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Fire under a Long Span Bridge

Incendie sous un pont à grande portée

Brand unter einer Brücke grosser Spannweite

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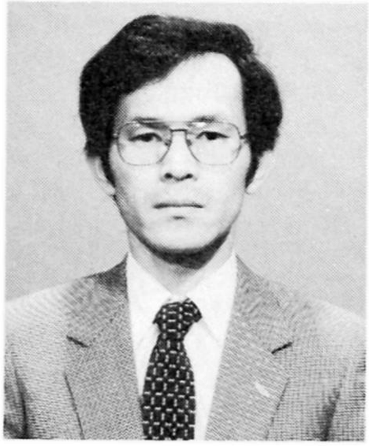

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SUMMARY
Structural behavior of cable-stayed and box girder bridges in fire environments is estimated numerically on the assumption that the ship runs against the bridge pier, or the ship collides with another ship under the bridge. Heat radiation from the fire to the surfaces of the girder is calculated by the finite element method. Thermal deformation of the bridge is evaluated by thermo-elasto-plastic finite element analysis, in which various combinations of bridge type and location of fire are compared.

RÉSUMÉ
Le comportement d'un pont à haubans et d'un pont en poutre-caisson dans un incendie est étudié dans les cas d'une collision d'un navire avec une pile du pont ou avec un autre navire sous le pont. L'échange de chaleur par radiation entre la source de chaleur et les surfaces de poutre est calculé par la méthode des éléments finis. La déformation thermique du pont est évaluée sur la base de l'analyse thermo-élasto-plastique des éléments finis, dans laquelle combinaisons du type du pont et la location du feu varient.

ZUSAMMENFASSUNG
Unter der Voraussetzung, daß ein Schiff an einen Brückenpfeiler prallt, oder daß zwei Schiffe unter der Brücke zusammenstoßen, wurde das Tragverhalten von Schragseilbrücken (Zx) und der Kastenträgerbrücken numerisch untersucht. Die Wärmestrahlung vom Feuer an den Brückenträger wurde mit der Methode der finiten Elementen berechnet. Die thermische Formänderung der Brücke ist in der thermo-elasto-plastischen Analyse erfaßt, wobei die verschiedenen Kombinationen von Brückentypen und Lage des Brandes verglichen werden.

1. INTRODUCTION

Due to an increased construction of long span bridges across a channel, the possibility of ship-fire under bridges cannot be ignored. The ship carrying combustibles such as petroleum and liquefied petroleum gas may run against a bridge pier, or collide with another ship under the bridge. Bridge deformation under such circumstances are numerically evaluated here. Object of numerical calculation are cable-stayed and box girder bridges with central span of 160 meters. Heat radiation from fire to the surfaces of the girder is calculated by FEM. Thermal deformation of the bridge is calculated also by thermo-elasto-plastic FE analysis, in which various combination of bridge type and location of fire are taken into account.

2. TYPE OF BRIDGES

Cable-stayed and box girder bridges as shown Fig.1 are considered in the article. In order to show the difference of stress state and deformation, we assume that both bridge sections be continuous girder, having span of 60m+160m+60m, with variable cross-section. These bridges are roughly designed according to allowable stress design considering dead and traffic loads. Cross-section at the span center is indicated in Fig.2 as a representative. In the case of cable-stayed bridges, the effect of cable sag is approximately evaluated by modified Young's modulus provided by Ernst, and towers are assumed to be stiff.

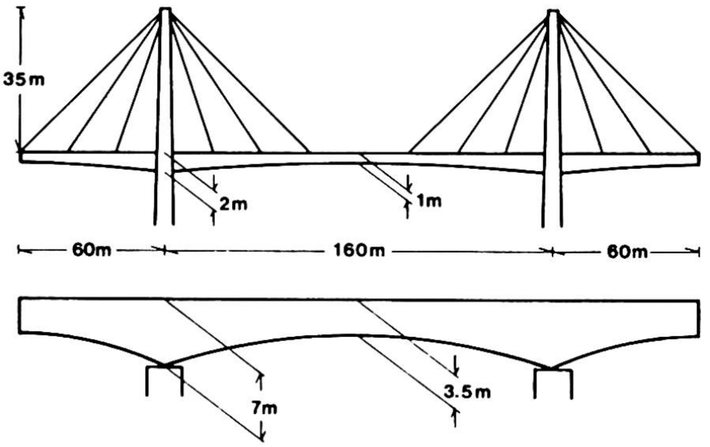

Fig.1 Bridge types.

