The above four parameters (Q_{max}, THR, α, α_d) are determined using the relational equations as shown in Table 1 [7)], that is, the fire growth rate α, the maximum heat release rate Q_{max}, and the total heat release THR are determined by the bulk density $\rho_b[\mathrm{kg/m^3}](= W/D^2 H_{ob})$, the bulk surface area $A_f[\mathrm{m}^2](= 4DH_{ob} + D^2)$, and the weight $W[kg]$, respectively. In Table 1, for example, the right side of the function equation on the parameter α of the woody combustible includes a numerical expression as "15.0 ± 17.1", and that indicates coefficients on "average value ± standard deviation value" on the statics of parameter α. (Natori et al. 2018). For the bulk density in this analysis, the values of 50 and 35 $\mathrm{kg/m^3}$ are used for the wood- and plastic-based combustibles, respectively (Fire Property Guidelines).

In the MC analysis, the fire growth rate α, the maximum heat release rate Q_{max}, the total heat release THR, and the fire decay rate α_d were given by probability variables, respectively, and those were assumed to follow a lognormal distribution. In addition, since those correlations among the above four parameters were not clarified in previous studies, the samples in the MC analysis were generated on the assumption that those do not depend each other. The average values and standard deviations were calculated using the above-mentioned equations as shown in Table 1. The reason adopting the lognormal distribution for the above probability variables is that; the fire growth rate α has already been examined to follow the lognormal distribution by the past research (Natori et al. 2018), however, the distribution of probability density function for the other three parameters (Q_{max} THR α_d) has never been examined. In this analysis, the lognormal distributions were used, because of avoiding to give the unrealistic negative values for those probability variables. The total number of each sample was 1,000 for the analysis in Chapter 3 and 10,000 for the analysis in Chapter 4. Fig. 3 shows the sample examples of heat release rate curves on wood and plastic combustibles, respectively (20 examples).

2.2. Temperature on fire source axis of fire source

Assuming that the unprotected steel beam is provided just above the combustibles, which is sufficiently away from walls in the room, the steel beam temperature is analyzed by using the air temperature extended alone the central axis of the fire source and the smoke layer temperature around the steel beam. The air temperature extended alone the central axis of the fire source were determined by the following equation (Fire Property Guidelines).

$$\Delta T = \begin{cases} 800 & (z^* \le 1.2) \\ 960/z^* & (1.2 \le z^* \le 2.4) \\ 1720/z^{*\frac{5}{3}} & (2.4 \le z^*) \end{cases} \quad (1)$$

$$z^* = (z + \Delta z)/(Q^{*\frac{2}{5}} D) \quad (2)$$

$$\Delta z = \begin{cases} 2.4D\left(Q^{*\frac{2}{5}} - Q^{*\frac{2}{3}}\right) & (Q^* \le 1) \\ 2.4D\left(1 - Q^{*\frac{2}{5}}\right) & (1 < Q^*) \end{cases} \quad (3)$$

$$T_f = T_0 + \Delta T \quad (4)$$

Where, T_0 is the ambient temperature (= 293K), ΔT is the incremental temperature of air temperature extended alone the central axis of the fire source [K], z is the fire height from the fire source surface [m], and z^* is the dimensionless fire height [-] , Δz is the position [m] of the virtual point of the fire source, D is the representative length [m] and T_f is flame temperature[K].
On the other hand, Q^*in the above equations (2) and (3) is a dimensionless heat release rate, which is evaluated by the following equation from Fire Property Guidelines .

$$Q^* = \frac{Q}{c_p \rho_0 T_0 \sqrt{g} D^{\frac{5}{2}}} = \frac{Q}{1116 D^{\frac{5}{2}}} \quad (5)$$

Where, c_p is the specific heat of air under the constant pressure [kJ/kgK], g is the gravitational acceleration $[m/s^2]$, and ρ_0 is the air density $[kg/m^3]$ and Q^* are dimensionless heat release rates [-].

