Studies on Thermal Stress Design Method for Reinforced Concrete Members of Nuclear Power Plant

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SUMMARY

In general, the thermal stress in a reinforced concrete(RC) structural member decreases due to cracking or creep. In this paper, only the cracking effects being noticed, the thermal stress design method(TSDM) for RC members is proposed and results of experiments are investigated to verify the TSDM.

The thermal stress under consideration is the one which occurs only when the flexural deformation caused by temperature gradient(ΔT_g) across the beam-cross-section is restrained, whereas the longitudinal deformation caused by the mean temperature change is left out of account.

In the TSDM, thermal bending moment(M_T) is expressed as follows by taking account of the equilibrium relationships of the axial force and moment, with respect to the neutral axis.

$$M_T = \phi_T E_c\{I_n - S_n(X_n - g)\}$$

where ϕ_T is curvature due to ΔT_g,Ec is Young's Modulus of concrete, g is centroid locus, and In, Sn and Xn are cross-sectional variables to define bending properties.

Two series of experiments were carried out using sixteen RC beams to verify the TSDM. One is loading experiment with heating(Test-T), the other is without-heating(Test-S). The latter is so-called the bending experiments up to yielding in the reinforcements under normal temperature for comparison with Test-T.

Both the Test-T and Test-S have the same two experimental parameters; magnitude of external loads and amount of reinforcements.

In Test-T, the temperature difference between top and bottom surface of a rectangular beam section is about 60°C.

The loading period is set comparatively short in order to avoid creep effects as much as possible.

Following results are obtained;

1) The thermal stresses of beams calculated from the TSDM closely coincide with those obtained from the Test-T.
2) The thermal stresses can be evaluated effectively from the Moment-Curvature relationship under atmospheric temperature.

Introduction

Thermal stress in reinforced concrete(RC), which differs from stress due to ordinary external loads, is so-called self-limiting stress. It tends to decrease as a result of cracking or the creep effect in the structure. Thermal stress depends on both the magnitude of external loads and the quantity of reinforcements, i.e., it is determined by the rigidity of the structure. The design of RC structure in which thermal stress must be taken into account, is generally performed in the following manner. Namely, elastic stress due to thermal loads and elastic stress due to external loads are combined mutually. In this case, however, elastic stress due to thermal loads is reduced by multipling certain coefficient uniformly before combining.

The combined stress is regarded as the total stress necessary for design of structural cross-sections. On the other hand, an alternative design method which evaluates the total stress at the same time by considering the reduction of thermal stress due to cracking, is often proposed. Many studies with respect to the qualitative tendency of thermal stress have been pursued, but they have been insufficient to comprehend and confirm the quantative tendency. And quantative supports[(1)~(3)] based on the experimental facts have rarely been found in the above two thermal design methods up to now. Structures at nuclear power plants are subjected to thermal load under ordinary and accidental operating conditions.

Under these circumastances, this paper will propose a member-design-method for thermal stress and then discuss the propriety of this method by investigating the experimental results obtained from several experiments.

1. Member-Design-Method for Thermal Stress

In this section, a member-design-method for thermal stress is proposed, first of all. This method is the one which evaluates thermal stress in a beam by considering material lineality of the concrete from the standpoint of member design. For subsequent formulations, the basic assumtions employed here are as follows;

(i) Temperature distibution in the direction of beam-height in any cross-section is assumed to be linear and remains unchanged even after cracking.

(ii) The rate of linear thermal expansion of concrete is assumed to be the same as that of reinforcement.

(iii) Changes in material properties under the scope of the considered temperature are assumed to be negligible.

(iv) Magnitude of strain is assumed to be proportional to the distance from the neutral axis in the beam.

(v) The tensile strength of concrete is assumed to be ignored.

(vi) The relationship between stress and strain (i.e., σ-ε curve) is given in Fig.1.

(vii) Axial load is assumed to act on the centroid locus of any beam cross-section.