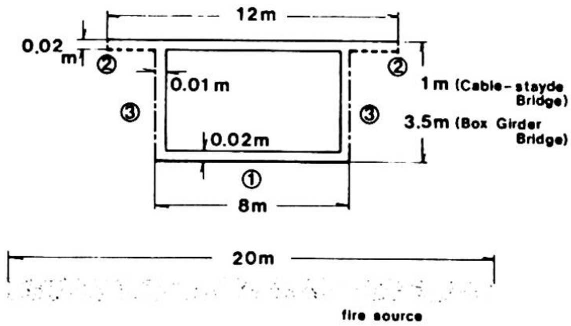

Fig.2 Cross-section at the span center of bridges.

3. HEAT TRANSFER ANALYSIS

3.1 Heat Transfer from Fire to Bridge

Heat transfer from fire source to the structural members in the building fire is conducted by heat radiation and convection [1-6]. For such cases, heat capacity can be put into members by "heated air to surface" transition, because the room is filled with heated air and flame as in a furnace. However, the bridge fire, inflow of heat is conducted through surfaces of the girder by "surface (heat-source) to surface" transition, because the bridge is no more than a strip of plate placed on an open space. Thus, heat capacity is not constant along the bridge, and should be determined by the horizontal and vertical distance between different parts of girder and fire source.

In this work, heat transfer between different parts of girder (called girder segments) and fire source is conducted only by heat radiation. The phenomenon can be defined analytically by heat radiation between girder segment and fire source as gray bodies; and spatial relation between the two is represented by a geometrical factor. On the contrary, in recent years, radiation-convection interaction has been formulated based on the continuum mechanics by limiting to the enclosed space problem [7]. However the procedure has not yet been so developed to be applied to the open space problem, even if we ignore the effect of wind.

Let the size of fire source be 20mx20m. Since the width of lower flange member (8m) is less than the width of fire (20m) as shown in Fig.2, inflow of heat is conducted by radiation through three surfaces, that is, ① bottom surface of lower flange, ② bottom surface of upper flange which is not screened by webs and lower flange, and ③ side walls of webs.

Let the fire source be placed directly beneath the bridge. Conserning the location of fire source, two cases are considered as shown in Fig.3, that is, (a) left end of central span on the supposition that the ship runs against bridge pier, and (b) center of central span on the supposition that the ship collides with another ship under the bridge. Also for the distance between bridge and fire source, two cases are considered as shown in Fig.3, that is, (a) 10m (river) and (b) 30m (channel).

3.2 Heat Radiation between Two Surfaces

Fig.4 shows a spatial relation between girder segment and fire source for the inflow of heat through bottom surface of lower flange. Inflow of heat for the n-th girder segment Q_n is represented by

$$Q_n = C_{lf}(\sigma_0 \varepsilon_s \varepsilon_f / \pi)(T_f^4 - T_{sn}^4) \qquad (1)$$

in which geometrical factor C_{lf} is as follows:

$$C_{lf} = \iiiint (Z_n - x_2 \sin\phi_n)\{Z_n + \tan\phi_n (X_n - x_1)\} \cos\phi_n / R^4 \cdot dx_1 dx_2 dy_1 dy_2$$

In Eq.(1), $\sigma_0 = 4.88\times10^{-8}\mathrm{kcal/m^2 h {}^\circ K^4}$ is coefficient of Stefan-Boltzmann, $\varepsilon_s = 0.5$ and $\varepsilon_f = 0.7$ are emissivities of heated air and steel, respectively. X_n, Z_n are horizontal and vertical distance between center of girder segment and fire source, respectively, ϕ_n is inclination of girder segment, T_{sn} and T_f are temperature of the n-th girder and fire source, which is substituted by the standard fire time-temperature curve. x_1, x_2, y_1, y_2 are local co-ordinates, R is expressed as under:

$$R^4 = \{(X_n + x_2\cos\phi_n - x_1)^2 + (y_2 - y_1)^2 + (Z_n - x_2 \sin\phi_n)^2\}^2$$