Table1 Average and standard deviation of numerical parameters of heat release rate curves

Woody combustibles	$\alpha = (15.0 \pm 17.1)/\rho_b^{1.2}$
	Q_{max}=$(148 \pm 90)A_f$
	$THR = 1000(10 \pm 7)W$
	$\alpha_d = 0.34 \pm 0.56$
Plastic combustible	$\alpha = (0.311 \pm 0.472)/\rho_b^{0.5}$
	$Q_{max} = (272 \pm 204)A_f$
	$THR = 1000(15 \pm 8)W$
	$\alpha_d = 0.035 \pm 0.059$

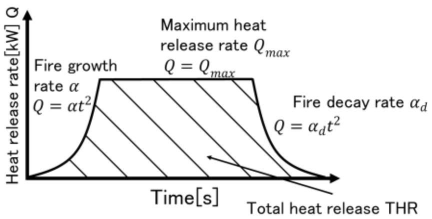
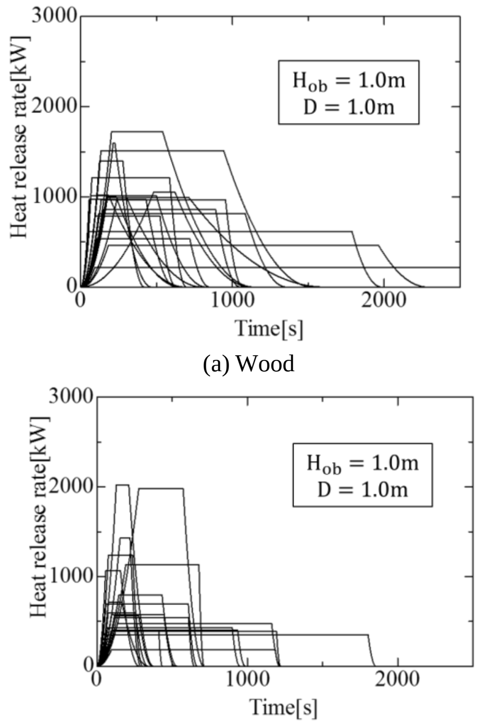


Figure.1 Modeling of a heat release curve



(b) Plastic
Figure.3 Samples of heat release rate curves

2.3 Smoke layer temperature

When considering the heat transfer from the smoke layer to the steel beam, the dimensions of room shape must be determined and those values were given by A_r = $400m^2$ A = $10m^2$ H_a = 2m, respectively, where, A_r is the ceiling area $[m^2]$, A is the opening area $[m^2]$, and H_a is the opening height [m].

The following equations (6) and (7) proposed by the Fire Property Guidelines are used, respectively.

$$\frac{\Delta T_{sm}}{T_0} = 0.023\left(\frac{Q}{A\sqrt{H_a}}\right)^{\frac{2}{3}}\left(\frac{A\sqrt{H_a}}{A_T}\right)^{\frac{1}{3}} h_k^{-\frac{1}{3}} \quad (6)$$

$$T_{sm} = T_0 + \Delta T_{sm} \quad (7)$$

Where, ΔT_{sm} is the smoke layer incremental temperature [K], A_T is the wall ceiling area exposed to the smoke layer [m^2], h_k is the effective heat transfer coefficient, and T_{sm} is the smoke layer temperature [K].
The effective heat transfer coefficient h_k is given by the following equation (Fire Property Guidelines).

$$h_k = \begin{cases} \frac{k}{\delta} & (t > \frac{c\rho\delta^2}{4k}) \\ \sqrt{\frac{k\rho c}{t}} & (t \le \frac{c\rho\delta^2}{4k}) \end{cases} \quad (8)$$

Where k is the thermal conductivity of wall [kW/mK], δ is the wall thickness [m], ρ is the wall density [kg/m^3], c is the specific heat [kJ/kgK], and t is the fire duration time [s].

The above values of k, δ, ρ, and c for the wall are k = 1.51×10^{-3}[kW/mK], δ = 0.6 [m], ρ = 2200 [kg/m^3] and c = 0.88[kJ/kgK], by assuming that the wall consists of concrete materials.

For the smoke layer height, the following equation using the information on the area of the wall and ceiling exposed to the smoke layer was used **(**Fire Property Guidelines).

$$z_{sm} = \left\{\frac{2}{n+3} \times \frac{k_z}{A_r} Q_0 t^{\frac{n+3}{3}} + H_r^{-\frac{2}{3}}\right\}^{-\frac{3}{2}} \quad (9)$$

$$k_z = 0.08/\rho_s \quad (10)$$

$$\rho_s = 353/T_{sm} \quad (11)$$

Where, z_{sm} is the smoke layer height [m], ρ_s is the smoke density [kg/m^3], and Q_0 is the value of heat release rate, which is given by either fire growth rate at the fire growth or the maximum heat release rate at the peak fire. n is 2 at the fire growth or 0 at the peak fire, respectively. H_r is the height of the ceiling [m], which is given by the distance from the floor to the flange below the beam(3.5 m).

