Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 10 (1976)

Artikel: Fire resistance of steel structures in neighbouring fire

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DOI: https://doi.org/10.5169/seals-10433

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Fire Resistance of Steel Structures in Neighbouring Fire

Résistance au feu des structures métalliques à proximité d'un incendie

Feuerwiderstand von Stahlkonstruktionen in benachbarten Brandstätten

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1. Thermal effects on bridge members.

It is not so usual to take so large thermal increment as to be produced by fire into considerations in design of bridges. But the anticipated high temperatures and long duration of fire in large scale oil plants forced us to do some studies on their effects against structural members of continuous truss bridges.

In our cases on preliminary design for Meiko Big Bridge and Bannosu Bridge, the effects of pressure by heated air enclosed in members with box type section, the effects of temperature differences between plates in a member, and the effects of temperature differences between members in three span continuous truss girder bridges were studied.

1-1. The effect of internal pressure.

The sections of the members were idealized as right square with width B, and the plate thicknesses are denoted as hf in cover plates and hw inweb plates. These are assumed to be made air-tight with diaphragms at the panel points, the both ends of these members. Then, the increment of inside pressure "P" must be

$$P = \frac{Po}{To}\,t$$

where Po is standard pressure of the air, "To" is the absolute value of normal temperature, and t is average temperature increment of the member.

Expected maximum stress σ_1 in transversal direction of the member can be estimated as

$$\sigma_1 = \frac{P}{2}\left(\frac{B}{h}\right)\left(1+\frac{B}{h}\right) = \frac{P}{2}\left(\frac{B}{h}\right)^2$$

where h is smaller one of hf and hw, and the maximum stress will appear at inside of corners. If B equals to 900 mm, and h is 12mm,

$$\sigma_1 = 9.75\ t \quad (\mathrm{kg/cm^2}).$$

1-2. The effects of temperature difference between plates in a member.

The temperature difference between plates will causes transversal and longitudinal stresses in a member.

Transversal maximum bending stress σ_2 will be estimated easily neglecting small amount of in-plane stress as

$$\sigma_2 = \frac{3E\alpha\Delta t}{2(1-\nu^2)\{1+3(Hf/hw)^3\}\ (B/hf)},$$

where Δt denotes the temperature difference, E is Young's modulus, ν is thermal elongation coefficient, and α is Poisson's ratio. This stress appears also at member corners, and if B equals to 900 mm, and hf 45mm, hw45mm,

$$\sigma_2 = 0.52\,\Delta t \quad (\mathrm{kg/cm^2}).$$

It seems not so dangerous, but must be added to σ_1 at corners of shaded/side of the members.

Longitudinal thermal stress σ_3 may appear by constraints against bending of the member, and they must be affected by boundary conditions at panel points. But we may assume safely that the panel points do not rotate at all. Then the stress σ_3 will be given as

$$\sigma_3 = \frac{E}{2}\alpha\Delta t = 12.6\,\Delta t \quad (\mathrm{kg/cm^2}).$$

1-3. Effects of temperature difference between truss members.

The temperatures of each member by the fire had to be estimated, at first, and the following approximated assumptions were adopted to this end:

a) The temperature of a member depends on the view factor of the surface of plate facing to the fire, and the relation can be represented approximately linear in the region of present temperature under consideration.

b) View factor itself varies inversly as square of distance from the member to the center of fire, and is proportion to cosine of the angle between direction to the fire and the normal line of the plate.

The view factors of members shaded by another members or deck of the bridge are so smaller than the ones facing the fire. The results of more or less troublesome calculation considering shading effects on Bannosu bridge showed us very lower temperature increments in members at shaded side of the structure (Fig. 1). In this case, upper chords of shaded side of the bridge have been affected largely by the wide deck slab. As the Meiko Big Bridge have been designed as double deck bridge, behavior of the lower chord members will be almost the same to the upper chords of Bannosu Bridge.