Longitudinal and cross-sectional distribution of geometrical factor of lower flange (C_{lf}) are calculated by Eq.(1). The rest of geometrical factors corresponding the upper flange and webs (C_{uf} and C_w) are also evaluated in the same manner as Eq.(1).

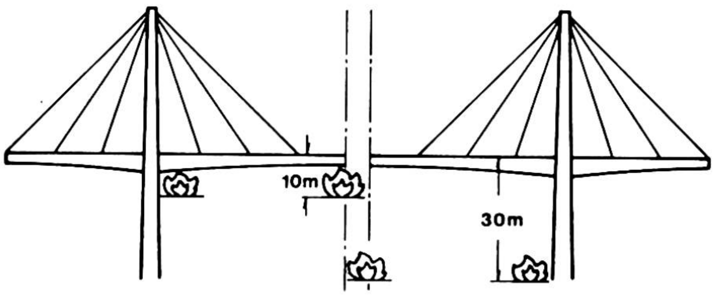

Fig.3 Locations of fire.

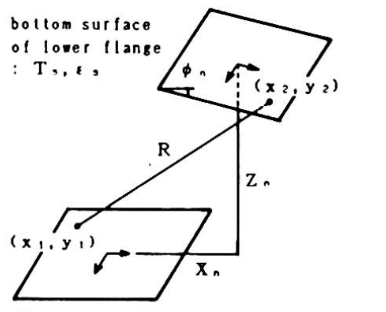

Fig.4 Heat radiation between two surfaces.

3.3 FE Analysis

Prior to a series of calculations, heat conduction in the longtitudinal direction is compared with that in the cross-sectional direction. The result shows that the former is negligibly small compared with the latter. It implies that the thermal distribution inside the girder cross-section can be calculated with good accuracy by using two-dimensional FE analysis.

Central span of the bridge is cut into 32 girder segments, and the typical cross-section of each segment is discretized by using three node three degrees-of-freedom triangular elements. Inflow of heat for each segment is evaluated by using geometrical factors according to the spatial relation between girder segment and fire source. Coefficient of heat conductivity and specific heat of steel follow the CTICM's recommendations. Integration by time is carried by the Crank-Nicholson method, and the temperature distributions of cross-sections are calculated at intervals of 0.05 hours (3 minutes).

Thermal deformations are calculated numerically in the combined cases of the following three parameters. Table of short signs representing the combination of (1), (2) and (3) are indicated in the Table 1.

(1) Bridge type : cable-stayed bridge / box girder bridge
(2) Location of fire source : bridge center / pier side
(3) Distance between bridge and fire : 10 meters / 30 meters

Maximum temparature for all cross-sections in the longitudinal direction are indicated in Fig.5. Temperature distribution at the span center in every hour after a break of fire is shown in Fig.5 for the case of (1) cable-stayed bridge, (2) bridge center and (3) 10 meters.

4. THERMO-ELASTO-PLASTIC ANALYSIS

4.1 Material Properties

Let the material be SS41 steel whose nominal strength is $41 kg/mm^2$ ($402 MN/m^2$). Due to the previous studies including material tests [3-6], the writers have presented material properties as function of temperature, which is distinct from CTICM's recommendations. That is, modulus of elasticity (E), yield strength (σ^Y), work-hardening parameter ($H=d\sigma^H/d\varepsilon^{ip}$; slope of tangent of instantaneous stress-strain curve) and coefficient of thermal expansion (α) are expressed as follows:

$$E(\theta)=E_0 \quad (\theta \leqq 350℃), \qquad E_0\,(-0.26\theta+271)/180 \qquad (\theta>350℃)$$