2.4. Calculation of uncoated steel beam temperature

The temperature of unprotected steel beams was determined by the calculation model proposed by Fire-Resistant Design Guidelines. The steel beam temperature is calculated under either different condition when the beam is exposed to the flame or not. Referring to the fire resistance design guidelines, the intermittent flame height L_i is estimated from the following equation (12), and the heat transfer rate *q* to the steel beam is determined in either case when the obtained L_i contacts with the ceiling(case (I) of the beam exposed to the flame) or not(case (II) of that in the smoke layer).

$$L_i = 0.2Q^{2/5} \quad (12)$$

(Ⅰ) The case when the beam is exposed to flame

$$q = q_c + q_r = h_c(T_f - T_{surf}) + \varepsilon_{eff}\sigma(T_f^4 - T_{surf}^4) \quad (13)$$

Where h_c is the convective heat transfer coefficient (= $23.0W/m^2K$), T_f is the air temperature extended alone the central axis of the fire source (equation (4)), [K], T_{surf} is the surface temperature of the steel beam [K], ε_{eff} is the total emissivity (= 0.9), σ is the Stefan-Boltzmann constant (= $5.67 \times 10^{-8}W/m^2K^4$) .

(Ⅱ) The case when beam is wrapped in smoke layer

$$q = q_c + q_r = h_c(T_0 - T_{surf}) + \varepsilon_{surf}\left[\begin{array}{l} \varepsilon_s\sigma(T_{sm}^4 - T_{surf}^4) + (1-\varepsilon_s)\{F_{f(c)}\sigma(T_{f(c)}^4 - T_{surf}^4) \\ +F_{f(f)}\sigma(T_{f(f)}^4 - T_{surf}^4) + (1 - F_{f(c)} - F_{f(f)})\sigma(T_0^4 - T_{surf}^4)\} \end{array}\right] \quad (14)$$

Where ε_{surf} is the emissivity of the member surface of the beam (= 0.9), ε_s is the emissivity of the smoke layer, $F_{f(c)}$ is the view factor when viewing the surface area of the continuous flame from the beam surface, and $F_{f(f)}$ is that when viewing the surface area of the intermittent flame from the beam surface, $T_{f(c)}$ was the temperature of the continuous flame (= 1093 [K]), and $T_{f(f)}$ was the temperature of the intermittent flame (= 977 [K]).

The above view factor $F_{f(f)}$ was determined by assuming that the unprotected H-shaped beam is subjected to three-side heating. The emissivity of the smoke layer is assumed to be $\varepsilon_s = 0$ (Architectural Institute of Japan 2013).For both (I) and (II) cases, the steel beam temperature is calculated by the following thermal equilibrium equation.

$$\rho_{st} c_s A_s \frac{dT_{st}}{dt} = H_{sr} q_r + H_r q_c \quad (15)$$

Where, ρ_{st} is steel density (= 7850 [kg/m^3]), c_s is specific heat of steel ($= 482 + 8.0 \times 10^{-7} \times T_{st}^2$ [J/kgK]), A_s is the beam cross section [m^2], T_{st} is the steel beam temperature [K], H_{sr} and H_r is the heating circumference of the cross section for the heat transfer rate of radiation and convection [m], respectively.

It was assumed that the steel beam temperature uniformly increased in the cross section. The sectional shape factor H/A of the used H-section was given by the analytical parameter, and those values were given by H/A=100, 217, and 289m^{-1}, respectively. Table 2 shows the H-shaped cross-sectional dimensions.

3. Analysis of Steel Beam Temperature in Cases without Variations on Heat Release Rate of Combustible

In this chapter, in order to examine the effect of combustible material dimensions, which were given as the definitive values in the MC analysis, on the maximum temperature of steel beam, the definitive analysis in the case when using the heating rate curve without the variations was performed.

3.1 Analytical model of unprotected steel beam subjected to localized fire

Fig.4 shows the analytical model. In Fig.4, the combustible material dimensions D and H_{ob}, the material constituents (wood and plastic) were also given as the parameters, which were the definitive values without the dispersion. The distance from the floor to the lower flange of the beam was given by the constant value of 3.5 m.

