A. Proposal on the Thermal Stress Evaluation for the Reinforced Concrete Structures

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Abstract

When the complicated structures such as reactor buildings are subjected to thermal loading, it is predicted that cracks would occur and develop to degrade its structural stiffness. In assessing the thermal stresses it is therefore necessary to analyse the nonlinear behaviours.

However it is usually difficult, at the present state of engineering, to perform so called nonlinear analysis of the complicated structures such as reactor buildings which have three structural dimensions.

In this paper a simplified method of analysis is proposed to assess the structural behaviours under the thermal stresses. We examine the applicability of this method by comparing the results by both rigorous nonlinear analysis and the present analysis.

It is generally of note that the main structural component consists of thick walls which have in-plane structural stiffness. When such structures are subjected to thermal loading, the cracks propagate in the wall loosing the in-plane rigidity. It is possible to predict how much in-plane rigidity looses using the results of elastic stress analysis. We can proceed to analyse numerically by means of finite element method from which we obtain equivalent linear stiffness, the cracks of walls. Then the out-of-plane stresses are determined by already known relationship between bending moment and the deflection curvature.

It will be seen as a conclusion that proposal can produce sufficient results of thermal stresses for complicated structures such as reactor buildings.

1. Introduction

The thermal stress in complicated structures such as reactor buildings are basically classified as constraining stresses which are produced by the degradation of structural stiffness due to cracks at each structural element or by the stress relaxation due to creep property of the structural materials. It is of primary importance to assess their structural stiffness accurately to make the stress analysis.

Particularly it would be the case for analysing complicated structures such as reactor buildings which consist of many rooms separated by walls. When such structures are subjected to thermal loading, the elastic analysis shows that cracks due to membrane stress propagate in walls and slabs of the rooms, which receive less thermal input than other portion of structure. As the results of the thermal loading, the in-plane rigidity,i.e. constraining rigidity degrades.

In this paper we propose a simplified equivalent linear stress analysis by considering the constraining rigidity degradation. The result will be compared with the rigorous non-linear analysis at a portion of structure where we can apply both methods,i.e. simplified analysis and rigorous analysis.

The important assumptions used in this analysis are as follows.

(1) The thermal loading time duration is relatively small.

(2) Material properties used in the analysis are assumed at normal temperature.

(3) No yielding at concrete and steel.

(4) Disregard the concrete creep.

2. Method of Analysis

2.1 Equivalent Linear Analysis

This method is to determine the thermal stresses by combining the linear finite element method(F.E.M.) based upon equivalent stiffness and already published methods. The model for stress analysis is assembled using plate elements without coupling between the in-plane stiffness and the out-of-plane stiffness. Both stiffnesses are independent. What follows are the procedures of this method.

(1) Elastic Analysis

This step is to determine the thermal stresses by F.E.M. based upon elastic rigidities of full cross section of concrete(A). The thermal forces obtained in this step are membrane force and bending moment, respectively denoted by N1 and M1.

(2) Assumption of Reinforcement

The reinforcement of structural members is assumed using N1 and M1.

(3) Modification of Stiffness [5]

The in-plane stiffness of an element where the thermal force (N1) exceeds the limit in tension(σ_t x A) is modified as indicated as Eq.(1) and (2). The stiffness of reinforcement of other elements where no thermal force (N1) exceeds the limit in tension is added to the in-plane stiffness of concrete alone. In this step the out-of-plane stiffness is assumed elastic.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ & E & 0 \\ \text{sym.} & & 0 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \qquad (1)$$

in which orthogonal coordinates are defined along the crack angle as shown in Fig. 1.

$$\begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix} = E \cdot \begin{pmatrix} \mu^4 & \lambda^2\mu^2 & -\lambda\mu^3 \\ & \lambda^4 & -\lambda^3\mu \\ \text{sym.} & & \lambda^2\mu^2 \end{pmatrix} \begin{Bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \gamma_{XY} \end{Bmatrix} \quad (2)$$

in which X,Y represent the directions of reinforcing steel bars,
and $\lambda = \cos\theta$, $\mu = \sin\theta$ (Crack angle (θ) is shown in Fig. 1)

(4) Linear Analysis (1)

The thermal forces are determined again by F.E.M. using modified stiffness mentioned at previous step. The thermal Forces in this step are denoted by N2 and M2.