In any case, no trouble will happen if the structure is statiscally determinate. But the continuous bridges are indeterminate, and the constraints at supports will make some effects on their stresses. Theoretical calculation of member stresses σ_T knowing each temperature increments is not so difficult one, and the maximum effect have been found at a chord member near the one of center piers in our cases. The estimated maximum stress due to the temperature differences reached $13.7\,\Delta T$ kg/cm^2 in Meiko Big Bridge and $17.4\,\Delta T$ kg/cm^2 in Bannosu Bridge, where ΔT denotes temperature difference at the nearest section of the bridge to the fire.

1-4. Permissible temperature conditions.

The permissible limit of the fire effects must be considered taking into account the resultant stresses of members and the buckling strength of compressed ones. But for buckling strength, the problem will be not so difficult if it is permitted to use increased allowable unit stresses of standard specifications.

For the stress limits, although local yield will occur at comparatively early stage of the fire because of the resultant effects of bending and in-plane stresses of the plate, the limit of the stresses plate may be considered as the instance when the one of principal stress on surface of the plate reaches yield point σ_Y member axes.

Standing on such considerations, the permissible limit of the temperature conditions can be decided from following three inequalities:

$$\frac{t}{t_0} + \frac{\Delta t}{\Delta t_1} \leq 1.0 \qquad \text{(for transversal stress),} \qquad - (1)$$

$$\left| \frac{\sigma_T + \sigma_d}{\sigma_Y} \pm \frac{\Delta t}{\Delta t_2} \right| \leq 0 \qquad \text{(for longitudinal stress),} \qquad - (2)$$

$$|\sigma_T| < \beta \sigma_{ca} \qquad \text{(for buckling if } \sigma_T \text{ is negative),} \qquad - (3)$$

where

$$t_0 = \frac{577h^2 \sigma_Y}{B}$$

$$\Delta t_1 = \frac{\{1+3(hf/hw)^3\}\ (B/hf)\sigma_Y}{41.54\ (hf/hw)}$$

$$\Delta t_2 = \sigma_Y / 12.6$$

and β is a coefficient smaller than the safety factor, σ_d is dead load stress.