(viii) Only flexural deformation due to temperature gradient in any cross-section is assumed to be restrained.

(ix) Flexural rigidity of a beam for external loads and for thermal loads are assumed to be equal with each other. This assumption is called 'the assumption of equivalent flexural rigidity'.

Strain gradient occurs in any beam cross-section when certain external loads (axial load N, external bending moment M*) and temperature difference ΔT_g between top and bottom surface of rectangular beam are supplied (see Fig.2). This curvature ϕ consists of ϕ_T due to ΔT_g and ϕ *due to M*, namely, the following relationship hold.

$$\phi = \phi^* + \phi_T \quad (1)$$

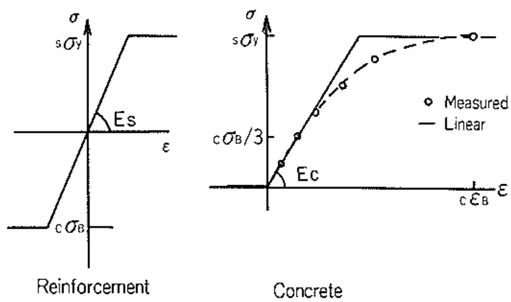


Fig.1 The relationship between stress and strain

Next, the equilibrium relationship of force and bending moment at any cross-section should be considered.

From the equilibrium relationship of axial load, the following equations are obtained.

$$N = \phi E_c S_n \quad (2)$$

From similar relationship of bending moment about the neutral axis of a beam cross-section, the following equation is obtained.

$$N(X_n - g + e) = \phi E_c I_n \quad (3)$$

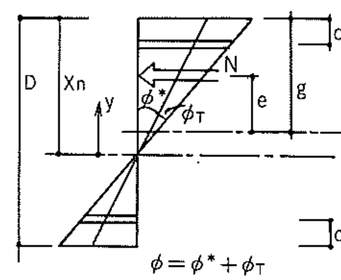


Fig.2 Strain distribution across the beam cross-section

where, D is beam-height; X_n is the neutral axis locus when external loads (i.e., axial load and external bending moment) and thermal bending moment are applied at the same time; g is the centroid locus of the equivalent cross-sectional area when there is no cracking, i.e.,

$$g = \frac{bD^2/2 + nA_{sc}d_c + nA_{st}(D - d_t)}{bD + n(A_{sc} + A_{st})} \quad (4)$$

Furthermore, Sn, In, are respectively geometrical moment of area and geometrical moment of inertia with respect to neutral axis. They are expressed as follows;

$$S_n = \frac{bX_n^2}{2} + nA_{sc}(X_n - d_c) + nA_{st}(D - d_t - X_n) \quad (5)$$

$$I_n = \frac{bX_n^3}{3} + nA_{sc}(X_n - d_c)^2 + nA_{st}(D - d_t - X_n)^2 \quad (6)$$

where, Ast, Asc are the areas of tension and compression reinforcements, dt, dc are the distances from surfaces to the tension or compression reinforcements, b is the beam width and n is the ratio of Young's moduli.

On the other hand, restraining-bending-moment given as

$$M = N \cdot e \tag{7}$$

is expressed alternatively by the use of Eqs. (2),(3) as follows;

$$M = \phi E_c \{ I_n - S_n (X_n - g) \} \tag{8}$$

Therefore, thermal bending moment (i.e., thermal stress) is given by taking account that it occurs because of ϕ_T due to ΔTg as follows;

$$M_T = \phi_T E_c \{ I_n - S_n (X_n - g) \} \tag{9}$$

It should be noticed that M_T in Eq. (9) is obtained from Eq.(8) by using the preceding assumption of equivalent flexural rigidity, and that the most suitable amounts of reinforcements for thermal stress are at the same time estimated when M_T is determined.