(5) Evaluation of Bending Moment (Already published method [1]-[4])

Using N2 and M2, bending moment is calculated in the direction of reinforcement as follows.

$$\phi 2 = \frac{M2}{EI_1} \quad , \quad M3 = f(N2,\phi 2) \quad (3)$$

where EI_1; Out-of-plane elastic rigidity

The thermal forces are determined as N2 and M3 following above procedure. The steps so far are called by METHOD-A.

For bending moment redistribution, we set up further two steps as follows.

(6) Modification of the Out-of-Plane Rigidity

Using M3 and $\phi 2$, the out-of-plane rigidities are modified along the direction of reinforcement as follows.

$$EI2 = \frac{M3}{\phi 2} \quad (4)$$

(7) Linear Analysis (2)

The thermal forces are determined again by F.E.M. based upon modified stiffness of both the in-plane rigidities and the out-of plane rigidities. The thermal forces in this step are denoted by N3 and M4.

The thermal forces are determined as N3 and M4 using above procedure. This is noted as METHOD-B.

2.2 Nonlinear Analysis

This method is the nonlinear finite element method. The model is assembled using quardrilateral plate elements divided into layers representing concrete and steel. Layers representing steel have stiffness only in the direction of reinforcement. Numerical analysis is performed using load increment method by modifying stiffnesses of each element. Stiffness of an element where the calculated stress exceeds the limit in tension(σt) is modified as Eq.(1) and (2) and exceeded stress is released as nodal forces.

3. Model for Analysis and the Objective

Using various types of following simple models, we examine the effectiveness of our proposed method by comparing the results between ours and nonlinear analysis.

3.1 Beam Model

As shown in Fig.2, beam elements are used to represent the members subjected to the thermal loadings. The peripheral portion is represented by both rotational and axial springs. By giving various values for springs we obtain the thermal stresses. The relationship between the stiffness degradation due to bending-cracks and the thermal stresses is obtained.

3.2 Plane Frame Model

As shown in Fig.6, this is a frame model with axial springs to represent peripheral constraint. By this model, we examine the thermal stress when one of three rooms is subjected to thermal loading.

3.3 Cylinder Model

As shown in Fig.11, this model is fixed at its and to represent constraint condition. This is to study the thermal stresses in the bi-axial stress-strain state.

3.4 Plane Model

As shown in Fig.12, this model is consisted of two walls. We examine how to assess the constraint of the other wall after memberane tensile cracks, when one of two walls is subjected to thermal loading, for following two cases.

CASE-1; is to predict the cracked zone and angle, using the principal stresses due to elastic analysis, and modify the in-plane stiffness in accordance with Eq.(1) and (2).

CASE-2; is to determine the cracked zone and angle, using nonlinear analysis, and modify the in-plane stiffness in accordance with Eq.(1) and (2).

3.5 Box Model

As shown in Fig.19, this is three dimensional Model which is consisted of three rooms. By this model, we examine the thermal stresses when one of three rooms is subjected to thermal loading.

4. Calculated Results

4.1 Beam Model

The calculated forces with rotational springs assumed infinite and various values for axial spring are shown in Figs.3-4. As shown in them, when the value of axial spring is constant, the axial forces are not reduced by the stiffness degradation of bending cracks. By giving a constant value for axial spring and various values for rotational springs, we examined relationship between the propagation of bending cracks in depth and axial forces due to thermal loading. This calculated result is shown in Fig.5. As shown in it, the axial forces conversely increased by the stiffness degradation of bending-cracks when the value of axial spring is constant.

4.2 Other Models

The calculated results in various types of models are as follows.

Plane Frame Model	;	Shown in Figs.7-10
Cylinder Model	;	Shown in Figs.13-15
Plane Model	;	Shown in Figs.16-18
Box Model	;	Shown in Figs.20-22

As shown in them, the calculated forces of both method agree well with the ones of nonlinear analysis.

5. Conclusion

It is very important to evaluate the in-plane forces accurately in assessing the thermal stresses of such complicated structures as reactor buildings.