$$\sigma^Y(\theta)=\sigma^Y_0 \quad (\theta \leqq 200℃), \qquad \sigma^Y_0\,(0.0002\theta^2-0.33\theta+142)/84 \qquad (\theta>200℃)$$

$$H(\theta,\varepsilon^{ip})=H_1(\theta)/[\varepsilon^{ip}+\exp\{-H_2(\theta)/H_1(\theta)\}]$$

$$H_1(\theta)=800/(\theta-250)-0.5, \qquad H_2(\theta)=10000/(\theta-164)-7.3$$

$$\alpha(\theta)=1.45\times10^{-9}\theta+1.32\times10^{-5}-3,85\times10^{-4}/\theta$$

where E_0(=198 GN/m^3) and σ^Y_0(=281 MPa) are those at room temperature (θ=20℃), and ε^{ip} is instantaneous plastic strain. By using these properties, and ignoring the effect of creep, good approximation in deformation analysis using FEM has been obtained [5].

4.2 FE Analysis and Numerical Results

A three node seven degrees-of-freedom beam-column element is used here under the Bernoulli-Euler's assumption and the additional assumptions such as in-plane and small deformation. Thermal and creep (ignored here) deformations are treated as initial deformation, and the modified incremental method is employed in the non-linear iterative calculation. Stress increment due to work-hardening is decided by assuming von Mises-type yield criterion with isotropic work-hardening [4-6].

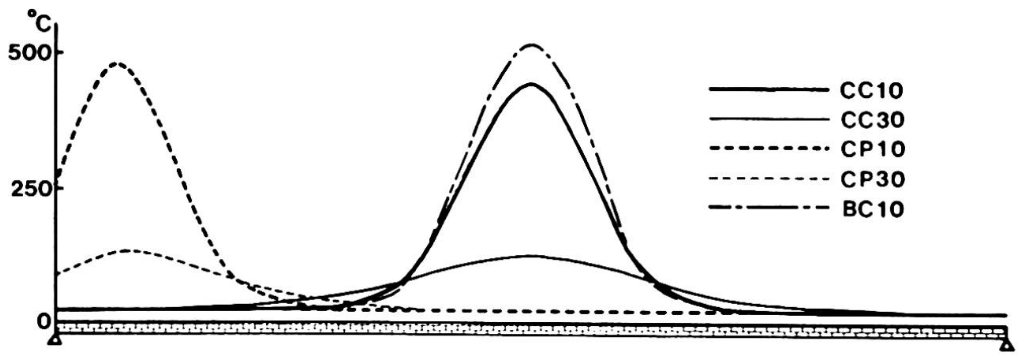

Fig.5 Temparature distribution of central span at two hours after fire breaks out.

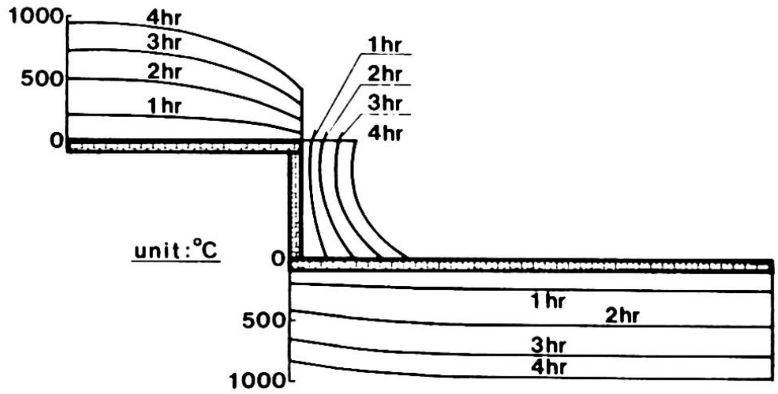

Fig.6 Temperature distribution of cross-section at every one hour (CC10).