As described in Chapter 2, the steel beam temperature is evaluated by the MC analysis taking into account the dispersions of the four parameters (α, Q_{max}, THR [kJ] and α_d) on the heating rate curve. The statistical properties of that maximum value are discussed in the following chapters.

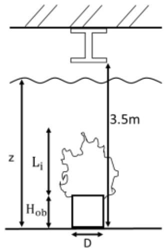


Figure.4 Analytical model

Table2 H-shaped steel size

H/A=100m^{-1}	H350×350×12×19[mm]
H/A=217m^{-1}	H194×150×6×9[mm]
H/A=289m^{-1}	H150×75×5×7[mm]

3.2 Combustible dimensions and steel beam maximum temperature relationships

Fig.5 and 6 show the maximum steel beam temperature — the bottom dimension D and height H_{ob} [m] of combustible relationships, respectively. For the four parameters (Q_{max}, THR, α, α_d) on the heating rate curve, those average values were used, respectively. In the analysis, both combustible material dimensions D and H_{ob} were given by the analytical parameters, on the other hand, the parameter of H/A was given by $100m^{-1}$.
In both analytical results of the woody and plastics combustibles, the maximum temperature of steel beam becomes higher with increasing the size of combustibles, it is, however, clarified that the effect of the bottom dimension D on the maximum temperature is less sensitive than the height H_{ob}. Based on the tendency of those analytical results, in the following MC analyses, the bottom dimension D of combustibles material was set to the constant value of 1 m, while the height H_{ob} was parametrically changed from 0.5 to 3.0 m in increments of 0.5 m.

4. Evaluation of Failure Probability of Unprotected Steel Beam and Code Calibration for Fire-resistant Design Guidelines

In this chapter, the failure probability of unprotected steel beam subjected to the localized fire is evaluated, and the code calibration for Fire-Resistant Design Guidelines is conducted based on the results of failure probability.

The analytical model of the steel beam is given by the simple support beam as shown in Fig. 7, which is the same model as it of the past research (Ozaki et al. 2015).

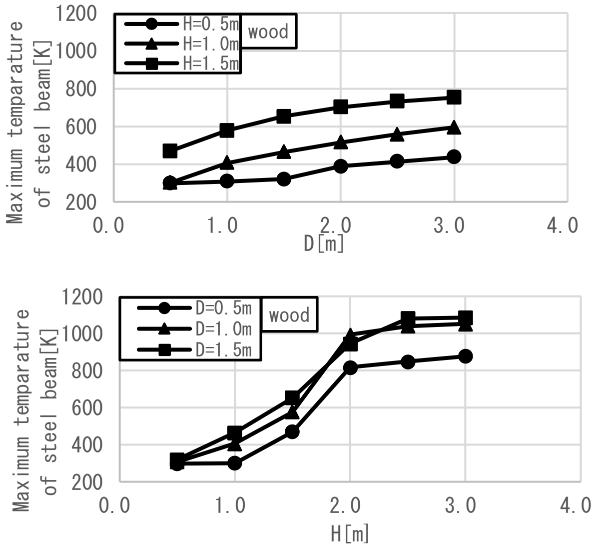


Figure.5 Height and bottom length of combustibles –steel beams maximum temperatures relationships (woody combustibles)

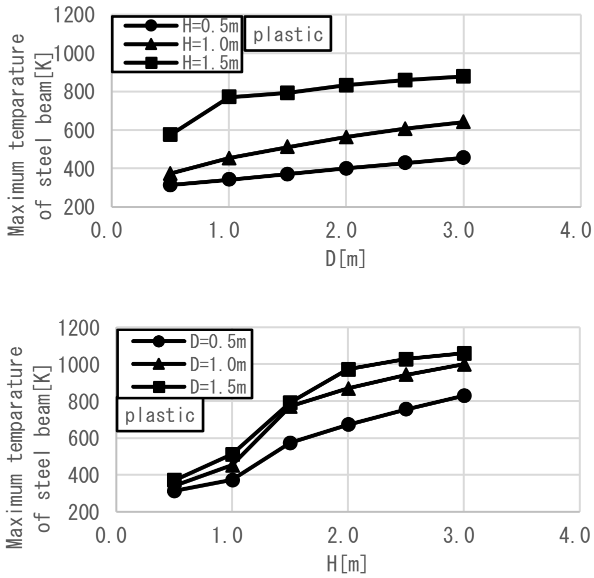


Figure.6 Height and Bottom length of combustibles – steel beams maximum temperatures relationships (plastic combustibles)