We believe our method herein proposed(METHOD-A) provides sufficient results to predict the thermal stresses in these structures as a structural design procedure, although we find advantages of METHOD-B when accuracy is desired for nonlinear stress analysis.

Table-1 Material Properties of Concrete and Steel Bar

Concrete		Steel Bar	
E_c = 210	t/cm²	E_s = 2100	t/cm²
α_c = 0.00001	1/°C	α_s = 0.00001	1/°C
ν = 0.167			
σ_t = 0 , 21	kg/cm²		

E : Young's Modulus

α : Thermal Expansion Coefficient

ν : Poisson's Ratio

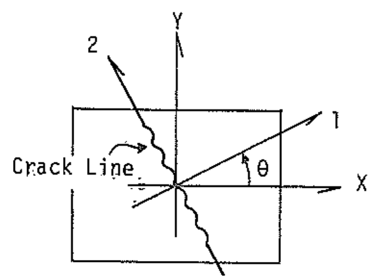

Fig. 1 Notation of Crack Angle(θ)

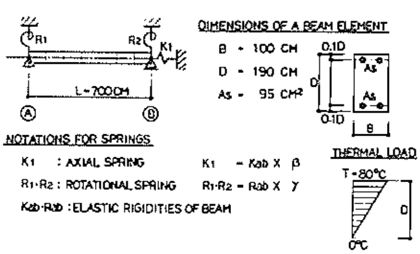

Fig. 2 Idealization of Beam Model

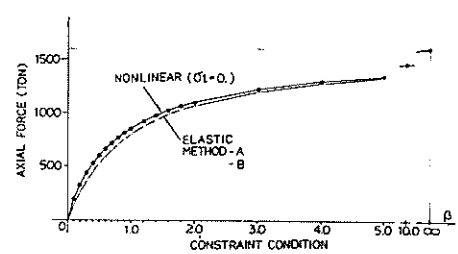

Fig. 3 Axial Force-Constraint Condition

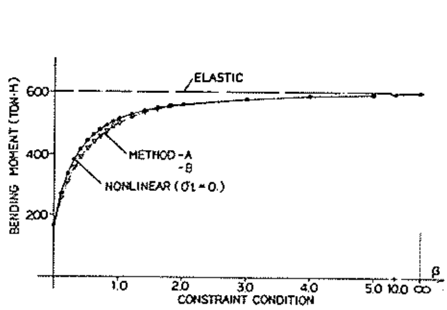

Fig. 4 Bending Moment-Constraint Condition

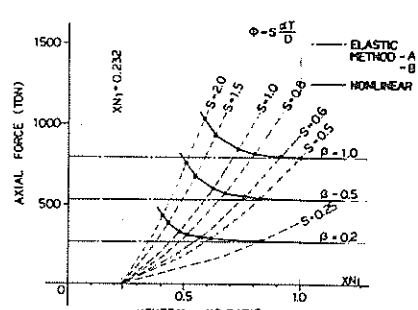

Fig. 5 Axial Force-Constraint Condition

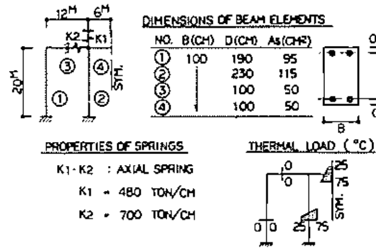

Fig. 6 Idealization of Plane Frame Model

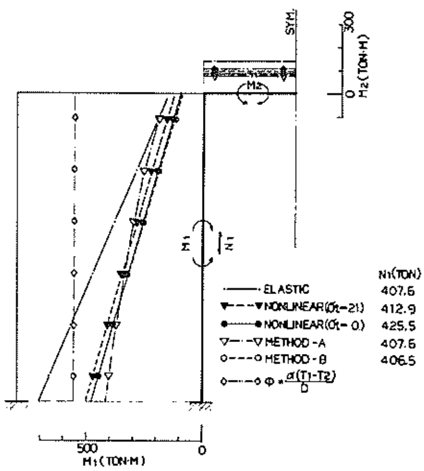

Fig. 7 Bending Moment

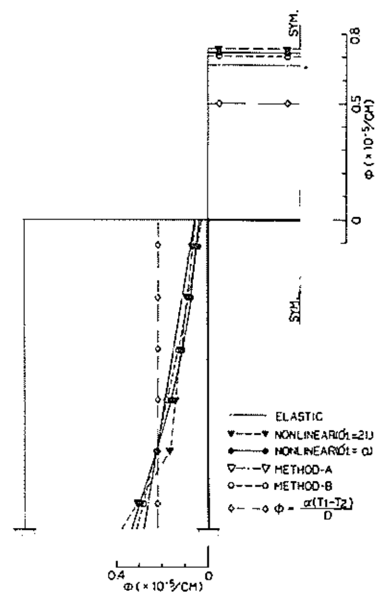

Fig. 8 Curvature Diagram

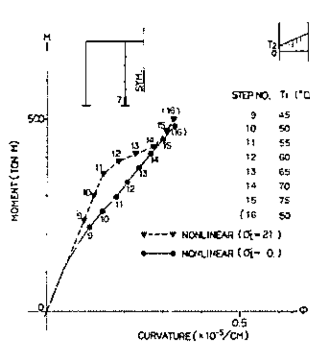

Fig. 9 M−Φ Diagram(ELEM. 7)

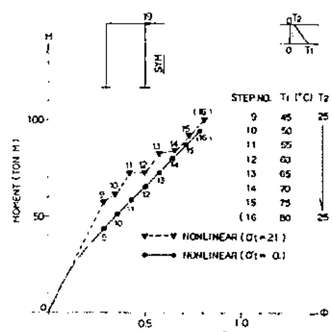

Fig. 10 M−Φ Diagram(ELEM. 19)