2. Experiment and its Procedure

2.1 Experimental Plan

It is impossible to evaluate thermal stress directly by any experimental device so far as every stress is measured through any deformation such as strain or displacement. Therefore, following experiments were carried out in order to evaluate thermal stress indirectly by setting off the preceding free deformation due to temperature difference. Thermal stress mentioned in these experiments, however, is the thermal bending moment equivalent to the internal stress which occurs in beam by restraining the free thermal flexural deformation due to temperature gradient across the rectangular beam cross-section.

Under these circumstances, experiments were carried out using a series of beams to simulate the structural portion where there are no stress irregularities affected by the structural boundaries.

In experiments, the loading period is set comparatively short in order to aboid the creep effect. The experiments consists of two kinds. One is so-called thermal stress experiments which detect thermal stress in beams under prescrived temperature gradient and external forces (i.e., axial foece and bending moment). This experiment is called Test-T for brevity. The other is so-called bending experiments up to the yielding point in reinforcement under normal temperature condition. This is called Test-S. Where, in the former experiments, only the thermal stress which occurs when flexural deformation due to temperature gradient in the direction of the beam-height is restrained, is noticed.

Experimental parameters considered are as follows;

(I) Magnitude of axial force(N), (II) Magnitude of external bending moment(M^*), (III) Magnitude of the reinforcement-ratio(Pt), (IV) Magnitude of temperature difference between top and bottom surfaces(ΔTg).

Before making clear the experimental procedure, we explain the method to evaluate the thermal stress approximately through experiment.

Figure 3 illustrates the typical diagram between the restraining-bending-moment M and beam-curvature ϕ obtained under these loading experiment.

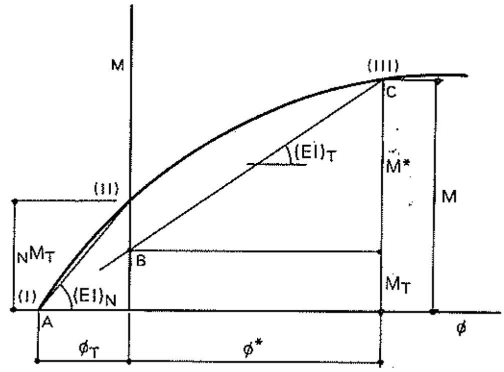
Experimental thermal stress is evaluated according to the following experimental processes.

(i) Supporsing that the prescribed temperature gradient across the beam-cross-section is applied first when there is no restriction to the beam. Incidental curvature due to thermal free deflection is given as

$$\phi_T = \alpha \cdot \Delta T_g / D \quad (10)$$

where α is the rate of linear thermal expansion of the testing beam. Corresponding state is illustrated at point A.

(ii) Let the preceding thermal free deflection be set off by applying the restraining-bending-moment. The restraining-bending-moment given by this procedure is the thermal bending moment of only when external axial load acts upon the beam. Thermal bending moment in this case is indicated as ${}_NM_T$.



M* : Bending moment due to external load

${}_NM_T$: Thermal bending moment when only axial load is applied

M : Restraining-bending-moment

M_T : Thermal bending moment

ϕ_T : Beam curvature due to temperature gradient

ϕ^* : Beam curvature due to external load and M_T

$(EI)_N$: Flexural rigidity due to axial load alone

$(EI)_T$: Equivalent flexural rigidity of beam

Fig.3 Experimental evaluation method of thermal bending moment

(iii) To give the additional bending moment (M*) as an external load is meant to apply the additional restraining-bending-moment. Corresponding restraining-bending-moment is illustrated by point C in Fig.3. Let the intersection of line from A to C and vertical axis be B, the ordinate of the point B may be estimated to be the desired thermal bending moment because of the zero curvature. And consequently the gradient of this line ABC is meant the equivalent flexural rigidity $(EI)_T$.