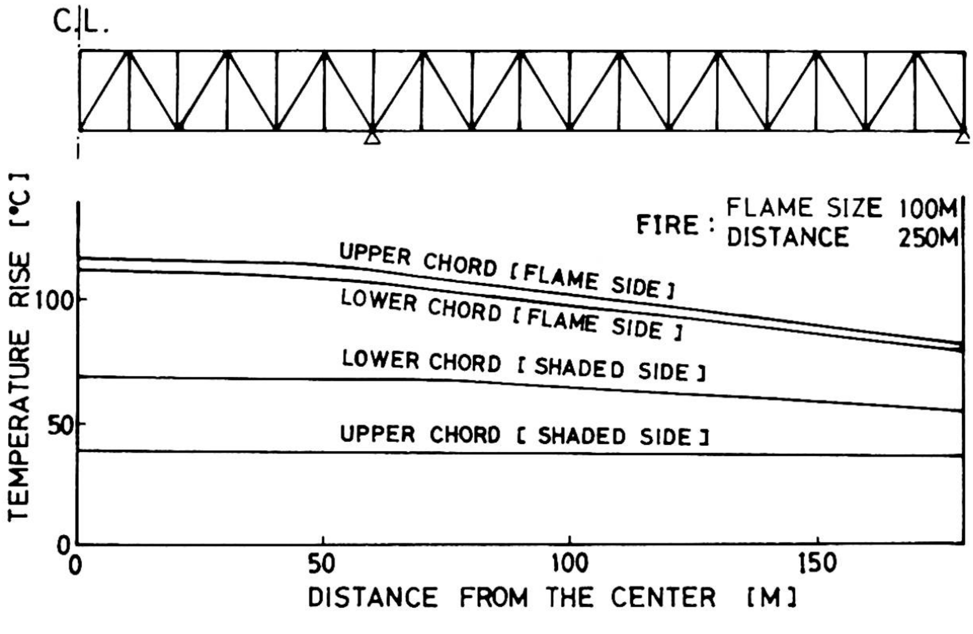


Fig. 1 Estimated temperature rises of cord members

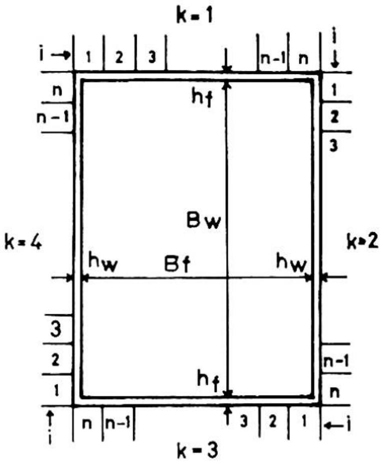


Fig. 2 Mathematical model of cross section of a member

2. Calculation of temperature of a bridge member.

In case of any fire occurring nearby a bridge, radiant heat from the fire should produce some temperature increase which has some harmful effects on bridge members as described above. The temperature increment depends on several conditions such as scale, severity and duration of the fire, distance from the bridge to the fire, and emissivity of surfaces of the member.

First of all an equation was introduced for estimating unsteady-state temperatures on different steel members having box type section. Then the equation was solved to obtain the temperature of a certain member to be used for a main truss girder of a bridge. The calculation was made by use of an electric computer for various values of the view factors for radiative heat exchange between the fire and the surfaces of the member. To examine the effects of paints applied on the surface on the temperature increase, we considered two kinds of paints, an ordinary paint with larger emissivity and an alumina paint with smaller one.

2-1. Equation for calculating the temperature.

Fig. 2 shows a cross section of a steel member as a mathematical model for deriving the equation which enables to calculate the unsteady-temperature distribution of the bridge member exposed to radiant heat from a fire. The equation was obtained from a heat balance on a small rectangular zone (k,i) in Fig. 2, by taking account of the following four heat exchanges;

(1) radiation between the external surface and the surroundings involving the fire
(2) radiation between any internal surfaces
(3) natural convection on the external and internal surfaces
(4) heat conduction in the solids of the member

The equation is written in finite-difference form as shown in Eg. (4), and the solution is accomplished by finite-time step advancement.

$$\begin{aligned}T(k, i, N+1) = {} & T(k,i,N) + \frac{\Delta\tau}{c\rho h(k)}\Big[\sigma\varepsilon_s \{ FF(k)T_F(N)^4 - T(k,i,N)^4 \\ & - [1 - FF(k)]T_0^4 - (\varepsilon_i/\varepsilon_s)\sum_{\eta=1}^{4}\sum_{j=1}^{n} F_{k\eta}(i.j)\ [T(k,i,N)^4 - T(\eta,j,N)^4] \\ & - H_0(k,i,N)\ [T(k,i,N) - T_0] - H_I(k,i,N)\ [T(k,i,N) - \sum_{k=1}^{4}\sum_{i=1}^{n} T \\ & (k,i,)/4n] + \frac{\lambda n^2}{B(k)}\Big\{\frac{T(k,i-1,N) - T(k,i,N)}{\alpha(i-1)} + \frac{T(k,i+1,N) - T(k,i,N)}{\alpha(i+1)}\Big\}\Big] \\ & \text{---}(4)\end{aligned}$$

where $\alpha(i-1) = \alpha(i+1) = B(k)/h(k)$, when $2 \leqq i \leqq n-1$;

$\alpha(i-1) = \alpha$, when $i = 1$; and $\alpha(i+1) = \alpha$, when $i = n$;

where $\alpha = (Bf + Bw)/(hf + hw)$

$B(k) = Bf$ and $h(k) = hf$, when $k = 1$ or 3;

$B(k) = Bw$ and $h(k) = hw$, when $k = 2$ or 4

$T(k,i,N)$: absolute temperature at the center of a zone (k,i) of a member at the time $\tau = N\Delta\tau$, where $\Delta\tau$ denotes a time interval

T_F, T_0 : equivalent radiative temperature of a fire and temperature of the air in absolute value respectively