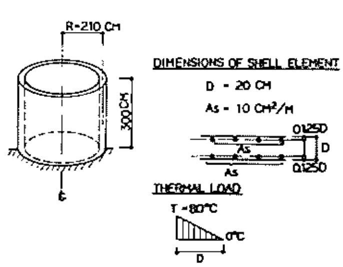

Fig. 11 Idealization of Cylinder Model

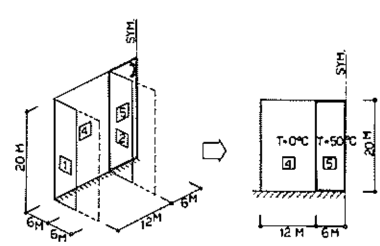

Fig. 12 Idealization of Plane Model

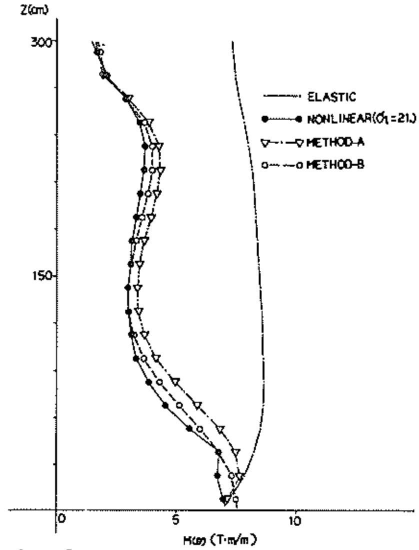

Fig. 13 Circumferential Bending Moment

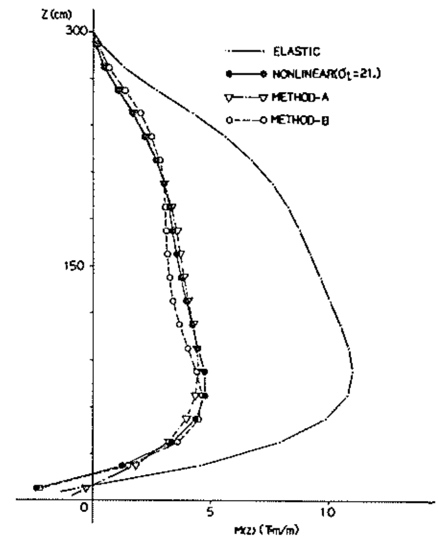

Fig. 14 Meridianal Bending Moment

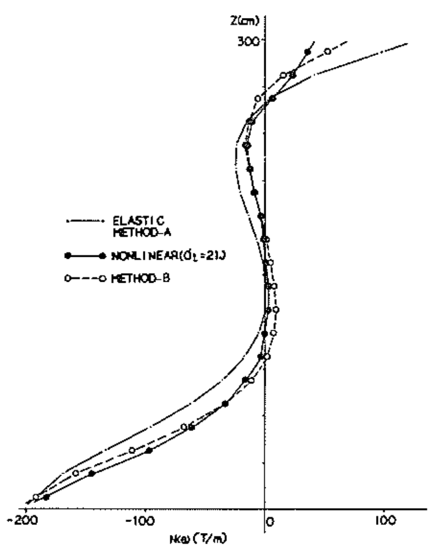

Fig. 15 Circumferential Membrane Force

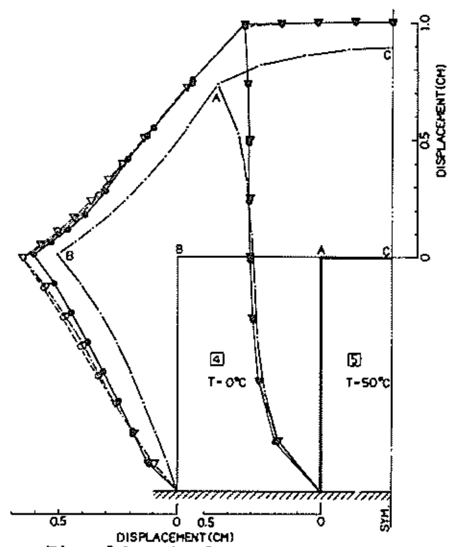

Fig. 16 Displacement

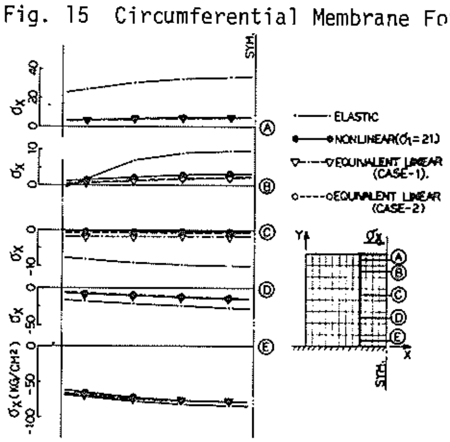

Fig. 17 Horizontal Stress

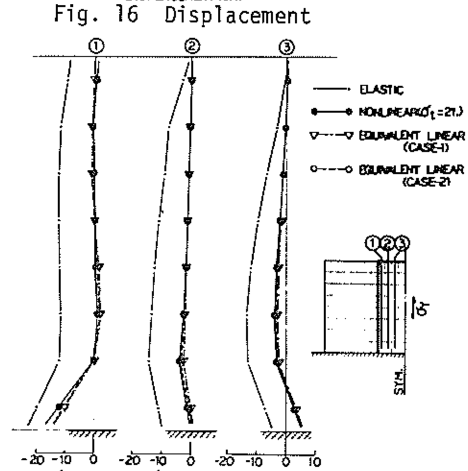