Thermal bending moment is hypothetically defined as the following equation.

$$M_T = \phi_T \cdot (EI)_T \quad (11)$$

Therefore bending moment as an external load M* is calculated by subtracting the M_T from the restraining-bending-moment M, namely,

$$M^* = M - M_T \quad (12)$$

2.2 Experiment

2.2.1 Testing Beams and Experimental Method

Table 1 shows the several kinds of properties of the testing beams.

Table 1 Testing beams and material properties of concrete

Kinds of test	Test beam number	Reinforcement (number and size)	Reinforcement ratio (%)	Material age of concrete (day)	Compressive strength of concrete (kgf/cm^2)	Tensile strength of concrete (kgf/cm^2)	Modulus of elasticity of concrete ($x10^5 kgf/cm^2$)
Test–T	T1	4–D16	0.50	40	258	24	2.48
	T2	4–D16	0.50	33	267	23	2.32
	T3	4–D16	0.50	32	294	29	2.50
	T4	4–D19	0.71	56	305	28	2.66
	T5	4–D19	0.71	40	300	24	2.52
	T6	4–D19	0.71	28	282	24	2.42
	T7	4–D19	0.71	27	296	24	2.60
	T8	4–D22	0.97	21	275	24	2.49
	T9	4–D22	0.97	39	296	24	2.53
Test–S	S1	4–D16	0.50	29	281	22	2.64
	S2	4–D16	0.50	26	238	21	2.39
	S3	4–D19	0.71	26	275	26	2.28
	S4	4–D19	0.71	27	282	24	2.47
	S5	4–D19	0.71	33	257	26	2.34
	S6	4–D22	0.97	22	281	23	2.40
	S7	4–D22	0.97	35	286	26	2.40

Figure 4 shows an outline of the testing beams and the loading device. All testing beams are supported by a pin at one end and pin-roller at the other end, and the total length is divided into an examined part and a fixed part. The examined part is 200cm in length. The cross-section of a beam is a rectangular which is 20cm in width and 40cm in height.

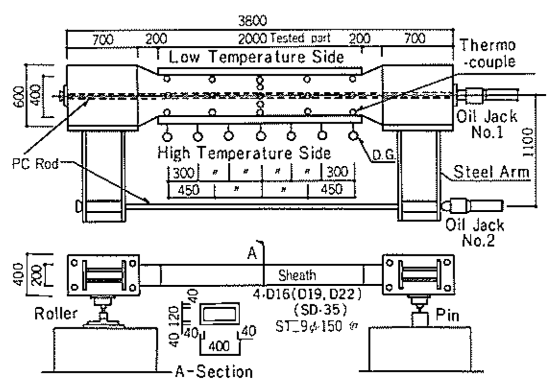


Fig.4 Testing beam and test setup

In all beams, deformed steel bars are used as the principal reinforcements, round steel bars as rib reinforcements. In addition, the principal reinforcements in the beams are arranged equally at both the compression side and the tension side. The test setup employed here maintaines a mechanically self-balanced state.

2.2.2 Test-T

Typical patterns of the heating and loading procedure are illustrated in Fig. 5. In these experiments, temperature difference between top and bottom surfaces of a rectangular beam is maintained by circulating hot water (60°C or 80°C) and cold water (15°C), and each temperature is controlled separately. Temperature distribution in beams is measured by twenty-two C-C thermocouples per a beam. Flexural deformation due to temperature gradient in a beam is let free until a steady state is attained. Then, axial load is applied up to the prescrived value by oil jack No.1, and restraining-bending-moment is given in succession by oil jack No.2 in order to set off the preceding free flexural deformation. External bending moment M^* in this case is applied repeatedly as shown in Fig.5. Curvature of a testing beam is calculated successively by the method of Least squares making use of the displacements measured by seven displacement-transducers placed at the center of each beam bottom. Several kinds of strains are detected by the strain-gauges which are attached to the surface of the RC beam and the surface of inner reinforcements. Axial load N is not controlled even if it is changed according to the restraining-bending-moment.