$\lambda, c, \rho,$: thermal conductivity, specific heat and density of steel respectively

σ : Stefan-Boltzmann constant

ε_s, ε_i : emissivity of external and internal surface of member respectively

FF(k) : view factor between internal surfaces of zone (k,i) and any zone

H_O, H_I : heat transfer coefficients by natural convection at an external and an internal surface of the zone respectively

2-2 Assumptions for calculation

Calculations were made on the following assumptions;

(1) cross section of the member: Bf = Bw = 900, hf = 22, hw = 25 (mm)

(2) number of zones (k,i): k = 4, n = 3, therefore 12 in total

(3) emissivity of the internal surfaces: $\varepsilon_i = 0.9$

(4) emissivity of the external surfaces: $\varepsilon_s = 0.9$ and ε_s 0.35 ($\varepsilon_s = 0.9$ for ordinary paint, $\varepsilon_s = 0.35$ for alumina paint)

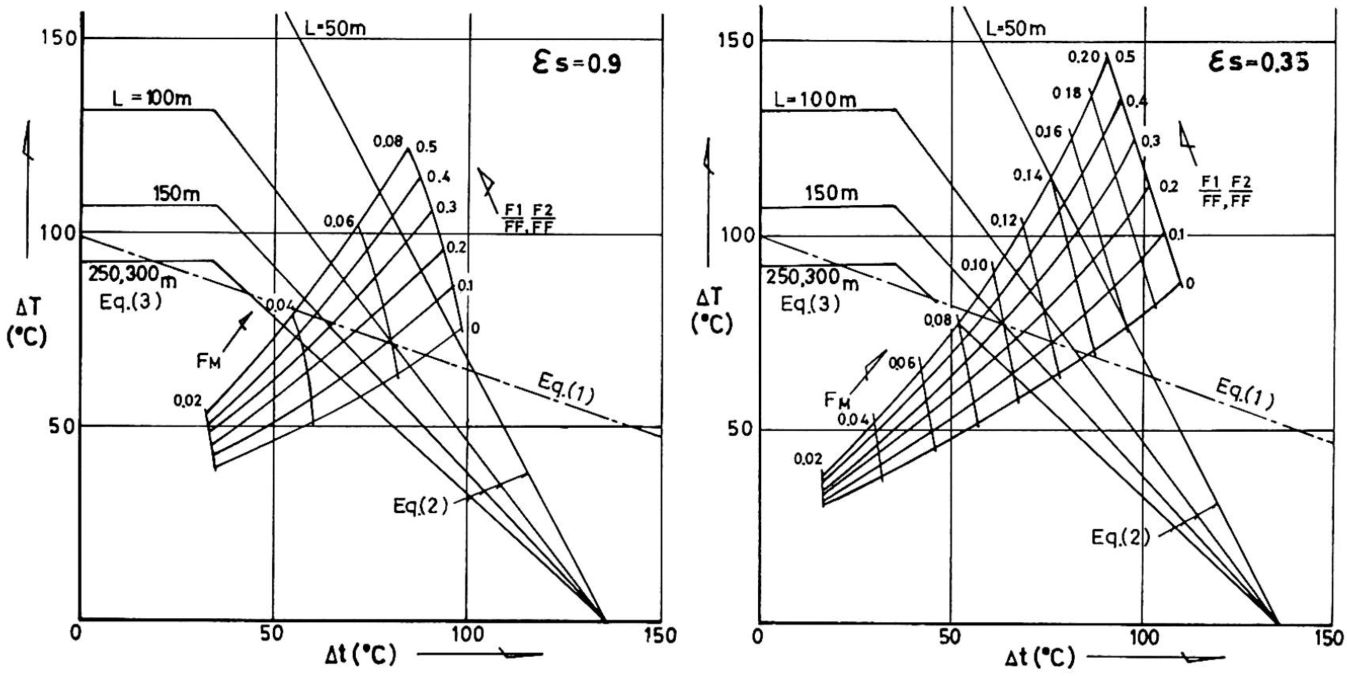
(5) temperatures T_F, T_O : $T_F = 1000$, $T_O = 298$ (°K)

(6) duration of the fire: three hours

(7) view factors between the fire and three external surfaces of the member FM, F1 and F2: FM is for the surface receiving the largest amount of the radiative heat among the three surfaces. F1 and F2 are for the two surfaces normal to the surface concerned with FM, where F2 ≤ F1 ≤ FM.