Uniformly distributed loads q is applied to the beam. For the beam model, the design collapse temperature based on Fire-Resistant Design Guidelines is evaluated by the temperature T, which is satisfied with the following equation.

$$\tilde{q} = \sigma_y(T)/F \qquad (16)$$

Where, F is the specified design strength (235MPa) of the steel(JIS SN400B) at the ambient temperature, and $\sigma_y(T)$ is the design steel strength (AIJ design value in Fig.8) at the elevated temperature T. $\tilde{q}$ is a dimensionless value of uniformly distributed loads denoted by Fire-Resistant Design Guidelines, and hereinafter, simply denoted as the load ratio of the beam.

It is assumed that the steel beam as shown in Fig.7 is designed based on Fire-Resistant Design Guidelines. The fire resistant performance is determined so that the design maximum temperature of steel beam at the localized fire is just equal to the design collapse temperature evaluated by equation (16). That concrete design process is follows.

Firstly, the combustible material height (H_{ob}) is parametrically changed by giving a combustible material shape (D=1m), and the combustible material is determined (wood or plastic). At the next, the design steel beam maximum temperature is evaluated by using the design heat release rate which was determined by adding the standard deviation to the average value of maximum heat release rate with reference to the design example in Fire-Resistant Design Guidelines (see Fig.9). The load ratio of beam is determined so that the obtained design maximum temperature of the steel beam is equal to the design collapse temperature, that is, the designed beam possesses the minimum value of the fire resistant performance required by Fire-Resistant Design Guidelines, and the load ratio at that time was defined as the optimum load ratio. In the general fire-resistant design, it is required that the value of load applied to the beam be equal to or less than that of the above optimum load ratio.

In the MC analyses, the four parameters ($Q_{max}, THR, \alpha, \alpha_d$) that determine the heat release rate curve, the steel strength at the elevated temperature, and the vertical loads(dead and live loads) are given by random variables, respectively. Those of the steel strength and the vertical loads (dead and live loads) are referred to the past research (Ozaki et al. 2018), and that outline is follows.

Fig. 8 shows the average values of steel strength at the elevated temperature (JIS SN400), which were used in the MC analysis **(**the thick solid line in Fig. 8**)**. Those were evaluated from the accumulated past coupon test results. The average values of effective steel strength is defined by the stress at 1% strain. The design effective steel strength (dotted line in Fig. 8) defined by Fire-Resistant Design Guidelines, which is given by a polygonal line approximated to the values obtained by subtracting three times values of the standard deviation from the average value of the coupon test results. Fig.10 shows the variation coefficient of steel strength at each temperature (Ozaki et al. 2015). The steel strength and the live and dead loads applied to the beam follow a log-normal distribution, respectively. The coefficient of variation of loads were 0.4 (dead load) and 0.1 (live load) (Ozaki et al. 2018). The average values of the loads were determined based on the past research (Ozaki et al. 2018).

Figures 11 and 12 show the analytical results of the failure probability p_f of the steel beam optimally designed to be satisfied with the fire resistant performance based on Fire-Resistant Design Guidelines. The temperature of the horizontal axes of Figs.11 and12 is the temperature of design point when the design maximum temperature of the steel beam at the localized fire is just equal to the design collapse temperature. The failure probability p_f on the vertical axes in Fig. 11 and 12 is represented by a reliability index $\beta(= \Phi^{-1}(1-p_f))$. Where, $\Phi^{-1}(*)$ is an inverse function of standard normal distribution function.

In the case of H/A=100 m^{-1} with the plastic combustibles (Fig. 12), the analytical result when the steel beam failed was not obtained even if the number of trials of the MC simulation was 10,000, because Fire-Resistant Design Guidelines gives the sufficient safe side design value for the thick H-shaped cross section such as H/A=100 m^{-1}, therefore, this analytical result is not shown.

As seen in Fig.11 and 12, the analytical results with the small cross-sectional shape factor H/A exhibit the low fracture probability (large reliability index). This reason is described as follows; the design heat release rate curve is simplified by the constant heat rate of the maximum heat release rate, in this case, the design temperature of the unprotected steel beam is evaluated regardless to the value of H/A. On the other hand, in actuality, the temperature rise is suppressed in the case of the small H/A, because the actual heating rate of localized fire is attenuated after the fire duration time. The actual maximum steel temperature is very lower than the design value, for this reason, the failure probability with the small H / A value becomes small.