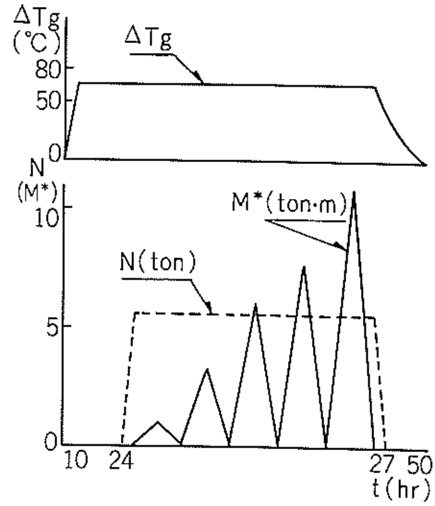


Fig.5 Typical pattern of heating and loading

2.2.3 Test-S

Bending experiments are conducted under an atmospheric temperature using the same loading device. In these cases, the relationship between bending moment and curveture are surveyed up to the yielding point of the reinforcements in order to make a comparison with the relationships obtained from Test-T.

3. Experimental Results

In investigating the experimental results, unless especially stated, the results only of testing beam T7 among all the testing beams are considered in this section. Moreover, only the right hand side of the testing beam is shown by taking account of the symmetry of the beam-shape.

Figure 6 indicates the typical

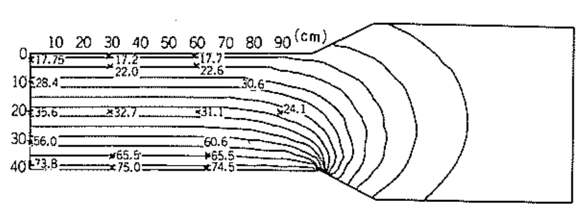


Fig.6 Temperature distribution at the steady state (T7)

steady state temperature distribution in model T7 beam just before loading. Solid lines denote the temperature contoure line calculated, and the values near symbol x denote the ones actually measured. From this figure, it can be seen that the values of calculation and measurement coincide well with each other, except for the central part of the beam.

Figure 7 shows the state of cracking observed in Test-T. The values shown near each cracking in this figure are the ones for total bending moment at the instant each cracking is observed. From Fig.7, it is known that the crackings occur at regular intervals of 10 to 20cm only on low temperature surfaces (namely, the tension-side).

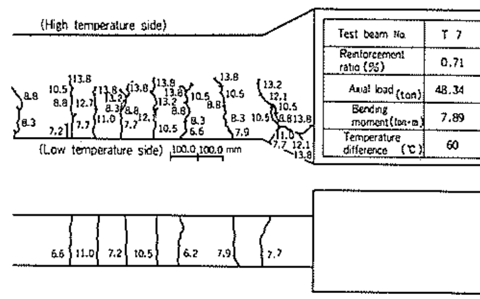


Fig.7 The state of crackings (T7)

Figure 8 shows the relationship between tensile stress in the reinforcement and maximum width of cracking. In this figure, concerning the maximum width of cracking for each testing beam, it may be seen that the ones for Test-S are to some extent larger than those for Test-T.

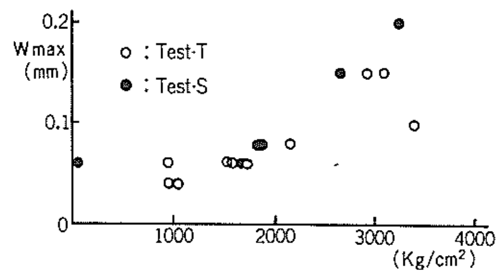


Fig.8 The stress of tension-reinforcement and the maximum width of crackings

4. Evaluated Values of Thermal Stress

In this section, thermal stress (i. e., thermal bending moment) in the testing beams are investigated on the basis of several previous estimation methods. They are illustrated in Figs. 9 to 12.