FM: 21 steps in range from 0.02 to 0.92
F1: 6 steps, 0, 10, ..., 50 percent of FM
F2: 3 steps, 0, 50, 100 percent of F1

Therefore the number of cases for calculation amounts to 672 in total.



(a) for an ordinary paint (emissivity $\varepsilon_s = 0.9$)

(b) for an alumina paint (emissivity $\varepsilon_s = 0.35$)

Fig. 3 Relation between temperature differences (ΔT and Δt) and view factors (FM, F1 and F2) for the case of F1 = F2 = 0.5FM

2-3 Results of calculation

Through these calculations, many available data have been obtained to know various thermal conditions on the member under different situations of fire. But two examples of several diagrams synthesized from the calculated results only are shown in Fig. 3 for two cases of the emissivity $\varepsilon_s = 0.9$ and $\varepsilon_s = 0.35$ in each of which F1 = F2 = 0.5FM. The figure shows the relation between the temperature differences (ΔT and Δt) and the view factors (FM, F1 and F2) in range concerned with permissible temperature limits represented by inequalities (1), (2) and (3), where ΔT and Δt denote respectively the temperature difference between two truss members and one between two plates of a member.

3. Geometrical requirement for ensuring bridge against fire

As shown in Fig. 3, we have clarified the relation between the permissible thermal conditions and the view factors. They are given from the diameter "ϕ" and the height "H" of a fire, the distance "L" from the center of the fire to the surface of the bridge member and so on.

Thus we have obtained finally the following geometrical conditions represented by ϕ/L required for ensuring a bridge against fire, assuming to be $H = 1.5\,\phi$.

Emissivity of external surface of a member	$\frac{F1}{FM}$ (= $\frac{F2}{FM}$)	ϕ / L
0.9 (for ordinary paint)	0	$\leq$ 0.33
	0.5	$\leq$ 0.29
0.35 (for alumina paint)	0	$\leq$ 0.46
	0.5	$\leq$ 0.40

SUMMARY

A problem how to ensure elevated bridges against fires of oil plants situated near the bridges has been submitted recently in Japan. Thermal effects on steel members of bridges are discussed and some permissible thermal requirements for the members are derived. An equation for calculating temperatures of a member having a box section is introduced and solved for various conditions of radiation. A method for estimating necessary clearance between bridge and an oil plant according to probable scale of the fire is suggested.

RESUME

Le problème de la protection d'un pont contre l'incendie d'une grande raffinerie près du pont s'est posé récemment au Japon. La discussion de l'effet thermique sur les éléments métalliques du pont a permis de tirer quelques règles de résistance thermique des éléments. Une équation pour calculer la variation de température d'un élément en caisson a été développée, tenant compte de différentes conditions de radiation. Une méthode pour estimer l'éloignement nécessaire entre le pont et la raffinerie en fonction de l'importance de l'incendie a été proposée.

ZUSAMMENFASSUNG

In jüngster Zeit befasste man sich in Japan mit der Frage, wie Brücken vor Bränden in nahegelegenen Erdölraffinerien geschützt werden können. Man untersuchte die Wärmeeinflüsse auf Brückenglieder und gewann daraus einige zulässige Widerstandsbedingungen. Es wurde eine Gleichung zur Errechnung der Temperaturen für Stäbe mit Hohlquerschnitt abgeleitet und für verschiedene Strahlungsbedingungen gelöst, und eine Berechnungsmethode für die erforderliche Entfernung der Brücke von der Erdölraffinerie in Funktion der Ausdehnung des Brandes vorgeschlagen.