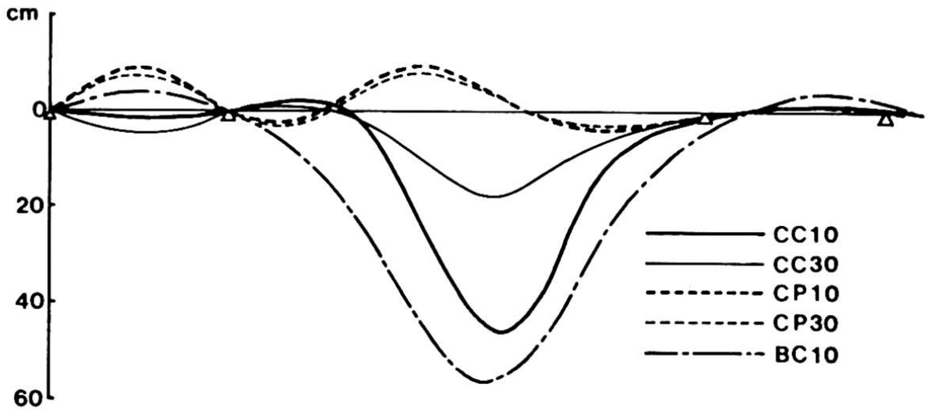

Fig.7 Deformation of bridges at two hours after fire breaks out.

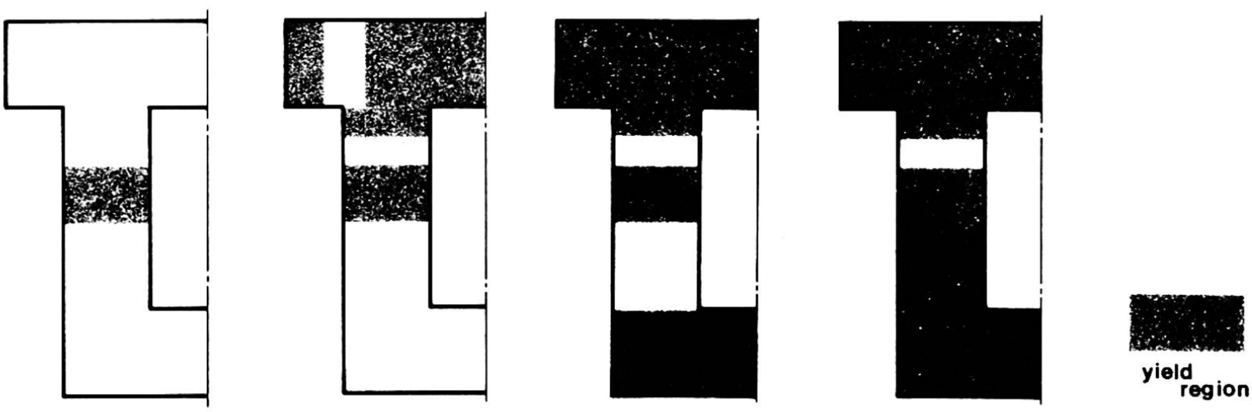

Fig.8 Progress of yield region in cross-section at every one hour (CC10).

Table 1 Endurance time of the bridge.

combination	short sign	endurance time (min.)
box girder center,10m	BC10	165
cable-stay center,10m	CC10	189
cable-stay pier, 10m	CP10	222
cable-stay center,30m	CC30	>240
cable-stay pier, 30m	CP30	>240

Concerning the external load during the fire, the live load is excluded from analysis, because no traffic will across the bridge during the fire.

Distributions of vertical deformation in the longitudinal direction are indicated in Fig.7. Progress of yield region after a start of fire is also shown in Fig.8 in the same case as the cross-sectional temparature. Endurance time of the bridge during fire is provided in Table 1.

5. CONCLUSIONS

The following conclusions have been obtained:

(1) Concerning the effect of bridge type on the structural behavior in fire, the "cable-stayed" type is stronger than the "box girder" type. However, the result may not be due to the difference of bridge type directly. It is due to the difference of temperature caused by the difference of vertical distance between fire and lower surface of the girder;

(2) Concerning the effect of longitudinal location of fire on the structural behavior, "center fire" causes serious effects on the bridge compared with "side fire";

(3) Concerning the effect of vertical distance between bridge and fire on the structural behavior in fire, there is a serious effect on the bridge only in the case of "height=10 meters". These results are only valid for a four hour fire.

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