Fig. 18 Vertical Stress

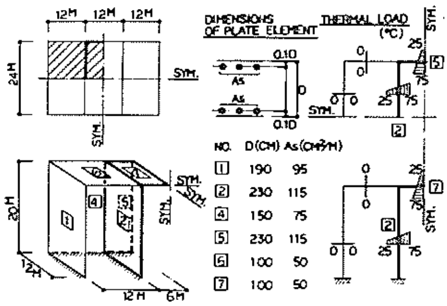

Fig. 19 Idealization of Box Model

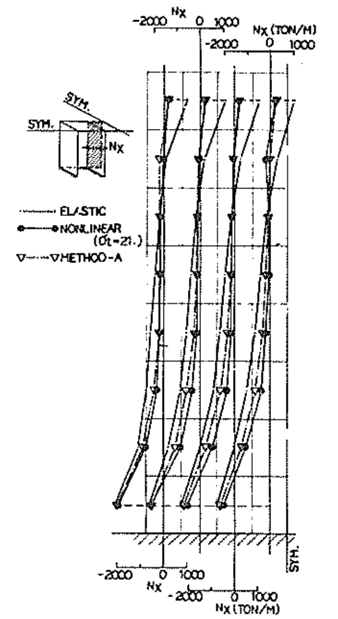

Fig. 20 Horizontal Membrane Force

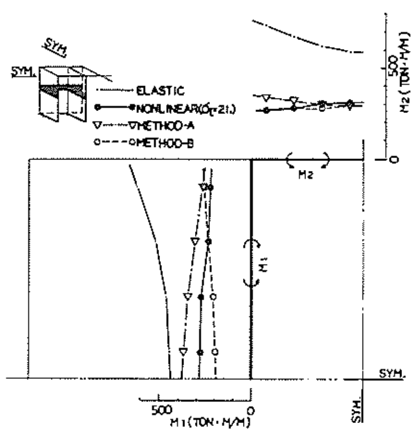

Fig. 21 Bending Moment

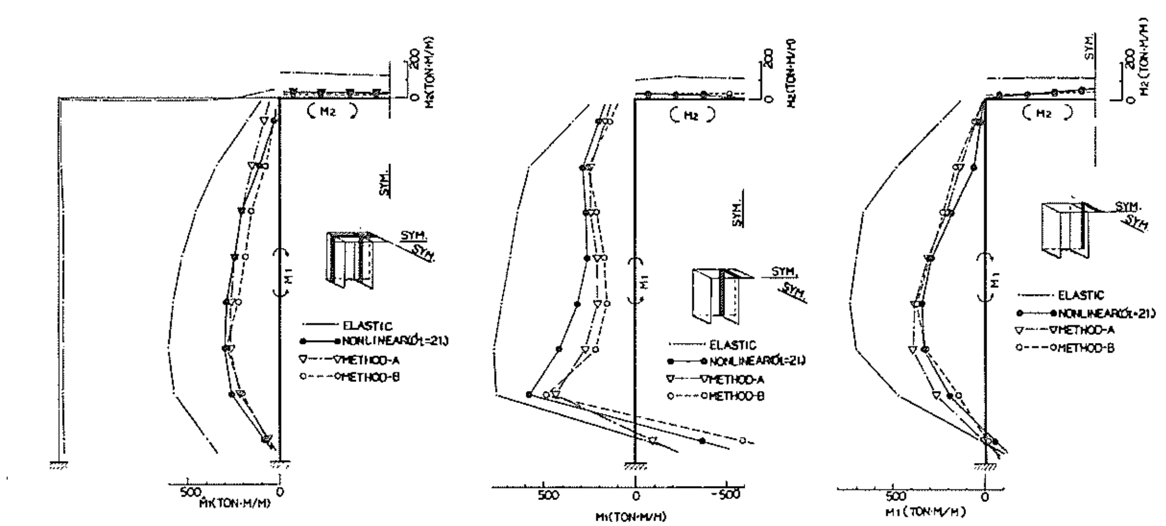

Fig. 22 Bending Moment

References

[1] K. IRIND, "A Design Method of Reinforced Concrete under Thermal Stresses", Annual Conference Papers, A.I.J. October, 1977. (In Japanese)

[2] M. UEDA, T. MOCHIDA, "A Calculus of Thermal Stress in Reinforced Members", Annual Conference Papers, A.I.J. September, 1978. (In Japanese)

[3] S. SATD, et al., "Pseudo Elastic-Plastic Analysis of Reinforced Concrete Considering Nonlinearity of Material", Technical Symposium of Computer Engineering, March, 1981. (In Japanese)

[4] G. GURFINKEL, "Thermal Effects in Wall of Nuclear Containments Elastic and In elastic Behaviour", SMIRT (Berlin), 1971

[5] H. Noguchi (Structural Standard Committee of A.I.J.), "Data of Ultimate Strength Design for Reinforced Concrete - Series 2", Journal of Architecture and Building Science, Vol. 94, No. 1146, February. 1979.(In Japanese)