As shown in Fig. 11, the analytical results of the failure probability become very small when the design temperature of the horizontal axis approaches about 700 °C, because the design steel strength is given by the small value above 700 °C and equal to zero at 750 °C. The design steel member strength in those temperature regions gives the large safety side evaluation.

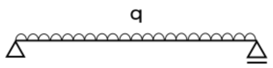


Figure.7 Analytical model

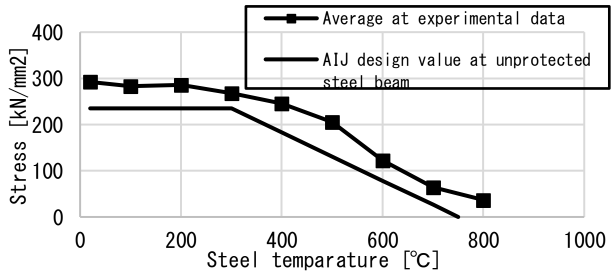


Figure.8 Steel strength at high temperatures

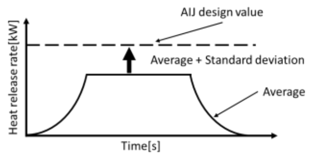


Figure.9 Concept of design heat release rate

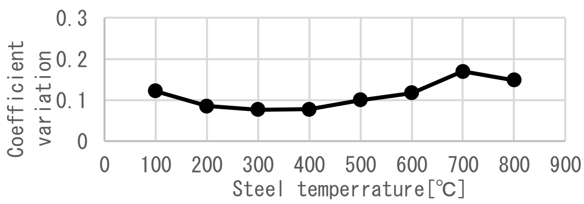


Figure.10 Coefficient variation of steel strength at high temperature

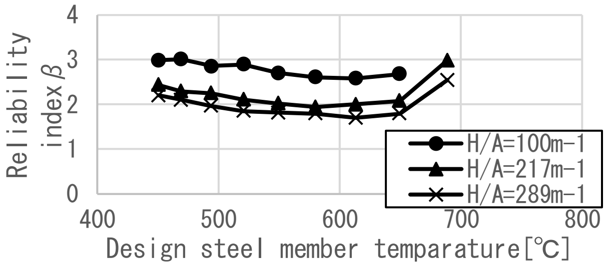


Figure.11 Reliability index β-design steel beam temperature relationships (wood)

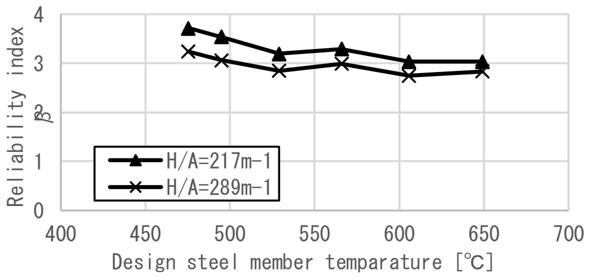


Figure.12 Reliability index β-design steel beam temperature relationships (plastic)

5. Summary

In this paper, by focusing on the values of the parameters on the heat release rate of the localized fire, which are the fire growth rate, maximum heat release rate, total heat release rate, and fire decay rate, the steel strength at the elevated temperature, and the vertical loads (live and dead loads), the failure probability of simply supported steel beam subjected to the localized fire was evaluated by the MC numerical analyses considering the dispersion of the above values. Furthermore, the code calibration for Fire-Resistant Design Guidelines was performed. According to the analytical results, the fracture probability of the steel beam designed by the above guidelines is changed at each design value, that is, the fire resistant performance-level required by the guidelines is changed under each design condition.

In the future research, it is necessary to examine the correlation between the various parameters on the heat release rate in detail and reflect the correlation in the MC analysis. Furthermore, in this research, the failure probability of unprotected steel beam under the conditional event probability limited to the occurrence of localized fire was evaluated. On the other hand, the evaluation of the probability in the case when the fire events continues from the occurrence of the fire to the grows of fire, the fire spreading and the fully developed fire after the flashover is required, and the overall risk assessment of the steel member subjected to the fire must be also examined.

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