From these figures, the following qualitative facts are found;

(1) Thermal bending moment M_T, provided that other parameters are kept constant, increases with an increase in the compressive axial load N.

(2) Thermal bending moment, provided that other parameters are kept constant, increases with an increase in external bending moment M^*.

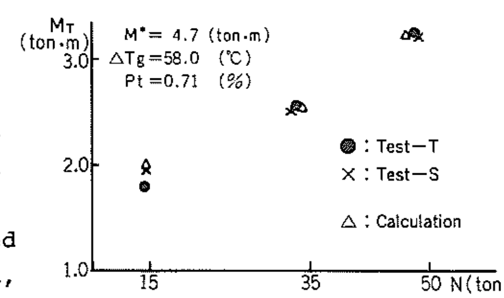


Fig.9 Compressive axial load and thermal bending moment

(3) Thermal bending moment, provided that other parameters are kept constant, increases with an increase in the reinforcements.

(4) Thermal bending moment, provided that other parameters are kept constant, increases with an increase in temperature difference between the

top and bottom surface of the rectangular beam.

(5) Thermal bending moment M_T evaluated using above three methods almost agree well with each other.

Furthermore, it is found that thermal bending moment M_T obtained from the above methods decreases about 50% compared with the onw obtained under the assumption of non-cracking in the beam of concrete alone (see Eq.(13)), and it is found that M_T decreases about 10% at most when compressive axial load N or amount of reinforcements Pt increases greatly.

$$M_T = \alpha \cdot \Delta T_g \cdot E_c \frac{bD^3}{12} \qquad (13)$$

5. Conclusion

The following conclusions have been obtained.

(1) Thermal stress calculated from member-design-method closely resembles the results from both Test-T and Test-S. Therefore, member-design-method proposed is satisfactorily practical in the design for the structural portions where are not affected by the boundary of the structure in the case of a comparativery short period of loading.

(2) Thermal stress calculated by applying hypothetical free thermal deflection curvature of beam ϕ , using the relationship between external bending moment and curvature (i.e., M-ϕ curve) obtained from the bending experiments up to the yielding point of the reinforcements under normal temperature (Test-S), almost agree with the thermal stress of Test-T. Therefore, under the same experimental conditions with respect to loading level, loading period and temperature range, thermal stress can be evaluated from the M-ϕ curve under normal temperature without necessarily performing the heating experiment.

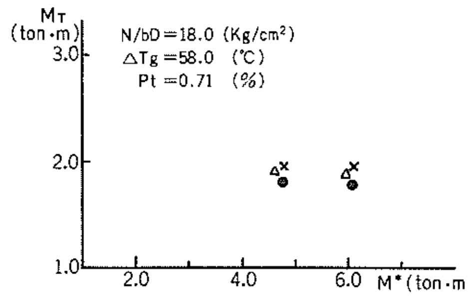


Fig.10 External bending moment and thermal bending moment

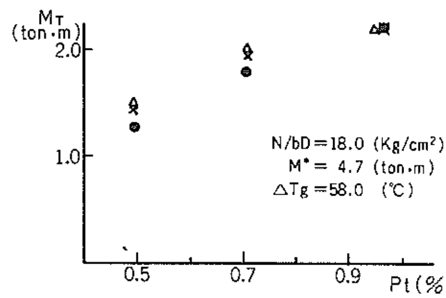


Fig.11 Tension-reinforcement ratio and thermal bending moment

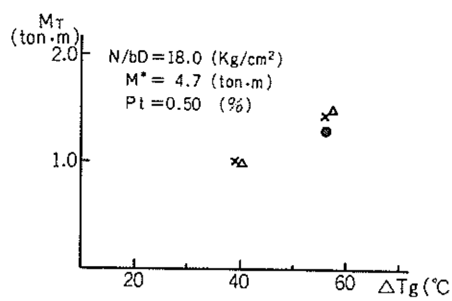


Fig.12 Temperature difference and thermal bending moment

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